Chapter 1

Qualities of Measurements

INTRODUCTION 1.1

Instrumentation is a technology of measurement which serves not only science but all branches of engineering, medicine, and almost every human endeavour. The knowledge of any parameter largely depends on the measurement. The indepth knowledge of any parameter can be easily understood by the use of measurement, and further modifications can also be obtained.

Measuring is basically used to monitor a process or operation, or as well as the controlling process. For example, thermometers, barometers, anemometers are used to indicate the environmental conditions. Similarly, water, gas and electric meters are used to keep track of the quantity of the commodity used, and also special monitoring equipment are used in hospitals.

Whatever may be the nature of application, intelligent selection and use of measuring equipment depends on a broad knowledge of what is available and how the performance of the equipment renders itself for the job to be performed.

But there are some basic measurement techniques and devices that are useful and will continue to be widely used also. There is always a need for improvement and development of new equipment to solve measurement problems.

The major problem encountered with any measuring instrument is the error. Therefore, it is obviously necessary to select the appropriate measuring instrument and measurement method which minimises error. To avoid errors in any experimental work, careful planning, execution and evaluation of the experiment are essential.

The basic concern of any measurement is that the measuring instrument should not effect the quantity being measured; in practice, this non-interference principle is never strictly obeyed. Null measurements with the use of feedback in an instrument minimise these interference effects.

PERFORMANCE CHARACTERISTICS 1.2

A knowledge of the performance characteristics of an instrument is essential for selecting the most suitable instrument for specific measuring jobs. It consists of two basic characteristics—static and dynamic.

STATIC CHARACTERISTICS 1.3

The static characteristics of an instrument are, in general, considered for instruments which are used to measure an unvarying process condition. All the static performance characteristics are obtained by one form or another of a process called calibration. There are a number of related definitions (or characteristics), which are described below, such as accuracy, precision, repeatability, resolution, errors, sensitivity, etc.

1. ***Instrument*** A device or mechanism used to determine the present value of the quantity under measurement.
2. ***Measurement*** The process of determining the amount, degree, or capacity by comparison (direct or indirect) with the accepted standards of the system units being used.
3. ***Accuracy*** The degree of exactness (closeness) of a measurement compared to the expected (desired) value.
4. ***Resolution*** The smallest change in a measured variable to which an instrument will respond.
5. ***Precision*** A measure of the consistency or repeatability of measurements, i.e. successive reading do not differ. (Precision is the consistency of the instrument output for a given value of input).
6. ***Expected value*** The design value, i.e. the most probable value that calculations indicate one should expect to measure.
7. ***Error*** The deviation of the true value from the desired value.
8. ***Sensitivity*** The ratio of the change in output (response) of the instrument to a change of input or measured variable.

ERROR IN MEASUREMENT 1.4

Measurement is the process of comparing an unknown quantity with an accepted standard quantity. It involves connecting a measuring instrument into the system under consideration and observing the resulting response on the instrument. The measurement thus obtained is a quantitative measure of the so-called "true value" (since it is very difficult to define the true value, the term "expected value" is used). Any measurement is affected by many variables, therefore the results rarely reflect the expected value. For example, connecting a measuring instrument into the circuit under consideration always disturbs (changes) the circuit, causing the measurement to differ from the expected value.

Some factors that affect the measurements are related to the measuring instruments themselves. Other factors are related to the person using the instrument. The degree to which a measurement nears the expected value is expressed in terms of the error of measurement.

Error may be expressed either as absolute or as percentage of error.

Absolute error may be defined as the difference between the expected value of the variable and the measured value of the variable, or

$$e = Y_n - X_n$$

where e = absolute error
Y_n = expected value
X_n = measured value

Therefore $$\% \text{ Error} = \frac{\text{Absolute value}}{\text{Expected value}} \times 100 = \frac{e}{Y_n} \times 100$$

Therefore $$\% \text{ Error} = \left(\frac{Y_n - X_n}{Y_n}\right) \times 100$$

It is more frequently expressed as a accuracy rather than error.

Therefore $$A = 1 - \left|\frac{Y_n - X_n}{Y_n}\right|$$

where A is the relative accuracy.
Accuracy is expressed as % accuracy

$$a = 100\% - \%\text{ error}$$
$$a = A \times 100\ \%$$

where a is the % accuracy.

Example 1.1 (a) *The expected value of the voltage across a resistor is 80 V. However, the measurement gives a value of 79 V. Calculate (i) absolute error, (ii) % error, (iii) relative accuracy, and (iv) % of accuracy.*

Solution

(i) Absolute error $e = Y_n - X_n = 80 - 79 = 1$ V

(ii) $\% \text{ Error} = \frac{Y_n - X_n}{Y_n} \times 100 = \frac{80 - 79}{80} \times 100 = 1.25\%$

(iii) Relative Accuracy

$$A = 1 - \left|\frac{Y_n - X_n}{Y_n}\right| = 1 - \left|\frac{80 - 79}{80}\right|$$

$\therefore$ $A = 1 - 1/80 = 79/80 = 0.9875$

(iv) % of Accuracy $a = 100 \times A = 100 \times 0.9875 = 98.75\%$
or $a = 100\% - \%\text{ of error} = 100\% - 1.25\% = 98.75\%$

Example 1.1 (b) *The expected value of the current through a resistor is 20 mA. However the measurement yields a current value of 18 mA. Calculate (i) absolute error (ii) % error (iii) relative accuracy (iv) % accuracy*

Solution

Step 1: Absolute error

$$e = Y_n - X_n$$

where e = error, Y_n = expected value, X_n = measured value

Given $Y_n = 20$ mA and $X_n = 18$ mA

Therefore $e = Y_n - X_n = 20\text{ mA} - 18\text{ mA} = 2\text{ mA}$

Step 2: % error

$$\%\text{ error} = \frac{Y_n - X_n}{Y_n} \times 100 = \frac{20\text{ mA} - 18\text{ mA}}{20\text{ mA}} \times 100 = \frac{2\text{ mA}}{20\text{ mA}} \times 100 = 10\%$$

Step 3: Relative accuracy

$$A = 1 - \left|\frac{Y_n - X_n}{Y_n}\right| = 1 - \left|\frac{20\text{ mA} - 18\text{ mA}}{20\text{ mA}}\right| = 1 - \frac{2}{20} = 1 - 0.1 = 0.90$$

Step 4: % accuracy

$$a = 100\% - \%\text{error} = 100\% - 10\% = 90\%$$

and $$a = A \times 100\% = 0.90 \times 100\% = 90\%$$

If a measurement is accurate, it must also be precise, i.e. Accuracy means precision. However, a precision measurement may not be accurate. (The precision of a measurement is a quantitative or numerical indication of the closeness with which a repeated set of measurement of the same variable agree with the average set of measurements.) Precision can also be expressed mathematically as

$$P = 1 - \left|\frac{X_n - \bar{X}_n}{\bar{X}_n}\right|$$

where X_n = value of the nth measurement

$\bar{X}_n$ = average set of measurement

Example 1.2 *Table 1.1 gives the set of 10 measurement that were recorded in the laboratory. Calculate the precision of the 6th measurement.*

Table 1.1

Measurement number	*Measurement value* X_n
1	98
2	101
3	102
4	97
5	101
6	100
7	103
8	98
9	106
10	99

Solution The average value for the set of measurements is given by

$$\bar{X}_n = \frac{\text{Sum of the 10 measurement values}}{10}$$

$$= \frac{1005}{10} = 100.5$$

$$\text{Precision} = 1 - \left|\frac{X_n - \bar{X}_n}{\bar{X}_n}\right|$$

For the 6th reading

$$\text{Precision} = 1 - \left|\frac{100 - 100.5}{100.5}\right| = 1 - \frac{0.5}{100.5} = \frac{100}{100.5} = 0.995$$

The accuracy and precision of measurements depend not only on the quality of the measuring instrument but also on the person using it. However, whatever the quality of the instrument and the case exercised by the user, there is always some error present in the measurement of physical quantities.

TYPES OF STATIC ERROR 1.5

The static error of a measuring instrument is the numerical difference between the true value of a quantity and its value as obtained by measurement, i.e. repeated measurement of the same quantity gives different indications. Static errors are categorised as gross errors or human errors, systematic errors, and random errors.

1.5.1 Gross Errors

These errors are mainly due to human mistakes in reading or in using instruments or errors in recording observations. Errors may also occur due to incorrect adjustment of instruments and computational mistakes. These errors cannot be treated mathematically.

The complete elimination of gross errors is not possible, but one can minimise them. Some errors are easily detected while others may be elusive.

One of the basic gross errors that occurs frequently is the improper use of an instrument. The error can be minimized by taking proper care in reading and recording the measurement parameter.

In general, indicating instruments change ambient conditions to some extent when connected into a complete circuit. (Refer Examples 1.3(a) and (b)).

(One should therefore not be completely dependent on one reading only; at least three separate readings should be taken, preferably under conditions in which instruments are switched off and on.)

1.5.2 Systematic Errors

These errors occur due to shortcomings of the instrument, such as defective or worn parts, or ageing or effects of the environment on the instrument.

These errors are sometimes referred to as bias, and they influence all measurements of a quantity alike. A constant uniform deviation of the operation of an instrument is known as a systematic error. There are basically three types of systematic errors—(i) Instrumental, (ii) Environmental, and (iii) Observational.

(i) Instrumental Errors

Instrumental errors are inherent in measuring instruments, because of their mechanical structure. For example, in the D'Arsonval movement, friction in the bearings of various moving components, irregular spring tensions, stretching of the spring, or reduction in tension due to improper handling or overloading of the instrument.

Instrumental errors can be avoided by

(a) selecting a suitable instrument for the particular measurement applications. (Refer Examples 1.3 (a) and (b)).
(b) applying correction factors after determining the amount of instrumental error.
(c) calibrating the instrument against a standard.

(ii) Environmental Errors

Environmental errors are due to conditions external to the measuring device, including conditions in the area surrounding the instrument, such as the effects of change in temperature, humidity, barometric pressure or of magnetic or electrostatic fields.

These errors can also be avoided by (i) air conditioning, (ii) hermetically sealing certain components in the instruments, and (iii) using magnetic shields.

(iii) Observational Errors

Observational errors are errors introduced by the observer. The most common error is the parallax error introduced in reading a meter scale, and the error of estimation when obtaining a reading from a meter scale.

These errors are caused by the habits of individual observers. For example, an observer may always introduce an error by consistently holding his head too far to the left while reading a needle and scale reading.

In general, systematic errors can also be subdivided into static and dynamic errors. Static errors are caused by limitations of the measuring device or the physical laws governing its behaviour. Dynamic errors are caused by the instrument not responding fast enough to follow the changes in a measured variable.

Example 1.3 (a) *A voltmeter having a sensitivity of 1 kΩ/V is connected across an unknown resistance in series with a milliammeter reading 80 V on 150 V scale. When the milliammeter reads 10 mA, calculate the (i) Apparent resistance of the unknown resistance, (ii) Actual resistance of the unknown resistance, and (iii) Error due to the loading effect of the voltmeter.*

Solution

(i) The total circuit resistance $R_T = \dfrac{V_T}{I_T} = \dfrac{80}{10\text{ mA}} = 8\text{ k}\Omega$

(Neglecting the resistance of the milliammeter.)

(ii) The voltmeter resistance equals $R_v = 1000\ \Omega/\text{V} \times 150 = 150\text{ k}\Omega$

$\therefore$ actual value of unknown resistance $R_x = \dfrac{R_T \times R_v}{R_v - R_T} = \dfrac{8\text{k} \times 150\text{k}}{150\text{k} - 8\text{k}}$

$$= \frac{1200\text{k}^2}{142\text{k}} = 8.45\ \Omega$$

(iii) $\%\text{ error} = \dfrac{\text{Actual value} - \text{Apparent value}}{\text{Actual value}} = \dfrac{8.45\text{k} - 8\text{k}}{8.45\text{k}} \times 100$

$$= 0.053 \times 100 = 5.3\%$$

Example 1.3 (b) *Referring to Ex. 1.3 (a), if the milliammeter reads 600 mA and the voltmeter reads 30 V on a 150 V scale, calculate the following: (i) Apparent, resistance of the unknown resistance. (ii) Actual resistance of the unknown resistance. (iii) Error due to loading effect of the voltmeter.*

Comment on the loading effect due to the voltmeter for both Examples 1.3 (a) and (b). (Voltmeter sensitivity given 1000 Ω/V.)

Solution

1. The total circuit resistance is given by

$$R_T = \frac{V_T}{I_T} = \frac{30}{0.6} = 50\ \Omega$$

2. The voltmeter resistance R_v equals

$$R_v = 1000\ \Omega/\text{V} \times 150 = 150\text{ k}\Omega$$

Neglecting the resistance of the milliammeter, the value of unknown resistance = 50 Ω

$$R_x = \frac{R_T \times R_v}{R_v - R_T} = \frac{50 \times 150\text{ k}}{150\text{ k} - 50} = \frac{7500\text{ k}}{149.5\text{ k}} = 50.167\ \Omega$$

$$\%\text{ Error} = \frac{50.167 - 50}{50.167} \times 100 = \frac{0.167}{50.167} \times 100 = 0.33\%$$

In Example 1.3 (a), a well calibrated voltmeter may give a misleading resistance when connected across two points in a high resistance circuit. The same voltmeter, when connected in a low resistance circuit (Example 1.3 (b)) may give a more dependable reading. This show that voltmeters have a loading effect in the circuit during measurement.

1.5.3 Random Errors

These are errors that remain after gross and systematic errors have been substantially reduced or at least accounted for. Random errors are generally an accumulation of a large number of small effects and may be of real concern only in measurements requiring a high degree of accuracy. Such errors can be analyzed statistically.

These errors are due to unknown causes, not determinable in the ordinary process of making measurements. Such errors are normally small and follow the laws of probability. Random errors can thus be treated mathematically.

For example, suppose a voltage is being monitored by a voltmeter which is read at 15 minutes intervals. Although the instrument operates under ideal environmental conditions and is accurately calibrated before measurement, it still gives readings that vary slightly over the period of observation. This variation cannot be corrected by any method of calibration or any other known method of control.

SOURCES OF ERROR 1.6

The sources of error, other than the inability of a piece of hardware to provide a true measurement, are as follows:

1. Insufficient knowledge of process parameters and design conditions
2. Poor design
3. Change in process parameters, irregularities, upsets, etc.
4. Poor maintenance
5. Errors caused by person operating the instrument or equipment
6. Certain design limitations

DYNAMIC CHARACTERISTICS 1.7

Instruments rarely respond instantaneously to changes in the measured variables. Instead, they exhibit slowness or sluggishness due to such things as mass, thermal capacitance, fluid capacitance or electric capacitance. In addition to this, pure delay in time is often encountered where the instrument waits for some reaction to take place. Such industrial instruments are nearly always used for measuring quantities that fluctuate with time. Therefore, the dynamic and transient behaviour of the instrument is as important as the static behaviour.

The dynamic behaviour of an instrument is determined by subjecting its primary element (sensing element) to some unknown and predetermined variations in the measured quantity. The three most common variations in the measured quantity are as follows:

1. *Step* change, in which the primary element is subjected to an instantaneous and finite change in measured variable.
2. *Linear* change, in which the primary element is following a measured variable, changing linearly with time.

3. *Sinusoidal* change, in which the primary element follows a measured variable, the magnitude of which changes in accordance with a sinusoidal function of constant amplitude.

The dynamic characteristics of an instrument are (i) speed of response, (ii) fidelity, (iii) lag, and (iv) dynamic error.

(i) *Speed of Response* It is the rapidity with which an instrument responds to changes in the measured quantity.

(ii) *Fidelity* It is the degree to which an instrument indicates the changes in the measured variable without dynamic error (faithful reproduction).

(iii) *Lag* It is the retardation or delay in the response of an instrument to changes in the measured variable.

(iv) *Dynamic Error* It is the difference between the true value of a quantity changing with time and the value indicated by the instrument, if no static error is assumed.

When measurement problems are concerned with rapidly varying quantities, the dynamic relations between the instruments input and output are generally defined by the use of differential equations.

1.7.1 Dynamic Response of Zero Order Instruments

We would like an equation that describes the performance of the zero order instrument exactly. The relations between any input and output can, by using suitable simplifying assumptions, be written as

$$a_n \frac{d^n x_o}{dt^n} + a_{n-1} \frac{d^{n-1} x_o}{dt^{n-1}} + \cdots + a_1 \frac{dx_o}{dt} + a_0 x_o$$

$$= b_m \frac{d^m x_i}{dt^m} + \cdots + b_{m-1} \frac{d^{m-1} x_i}{dt^{m-1}} + \cdots + b_1 \frac{dx_i}{dt} + b_0 \simeq x_i \quad (1.1)$$

where x_o = output quantity

x_i = input quantity

t = time

a's and b's are combinations of systems physical parameters, assumed constant.

When all the a's and b's, other than a_0 and b_0 are assumed to be zero, the differential equation degenerates into the simple equation given as

$$a_0 x_o = b_0 x_i \quad (1.2)$$

Any instrument that closely obeys Eq. (1.2) over its intended range of operating conditions is defined as a zero-order instrument. The static sensitivity (or steady state gain) of a zero-order instrument may be defined as follows

$$x_o = \frac{b_0}{a_0} x_i = K.x_i$$

where $K = b_0/a_0$ = static sensitivity

Since the equation $x_o = K\, x_i$ is an algebraic equation, it is clear that no matter how x_i might vary with time, the instrument output (reading) follows it perfectly with no distortion or time lag of any sort. Thus, a zero-order instrument represents ideal or perfect dynamic performance. A practical example of a zero order instrument is the displacement measuring potentiometer.

1.7.2 Dynamic Response of a First Order Instrument

If in Eq. (1.1) all a's and b's other than a_1, a_0, b_0 are taken as zero, we get

$$a_1 \frac{dx_o}{dt} + a_0 x_o = b_0 x_i$$

Any instrument that follows this equation is called a first order instrument. By dividing by a_0, the equation can be written as

$$\frac{a_1}{a_0}\frac{dx_o}{dt} + x_o = \frac{b_0}{a_0} x_i$$

or $$(\tau \cdot D + 1) \cdot x_o = K\, x_i$$

where $\tau = a_1/a_0$ = time constant

$K = b_0/a_0$ = static sensitivity

The time constant τ always has the dimensions of time while the static sensitivity K has the dimensions of output/input. The operational transfer function of any first order instrument is

$$\frac{x_o}{x_i} = \frac{K}{\tau D + 1}$$

A very common example of a first-order instrument is a mercury-in-glass thermometer.

1.7.3 Dynamic Response of Second Order Instrument

A second order instrument is defined as one that follows the equation

$$a_2 \frac{d^2 x_o}{dt^2} + a_1 \frac{dx_o}{dt} + a_0 x_o = b_0 x_i$$

The above equations can be reduced as

$$\left(\frac{D^2}{\omega_n^2} + \frac{2\xi D}{\omega_n} + 1\right) \cdot x_o = K x_i$$

where $\omega_n = \sqrt{\dfrac{a_0}{a_2}}$ = undamped natural frequency in radians/time

$2\xi = a_1/\sqrt{a_0\, a_2}$ = damping ratio

$K = b_0/a_0$ = static sensitivity

Any instrument following this equation is a second order instrument. A practical example of this type is the spring balance. Linear devices range from mass spring arrangements, transducers, amplifiers and filters to indicators and recorders.

Most devices have first or second order responses, i.e. the equations of motion describing the devices are either first or second order linear differentials. For example, a search coil and mercury-in-glass thermometer have a first order response. Filters used at the output of a phase sensitive detector and amplifiers used in feedback measuring systems essentially have response due to a single time constant. First order systems involve only one kind of energy, e.g. thermal energy in the case of a thermometer, while a characteristic feature of second order system is an exchange between two types of energy, e.g. electrostatic and electromagnetic energy in electrical LC circuits, moving coil indicators and electromechanical recorders.

STATISTICAL ANALYSIS 1.8

The statistical analysis of measurement data is important because it allows an analytical determination of the uncertainty of the final test result. To make statistical analysis meaningful, a large number of measurements is usually required. Systematic errors should be small compared to random errors, because statistical analysis of data cannot remove a fixed bias contained in all measurements.

1.8.1 Arithmetic Mean

The most probable value of a measured variable is the arithmetic mean of the number of readings taken. The best approximation is possible when the number of readings of the same quantity is very large. The arithmetic mean of n measurements at a specific count of the variable x is given by the expression

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \cdots + x_n}{n} = \frac{\sum_{n=1}^{n} x_n}{n}$$

where $\bar{x}$ = Arithmetic mean
x_n = nth reading taken
n = total number of readings

1.8.2 Deviation from the Mean

This is the departure of a given reading from the arithmetic mean of the group of readings. If the deviation of the first reading, x_1, is called d_1 and that of the second reading x_2 is called d_2, and so on,

The deviations from the mean can be expressed as

$$d_1 = x_1 - \bar{x},\ d_2 = x_2 - \bar{x}\ \ldots,\ \text{similarly } d_n = x_n - \bar{x}$$

The deviation may be positive or negative. The algebraic sum of all the deviations must be zero.

Example 1.4 *For the following given data, calculate*
(i) Arithmetic mean; (ii) Deviation of each value; (iii) Algebraic sum of the deviations
Given

$$x_1 = 49.7;\ x_2 = 50.1;\ x_3 = 50.2;\ x_4 = 49.6;\ x_5 = 49.7$$

Solution

(i) The arithmetic mean is calculated as follows

$$\bar{x} = \frac{x_1 + x_2 + x_3 + x_4 + x_5}{5}$$

$$= \frac{49.7 + 50.1 + 50.2 + 49.6 + 49.7}{5} = 49.86$$

(ii) The deviations from each value are given by

$$d_1 = x_1 - \bar{x} = 49.7 - 49.86 = -0.16$$
$$d_2 = x_2 - \bar{x} = 50.1 - 49.86 = +0.24$$
$$d_3 = x_3 - \bar{x} = 50.2 - 49.86 = +0.34$$
$$d_4 = x_4 - \bar{x} = 49.6 - 49.86 = -0.26$$
$$d_5 = x_5 - \bar{x} = 49.7 - 49.86 = -0.16$$

(iii) The algebraic sum of the deviation is

$$d_{\text{total}} = -0.16 + 0.24 + 0.34 - 0.26 - 0.16$$
$$= +0.58 - 0.58 = 0$$

1.8.3 Average Deviations

The average deviation is an indication of the precision of the instrument used in measurement. Average deviation is defined as the sum of the absolute values of the deviation divided by the number of readings. The absolute value of the deviation is the value without respect to the sign.

Average deviation may be expressed as

$$D_{\text{av}} = \frac{|d_1| + |d_2| + |d_3| + \cdots + |d_n|}{n}$$

or

$$D_{\text{av}} = \frac{\sum |d_n|}{n}$$

where D_{av} = average deviation

$|d_1|, |d_2|, \ldots, |d_n|$ = Absolute value of deviations

and n = total number of readings

Highly precise instruments yield a low average deviation between readings.

Example 1.5 *Calculate the average deviation for the data given in Example 1.4.*

Solution The average deviation is calculated as follows

$$D_{av} = \frac{|d_1| + |d_2| + |d_3| + \cdots + |d_n|}{n}$$

$$= \frac{|-0.16| + |0.24| + |0.34| + |-0.26| + |-0.16|}{5}$$

$$= \frac{1.16}{5} = 0.232$$

Therefore, the average deviation = 0.232.

1.8.4 Standard Deviation

The standard deviation of an infinite number of data is the Square root of the sum of all the individual deviations squared, divided by the number of readings. It may be expressed as

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + \cdots + d_n^2}{n}} = \sqrt{\frac{d_n^2}{n}}$$

where σ = standard deviation

The standard deviation is also known as root mean square deviation, and is the most important factor in the statistical analysis of measurement data. Reduction in this quantity effectively means improvement in measurement.

For small readings ($n < 30$), the denominator is frequently expressed as $(n - 1)$ to obtain a more accurate value for the standard deviation.

Example 1.6 *Calculate the standard deviation for the data given in Example 1.4.*

Solution

$$\text{Standard deviation} = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + \cdots + d_n^2}{n - 1}}$$

$$\sigma = \sqrt{\frac{(-0.16)^2 + (0.24)^2 + (0.34)^2 + (-0.26)^2 + (-0.16)^2}{5 - 1}}$$

$$\sigma = \sqrt{\frac{0.0256 + 0.0576 + 0.1156 + 0.0676 + 0.0256}{4}}$$

$$\sigma = \sqrt{\frac{0.292}{4}} = \sqrt{0.073} = 0.27$$

Therefore, the standard deviation is 0.27.

1.8.5 Limiting Errors

Most manufacturers of measuring instruments specify accuracy within a certain % of a full scale reading. For example, the manufacturer of a certain voltmeter may specify the instrument to be accurate within ± 2% with full scale deflection. This specification is called the limiting error. This means that a full scale deflection reading is guaranteed to be within the limits of 2% of a perfectly accurate reading; however, with a reading less than full scale, the limiting error increases.

Example 1.7 *A 600 V voltmeter is specified to be accurate within ± 2% at full scale. Calculate the limiting error when the instrument is used to measure a voltage of 250 V.*

Solution The magnitude of the limiting error is $0.02 \times 600 = 12$ V.

Therefore, the limiting error for 250 V is $12/250 \times 100 = 4.8\%$

Example 1.8 (a) *A 500 mA voltmeter is specified to be accurate with ±2%. Calculate the limiting error when instrument is used to measure 300 mA.*

Solution Given accuracy of $0.02 = \pm 2\%$

Step 1: The magnitude of limiting error is $= 500 \text{ mA} \times 0.02 = 10$ mA

Step 2: Therefore the limiting error at 300 mA $= \dfrac{10 \text{ mA}}{300 \text{ mA}} \times 100\% = 3.33\%$

Example 1.8 (b) *A voltmeter reading 70 V on its 100 V range and an ammeter reading 80 mA on its 150 mA range are used to determine the power dissipated in a resistor. Both these instruments are guaranteed to be accurate within ±1.5% at full scale deflection. Determine the limiting error of the power.*

Solution The magnitude of the limiting error for the voltmeter is

$$0.015 \times 100 = 1.5 \text{ V}$$

The limiting error at 70 V is

$$\frac{1.5}{70} \times 100 = 2.143 \%$$

The magnitude of limiting error of the ammeter is

$$0.015 \times 150 \text{ mA} = 2.25 \text{ mA}$$

The limiting error at 80 mA is

$$\frac{2.25 \text{ mA}}{80 \text{ mA}} \times 100 = 2.813 \%$$

Therefore, the limiting error for the power calculation is the sum of the individual limiting errors involved.

Therefore, limiting error = 2.143 % + 2.813 % = 4.956 %

STANDARD 1.9

A standard is a physical representation of a unit of measurement. A known accurate measure of physical quantity is termed as a standard. These standards are used to determine the values of other physical quantities by the comparison method.

In fact, a unit is realized by reference to a material standard or to natural phenomena, including physical and atomic constants. For example, the fundamental unit of length in the International system (SI) is the metre, defined as the distance between two fine lines engraved on gold plugs near the ends of a platinum-iridium alloy at 0°C and mechanically supported in a prescribed manner.

Similarly, different standards have been developed for other units of measurement (including fundamental units as well as derived mechanical and electrical units). All these standards are preserved at the International Bureau of Weight and Measures at Sèvres, Paris.

Also, depending on the functions and applications, different types of "standards of measurement" are classified in categories (i) international, (ii) primary, (iii) secondary, and (iv) working standards.

1.9.1 International Standards

International standards are defined by International agreement. They are periodically evaluated and checked by absolute measurements in terms of fundamental units of Physics. They represent certain units of measurement to the closest possible accuracy attainable by the science and technology of measurement. These International standards are not available to ordinary users for measurements and calibrations.

International Ohms It is defined as the resistance offered by a column of mercury having a mass of 14.4521 gms, uniform cross-sectional area and length of 106.300 cm, to the flow of constant current at the melting point of ice.

International Amperes It is an unvarying current, which when passed through a solution of silver nitrate in water (prepared in accordance with stipulated specifications) deposits silver at the rate of 0.00111800 gm/s.

Absolute Units International units were replaced in 1948 by absolute units. These units are more accurate than International units, and differ slightly from them. For example,

1 International ohm = 1.00049 Absolute ohm

1 International ampere = 0.99985 Absolute ampere

1.9.2 Primary Standards

The principle function of primary standards is the calibration and verification of secondary standards. Primary standards are maintained at the National Standards Laboratories in different countries.

The primary standards are not available for use outside the National Laboratory. These primary standards are absolute standards of high accuracy that can be used as ultimate reference standards.

1.9.3 Secondary Standards

Secondary standards are basic reference standards used by measurement and calibration laboratories in industries. These secondary standards are maintained by the particular industry to which they belong. Each industry has its own secondary standard. Each laboratory periodically sends its secondary standard to the National standards laboratory for calibration and comparison against the primary standard. After comparison and calibration, the National Standards Laboratory returns the Secondary standards to the particular industrial laboratory with a certification of measuring accuracy in terms of a primary standard.

1.9.4 Working Standards

Working standards are the principal tools of a measurement laboratory. These standards are used to check and calibrate laboratory instrument for accuracy and performance. For example, manufacturers of electronic components such as capacitors, resistors, etc. use a standard called a working standard for checking the component values being manufactured, e.g. a standard resistor for checking of resistance value manufactured.

ELECTRICAL STANDARDS 1.10

All electrical measurements are based on the fundamental quantities *I*, *R* and *V*. A systematic measurement depends upon the definitions of these quantities. These quantities are related to each other by the Ohm's law, $V = I.R$. It is therefore sufficient to define only two parameters to obtain the definitions of the third. Hence, in electrical measurements, it is possible to assign values of the remaining standard, by defining units of other two standards. Standards of emf and resistance are, therefore, usually maintained at the National Laboratory. The base values of other standards are defined from these two standards. The electrical standards are

(a) Absolute Ampere (b) Voltage Standard (c) Resistance Standard

1.10.1 Absolute Ampere

The International System of Units (SI) defines the Ampere, that is, the fundamental unit of electric current, as the constant current which if maintained in two straight parallel conductors of infinite length placed one metre apart in vacuum, will produce between these conductors a force equal to 2×10^7 newton per metre length. These measurements were not proper and were very crude. Hence, it was required to produce a more practical, accurate and reproducible standard for the National Laboratory.

Hence, by international agreement, the value of international ampere as discussed in the previous topic, was then based on the electrolytic deposition of silver from a silver nitrate solution. In this method, difficulties were encountered in determining the exact measurement of the deposited silver and slight differences existed between the measurements made independently by various National Standard laboratories.

The International Ampere was then replaced by the Absolute Ampere. This Absolute Ampere was determined by means of a current balance, which measures the force exerted between two current-carrying coils. This technique of force measurement was further improved to a value of ampere which is much superior to the early measurement (the relationship between force and the current which produces the force, can be calculated from the fundamental electromagnetic theory concepts).

The Absolute Ampere is now the fundamental unit of electric current in the SI system and is universally accepted by international agreements.

Voltage (V), current (I) and resistance (R) are related by Ohm's law $V = I.R$. If any of the two quantities is defined, the third can be easily known. In order to define the Ampere with high precision over long periods of time, the standard voltage cell and the standard resistor are used.

1.10.2 Voltage Standards

As described before, if two parameters of Ohm's law are known, the third can be easily derived. Standard voltage cell is used as one of the parameter.

The *standard voltage* called the *saturated standard cell* or *standard cell* was based on the principle of electrochemical cell for many years. But the standard cell had a drawback that it suffered from temperature dependence. This voltage was a function of a chemical reaction and was not directly related to any other physical constants. Hence, a new standard for volt was developed. This standard used a thin film junction, which is cooled to nearly absolute zero and irradiated with microwave energy, a voltage is developed across the junction. This voltage is related to the irradiating frequency by the relation $V = (h.f)/2e$ where h is the Planck's constant (6.63×10^{-34} J-s), 'e' is the charge of an electron (1.602×10^{-19}C) and 'f' is the frequency of the microwave irradiation. Since 'f', the irradiating frequency is the only variable in the equation, hence the standard volt is related to the standard frequency (or time).

The accuracy of the standard volt including all system inaccuracies approximately is one part in 10^9, when the microwave irradiating frequency is locked to an atomic clock or to a broadcast frequency standard.

Standard cells are used for transferring the volt from the standard. Based on the thin film junction to the secondary standards used for calibration, this device is called the normal or saturated Weston cell.

The saturated cell has mercury as the positive electrode and cadium amalgam (10% cadium). The electrolyte used is a solution of cadium sulphate. These electrodes with the electrolyte are placed in a H-shaped glass container as shown in Fig 1.1.

There are two types of Weston cells called the saturated cell and the unsaturated cell. In a saturated cell, the electrolyte used is saturated at all temperatures by the cadium sulphate crystals covering the electrodes.

In the unsaturated cell, the concentration of cadium sulphate is such that it produces saturation at 40°C. The unsaturated cell has a negligible temperature coefficient of voltage at normal room temperature.

The saturated cell has a voltage variation of approximately 40 μV/°C ,but is better reproducible and more stable than the unsaturated cell.

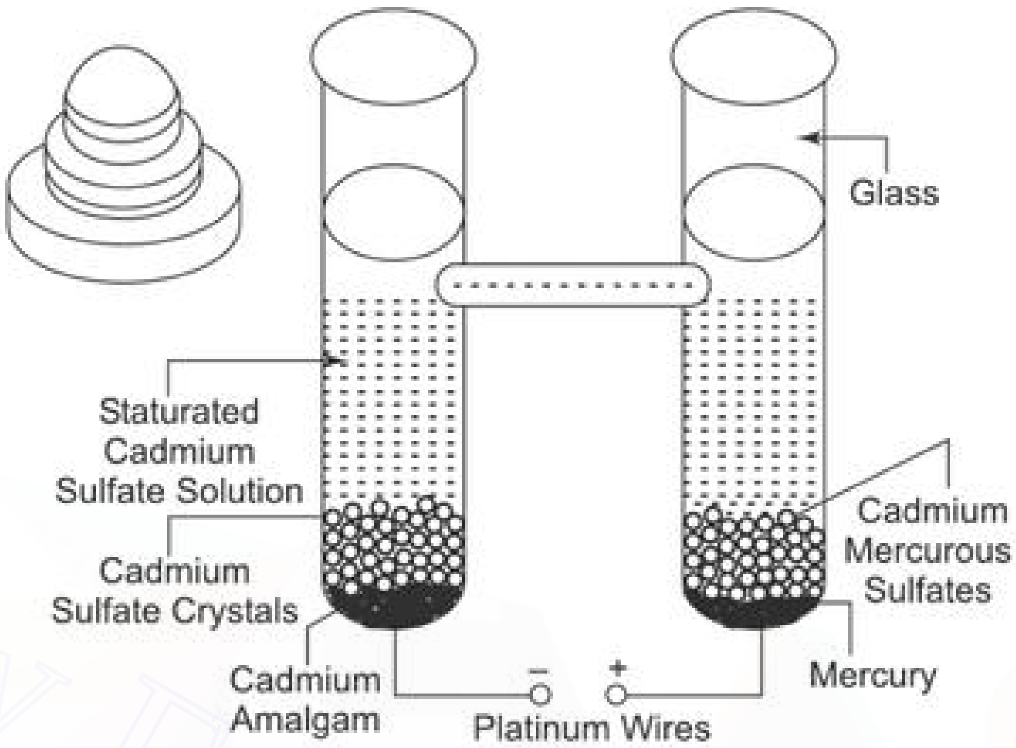


Fig 1.1 Voltage Standard

More rugged portable secondary and working standards are made of unsaturated Weston cells. These cells are very similar to the normal cell, but they do not require exact temperature control. The emf of an unsaturated cell lies in the range of 1.0180 V to 1.0200 V and the variation is less than 0.01%.

The internal resistance of Weston cells range from 500 to 800 ohms. The current drawn from these cells should therefore not exceed 100 μA.

Laboratory working standards have been developed based on the operation of Zener diodes as the voltage reference element, having accuracy of the same order as that of the standard cell. This instrument basically consists of Zener controlled voltage placed in a temperature controlled environment to improve it's long-term stability and having a precision output voltage. The temperature controlled oven is held within + 0.03°C over an ambient temperature range of 0 to 50°C giving an output stability in the order of 10 ppm/month. Zener controlled voltage sources are available in different ranges such as

(a) 0–1000 μV source with 1 μV resolution
(b) A 1.000 V reference for volt box potentiometric measurements
(c) A 1.018 V reference for saturated cell comparison

1.10.3 Resistance Standards

The absolute value of resistance is defined as ohms in the SI system of units. We know that the resistance R is given by $R = \rho \cdot l/A$ in terms of the length of wire (l), area of cross-section (A) of the wire and the resistivity of the wire (ρ) . Standard resistors are made of high resistivity conducting material with low temperature coefficient of resistance. Manganin, an alloy of copper, having a resistivity and whose temperature resistance relationship is almost constant, is used as the resistance wire. The construction of a resistance standard is as shown in Fig 1.2.

A coil of manganin wire as shown in Fig 1.2. is mounted on a double-walled sealed container to prevent the change in resistance due to humidity. The unit of resistance can be represented with precision values of a few parts in 10^7 over several years, with a set of four or five resistors of this type.

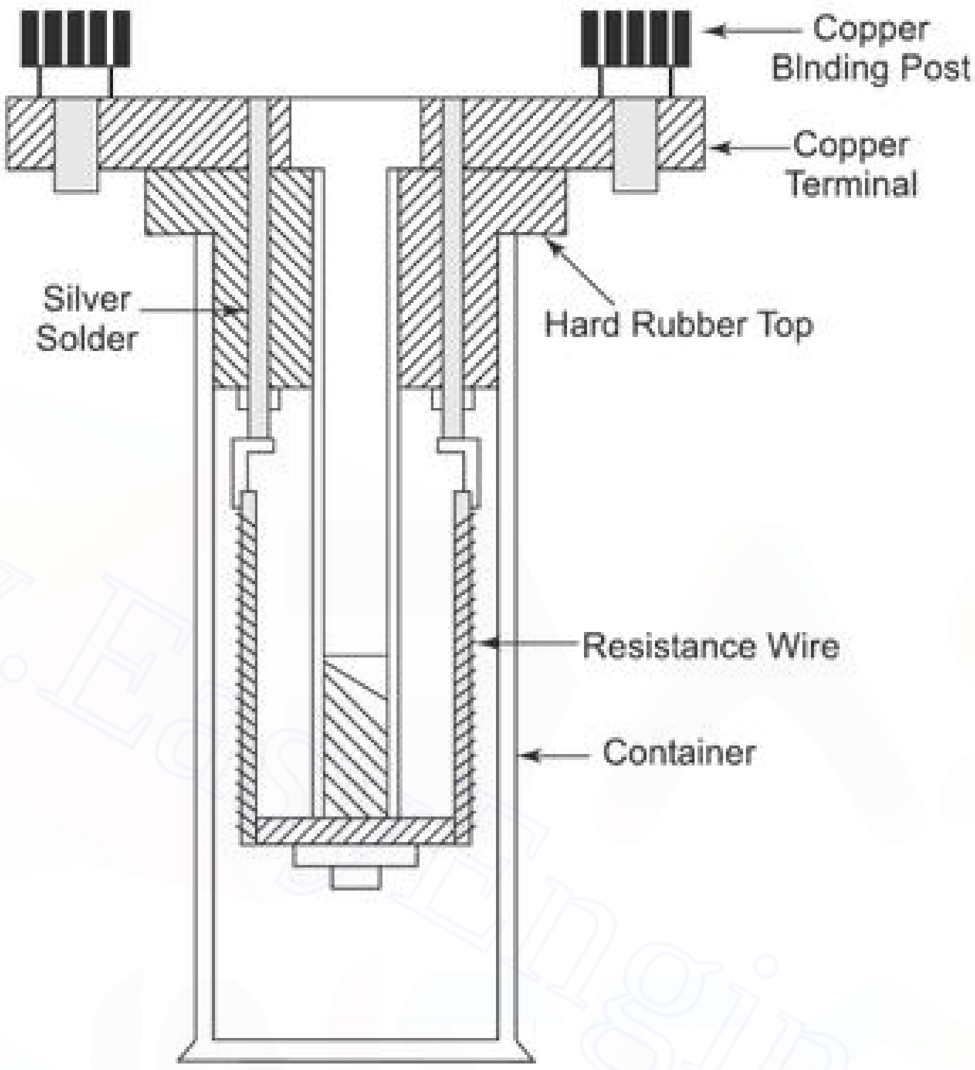


Fig 1.2 Resistance Standard

The secondary standard resistors are made of alloy of resistance wire such as manganin or Evan Ohm. The secondary standard or working standard are available in multiple of 10. These laboratory standards can also be referred to as transfer resistors. The resistance coil of the transfer resistance is supported between polyester film, in order to reduce stress on the wire and to improve it's stability. The coil is immersed in moisture-free oil and placed in a sealed container. The connections to the coils are silver soldered and terminals hooks are made of nickel-plated oxygen-free copper. These are checked for stability and temperature characteristics at it's rated power and operating.

Transfer resistors are used in industrial research and calibration laboratory. It is used in determining the value of the unknown resistance and ratio value. These resistors are also used as linear decade dividers resistors. These dividers are used in calibrating universal ratio sets and volt boxes.

ATOMIC FREQUENCY AND TIME STANDARDS 1.11

The measurement of time has two different aspects, civil and scientific. In most scientific work, it is desired to know how long an event lasts, or if dealing with an oscillator, it is desired to know its frequency of oscillation. Thus any time standard must be able to answer both the question "what time is it" and the two related questions "how long does it last" or "what is its frequency".

Any phenomena that repeats itself can be used as a measure of time, the measurement consisting of counting the repetitions. Of the many repetitive phenomena occurring in nature, the rotation of the earth on its axis which determines the length of the day, has been long used as a time standard. Time defined in terms of rotation of the earth is called *Universal time* (UT).

Time defined in terms of the earth's orbital motion is called *Ephemersis time* (ET). Both UT and ET are determined by astronomical observation. Since these astronomical observations extend over several weeks for UT and several years for ET, a good secondary terrestrial clock calibrated by astronomical observation is needed. A quartz crystal clock based on electrically sustained natural periodic vibrations of a quartz wafer serves as a secondary time standard. These clocks have a maximum error of 0.02 sec per year. One of the most common of time standards is the determination of frequency.

In the RF range, frequency comparisons to a quartz clock can be made electronically to a precision of atleast 1 part in 10^{10}.

To meet a better time standard, atomic clocks have been developed using periodic atomic vibrations as a standard. The transition between two energy levels, E_1 and E_2 of an atom is accompanied by the emission (or absorption) of radiation given by the following equation

$$v = \frac{E_2 - E_1}{h}$$

where v = frequency of emission and depends on the internal structure of an atom

h = Planck's constant = 6.636×10^{-34} J-sec.

Provided that the energy levels are not affected by the external conditions such as magnetic field etc.

Since frequency is the inverse of the time interval, time can be calibrated in terms of frequency.

The atomic clock is constructed on the above principle. The first atomic clock was based on the Cesium atom.

The International Committee of Weights and Measures defines the second in terms of the frequency of Cesium transitions, assigning a value of 9,192, 631,770 Hz to the hyperfine transitions of the Cesium atom unperturbed by external fields. If two Cesium clocks are operated at one precision and if there are no other sources of error, the clocks will differ by only 1s in 5000 years.

GRAPHICAL REPRESENTATION OF MEASUREMENTS AS A DISTRIBUTION 1.12

Suppose that a certain voltage is measured 51 times. The result which might be obtained are shown in Table 1.2.

Table 1.2

x Voltage (V)	Number of Occurrences (n)	x_n (v)	$d_n = x_n - \bar{x}$	$n\,\|d_n\|$	$(d_n)^2$	$n\,(d_n)^2$
1.01	1	1.01	− 0.04	0.04	16×10^{-4}	16×10^{-4}
1.02	3	3.06	− 0.03	0.09	9×10^{-4}	27×10^{-4}
1.03	6	6.18	− 0.02	0.12	4×10^{-4}	24×10^{-4}
1.04	8	8.32	− 0.01	0.08	1×10^{-4}	8×10^{-4}
1.05	10	10.50	0.00	0.00	0×10^{-4}	00×10^{-4}
1.06	7	7.42	+ 0.01	0.07	1×10^{-4}	7×10^{-4}
1.07	8	8.56	+ 0.02	0.16	4×10^{-4}	32×10^{-4}
1.08	4	4.32	+ 0.03	0.12	9×10^{-4}	36×10^{-4}
1.09	3	3.27	+ 0.04	0.12	16×10^{-4}	48×10^{-4}
1.10	0	0.00	+ 0.05	0.00	25×10^{-4}	00×10^{-4}
1.11	1	1.11	+ 0.06	0.06	36×10^{-4}	36×10^{-4}
	51	53.75		0.86		234×10^{-4}
	$= \Sigma_n$	$= \sum_{n=1}^{51} x_n$		$= \sum_{n=1}^{51} \|d_n\|$		$\sum_{n=1}^{51} (d_n)^2$

$$\text{Average } \bar{x} = \frac{\sum_{n=1}^{51} x_n}{n} = \frac{53.75}{51} = 1.054 \text{ V}$$

$$\text{Average deviation } D_{\text{av}} = \frac{\sum_{n=1}^{51} |d_n|}{n} = \frac{0.86}{51} = 0.0168 \text{ V}$$

$$\text{Standard deviation } \sigma = \sqrt{\frac{\sum_{n=1}^{51} (d_n)^2}{n}} = \sqrt{\frac{234 \times 10^{-4}}{51}} = \sqrt{4.588 \times 10^{-4}} \text{ V}$$
$$= 2.142 \times 10^{-2} \text{ V}$$

The first column shows the various measured values and the second column, the number of times each reading has occurred. For example, in the fourth row, the measured value is 1.04 V and the next column indicates that this reading is obtained 8 times.

The data given in Table 1.2 may be represented graphically as shown in Fig. 1.3.

We imagine the range of values of x to be divided into equal intervals dx, and plot the number of values of x lying in the interval versus the average value of x

within that interval. Hence the eight measurements of 1.04 V might be thought of lying in an 0.01 V interval centred upon 1.04 V, i.e. between 1.035 V to 1.045 V on the horizontal scale. Since with a small number (such as 51), these points do not lie on a smooth curve, it is conventional to represent such a plot by a histogram consisting of series of horizontal lines of length *dx* centred upon the individual points. The ends of adjacent horizontal lines being connected by vertical lines of appropriate length.

If another 51 measurements are taken and plotted we would, in general get a graph which does not coincide with the previous one. The graph plotted is called a Gauss error or Gaussian graph, shown in Fig. 1.3.

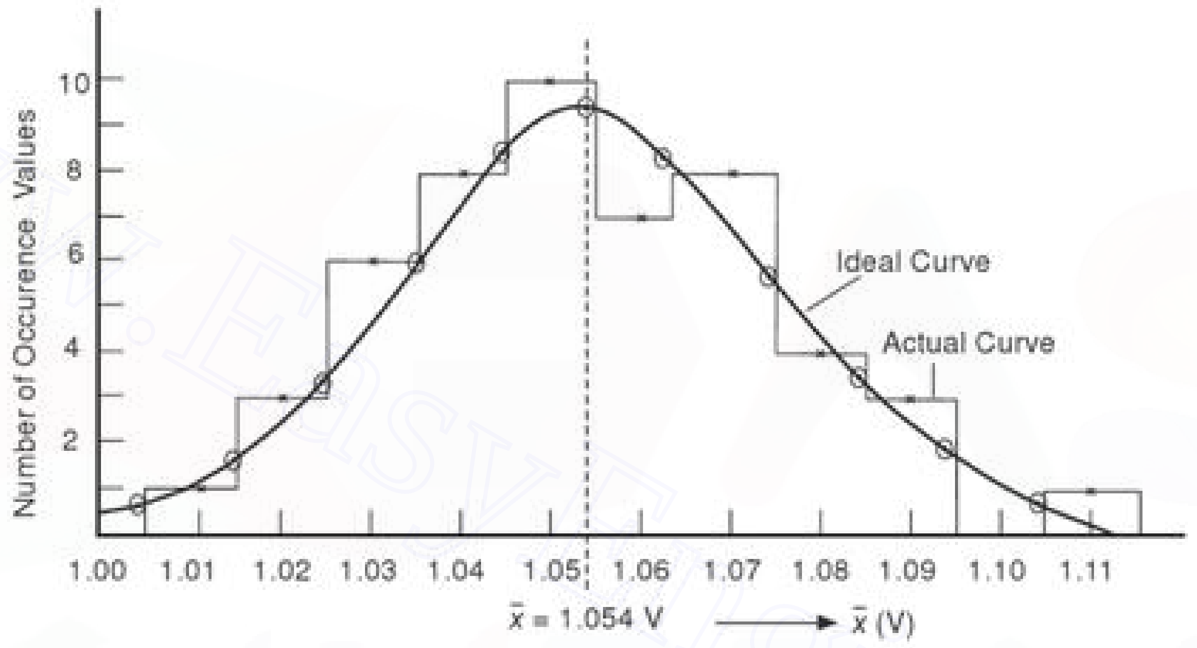


Fig. 1.3 Gaussian graph

Review Questions

1. What do you understand by static characteristics?
2. List different static characteristics.
3. Define the terms: instrument, accuracy, precision and errors.
4. Define the terms: resolution, sensitivity and expected value.
5. Discuss the difference between accuracy and precision of a measurement
6. List different types of errors.
7. Explain gross error in details. How can it be minimized?
8. Explain systematic error in detail. How can it be minimized?
9. Explain random error in detail.
10. A person using an ohmmeter reads the measured value as 470 Ω, when the actual value is 47 Ω. What kind of error does this represent?
11. What are the causes of environment errors?
12. How are instrumental errors different from gross errors? Explain.
13. Define absolute errors.
14. How is accuracy expressed?
15. What are the different types of errors that occur during measurement? Explain each.
16. What do you understand by dynamic characteristics of an instrument?
17. Define speed of response and fidelity.
18. Differentiate between lag and dynamic error.
19. What are limiting errors? What is the significance of limiting errors?
20. Define the following terms:

(i) Average value (ii) Arithmetic mean (iii) Deviation (iv) Standard deviation

21. What do you mean by a standard? What is the significance of standard?
22. What are international standards? List various international standards.
23. Define primary and secondary standards?
24. What are primary standards? Where are they used?
25. What are secondary standards? Where are they used?
26. What do you understand by a working standard?
27. State the difference between secondary and working standards.
28. Explain in brief atomic frequency and time standards.
29. How is time defined?
30. What do you understand by electrical standard?
31. List different types of electrical standards.

Multiple Choice Questions

1. The closeness of values indicated by an instrument to the actual value is defined as
   (a) repeatability (b) reliability
   (c) uncertainty (d) accuracy.
2. Precision is defined as
   (a) repeatability (b) reliability
   (c) uncertainty (d) accuracy
3. The ratio of change in output to the change in the input is called
   (a) precision (b) resolution
   (c) sensitivity (d) repeatability
4. The deviation of the measured value to the desired value is defined as
   (a) error (b) repeatability
   (c) hystersis (d) resolution
5. Improper setting of range of a multimeter leads to an error called
   (a) random error
   (b) limiting error
   (c) instrumental error
   (d) observational error
6. Errors that occur even when all the gross and systematic errors are taken care of are called
   (a) environmental errors
   (b) instrumental errors
   (c) limiting errors
   (d) random errors.
7. A means of reducing environmental errors is the regulation of ambient
   (a) noise (b) temperature
   (c) light (d) mains voltage
8. The ability of an instrument to respond to the weakest signal is defined as
   (a) sensitivity (b) repeatability
   (c) resolution (d) precision.
9. The difference between the expected value of the variable and the measured variable is termed
   (a) absolute error
   (b) random error
   (c) instrumental error
   (d) gross error
10. Accuracy is expressed as
    (a) relative accuracy
    (b) % accuracy
    (c) error
    (d) % error
11. Error is expressed as
    (a) absolute error (b) relative error
    (c) % error (d) % accuracy
12. Gross errors occurs due to
    (a) human error
    (b) instrumental error
    (c) environmental error
    (d) random error
13. Static errors are caused due to
    (a) measuring devices
    (b) human error
    (c) environmental error
    (d) observational error

14. Dynamic errors are caused by
    (a) instrument not responding fast
    (b) human error
    (c) environmental error
    (d) observational error

15. Limiting errors are
    (a) manufacturer's specifications of accuracy
    (b) manufacturer's specifications of instrumental error
    (c) environmental errors
    (d) random errors

Practice Problems

1. The current through a resistor is 3.0 A, but measurement gives a value of 2.9 A. Calculate the absolute error and % error of the measurement.
2. The current through a resistor is 2.5 A, but measurement yields a value of 2.45 A. Calculate the absolute error and % error of the measurement.
3. The value of a resistor is 4.7 k-ohms, while measurement yields a value of 4.63 K-ohms.
   Calculate (a) the relative accuracy, and (b) % accuracy.
4. The value of a resistor is 5.6 K-ohms, while measurement reads a value of 5.54 K-ohms. Calculate (a) the relative accuracy, and (b) % accuracy.
5. The output voltage of an amplifier was measured at eight different intervals using the same digital voltmeter with the following results: 20.00, 19.80, 19.85, 20.05, 20.10, 19.90, 20.25, 19.95.
   Which is the most precise measurement?
6. A 270 $\Omega \pm 10\%$ resistance is connected to a power supply source operating at 300 V dc.
   What range of current would flow if the resistor varied over the range of $\pm$ 10% of its expected value? What is the range of error in the current?
7. A voltmeter is accurate to 98% of its full scale reading.
   (i) If a voltmeter reads 200 V on 500 V range, what is the absolute error?
   (ii) What is the percentage error reading of Part (i)?
8. The expected value of voltage across a resistor is 100 V. However, the voltmeter reads a value of 99 V. Calculate (a) absolute error, (b) % error, (c) relative error, and (d) % accuracy.

Further Reading

1. Barry Jones, *Instrumentation Measurements and Feedback*.
2. Larry D. Jones and A. Foster Chin, *Electronic Instruments and Measurement*, John Wiley and Sons, 1987.
3. Yardley Beers, *Theory of Errors*, 1967.
4. Resnick and Halliday, *Physics*, Wiley Eastern, 1987.

Chapter 2

Indicators and Display Devices

INTRODUCTION 2.1

Analogue ammeters and voltmeters are classified together, since there is no basic difference in their operating principles. The action of all ammeters and voltmeters, except those of the electrostatic variety, depends upon a deflecting torque produced by an electric current. In an ammeter this torque is produced by the current to be measured, or by a definite fraction of it. In a voltmeter it is produced by a current that is proportional to the voltage to be measured. Hence both voltmeters and ammeters are essentially current measuring devices.

The essential requirements of a measuring instrument are (a) that its introduction into the circuit where measurements are to be made, should not alter the circuit conditions, and (b) the power consumed by it be small.

2.1.1 Types of Instrument

The following types of instrument are mainly used as ammeters and voltmeters.

1. PMMC
2. Moving Iron
3. Electrodynamometer
4. Hot wire
5. Thermocouple
6. Induction type
7. Electrostatic
8. Rectifier

Of these, the PMMC type can be used for dc measurements only, and the induction type for ac measurements only. The other types can be used for both.

The moving coil and moving iron types depend upon the magnitude effect of current. The latter is the most commonly used form of indicating instrument, as well as the cheapest. It can be used for both ac and dc measurements and is very accurate, if properly designed.

The PMMC instrument is the most accurate type for dc measurement. Instrument of this type are frequently constructed to have substandard accuracy.

The calibration of the electrodynamometer type of instrument is the same for ac and dc. The same situation prevails for thermal instruments. These are particularly suitable for ac measurements, since their deflection depends directly upon the heating effect of the ac, i.e. upon the rms value of the current. Their readings are therefore independent of the frequency.

Electrostatic instruments used as voltmeters have the advantage that their power consumption is exceedingly small. They can be made to cover a large range of voltage and can be constructed to have sub-standard accuracy.

The induction principle is most generally used for Watt-hour meters. This principle is not preferred for use in ammeters and voltmeters because of the comparatively high cost and inaccuracy of the instrument.

BASIC METER MOVEMENT 2.2

The action of the most commonly dc meter is based on the fundamental principle of the motor. The motor action is produced by the flow of a small current through a moving coil, which is positioned in the field of a permanent magnet. This basic moving coil system is often called the D'Arsonval galvanometer.

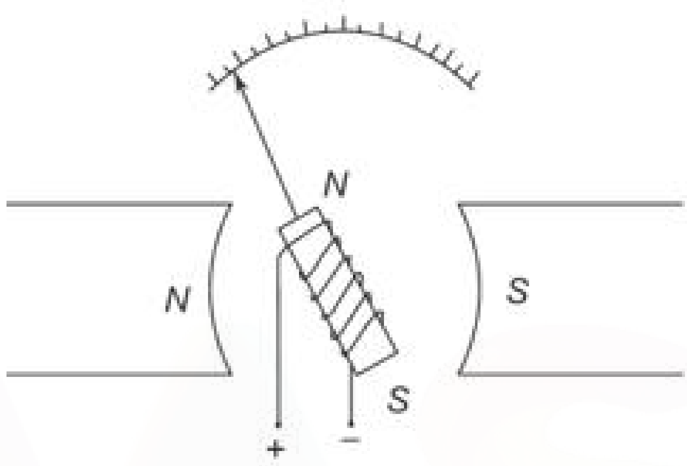


Fig. 2.1 D'Arsonval principle

The D'Arsonval movement shown in Fig. 2.1 employs a spring-loaded coil through which the measured current flows. The coil (rotor) is in a nearly homogeneous field of a permanent magnet and moves in a rotary fashion. The amount of rotation is proportional to the amount of current flowing through the coil. A pointer attached to the coil indicates the position of the coil on a scale calibrated in terms of current or voltage. It responds to dc current only, and has an almost linear calibration. The magnetic shunt that varies the field strength is used for calibration.

2.2.1 Permanent Magnetic Moving Coil Movement

In this instrument, we have a coil suspended in the magnetic field of a permanent magnet in the shape of a horse-shoe. The coil is suspended so that it can rotate freely in the magnetic field. When current flows in the coil, the developed (electromagnetic) torque causes the coil to rotate. The electromagnetic (EM) torque is counterbalanced by a mechanical torque of control springs attached to the movable coil. The balance of torques, and therefore the angular position of the movable coil is indicated by a pointer against a fixed reference called a scale. The equation for the developed torque, derived from the basic law for electromagnetic torque is

$$\tau = B \times A \times I \times N$$

where τ = torque, Newton-meter
B = flux density in the air gap, Wb/m^2
A = effective coil area (m^2)
N = number of turns of wire of the coil
I = current in the movable coil (amperes)

The equation shows that the developed torque is proportional to the flux density of the field in which the coil rotates, the current coil constants (area and number of turns). Since both flux density and coil constants are fixed for a given instrument, the developed torque is a direct indication of the current in the coil. The pointer deflection can therefore be used to measure current.

Example 2.1 (a) *A moving coil instrument has the following data.*
Number of turns = 100
Width of the coil = 20 mm
Depth of the coil = 30 mm
Flux density in the gap = 0.1 Wb/m^2
Calculate the deflecting torque when carrying a current of 10 mA. Also calculate the deflection, if the control spring constant is 2×10^{-6} Nm/degree.

Solution The deflecting torque is given by

$$\begin{aligned}\tau_d &= B \times A \times N \times I \\ &= 0.1 \times 30 \times 10^{-3} \times 20 \times 10^{-3} \times 100 \times 10 \times 10^{-3} \\ &= 600 \times 1000 \times 0.1 \times 10^{-9} \\ &= 600 \times 1000 \times 10^{-10} \\ &= 60 \times 10^{-6} \text{ Nm}\end{aligned}$$

The spring control provides a restoring torque, i.e. $\tau_c = K\theta$,
where K is the spring constant
As deflecting torque = restoring torque

$$\therefore \quad \tau_c = 6 \times 10^{-5} \text{ Nm} = K\theta, \qquad \therefore \theta = \frac{6 \times 10^{-5}}{2 \times 10^{-6}} = 3 \times 10 = 30°$$

Therefore, the deflection is 30°.

Example 2.1 (b) *A moving coil instrument has the following data*
No. of turns = 100
Width of the coil = 20 mm
Depth of the coil = 30 mm
Flux density in the gap = 0.1 Wb/m^2
The deflection torque = 30×10^{-6} Nm
Calculate the current through the moving coil.

Solution The deflecting torque is given by

$$\tau_d = B \times A \times N \times I$$

Therefore $$30 \times 10^{-6} = 0.1 \times 30 \times 10^{-3} \times 20 \times 10^{-3} \times 100 \times I$$

$$I = \frac{30 \times 10^{-6}}{0.1 \times 30 \times 10^{-3} \times 20 \times 10^{-3} \times 100}$$

$$I = \frac{30 \times 10^{-6}}{0.1 \times 600 \times 10^{-6} \times 100} = 5 \text{ mA}$$

2.2.2 Practical PMMC Movement

The basic PMMC movement (also called a D'Arsonval movement) offers the largest magnet in a given space, in the form of a horse-shoe, and is used when a large flux is required in the air gap. The D'Arsonval movement is based on the principle of a moving electromagnetic coil pivoted in a uniform air gap between the poles of a large fixed permanent magnet. This principle is illustrated in Fig. 2.1 With the polarities as shown, there is a repelling force between like poles, which exerts a torque on the pivoted coil. The torque is proportional to the magnitude of current being measured. This D'Arsonval movement provides an instrument with very low power consumption and low current required for full scale deflection (fsd).

Figure 2.2 shows a permanent horse-shoe magnet with soft iron pole pieces attached to it. Between the pole pieces is a cylinder of soft iron which serves to provide a uniform magnetic field in the air gap between the pole pieces and the cylindrical core.

The coil is wound on a light metal frame and is mounted so that it can rotate freely in the air gap. The pointer attached to the coil moves over a graduated scale and indicates the angular deflection of the coil, which is proportional to the current flowing through it.

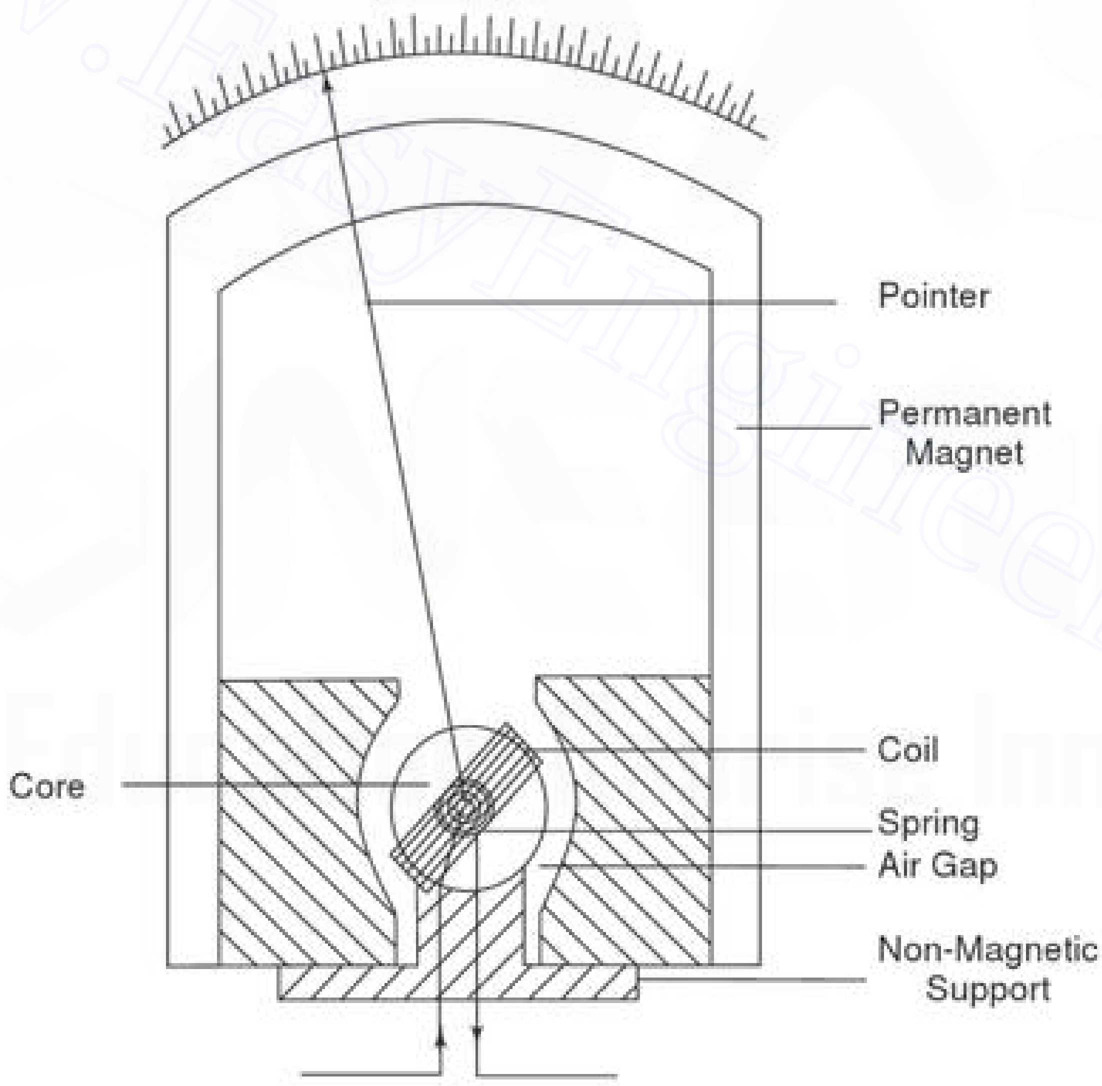


Fig. 2.2 Modern D'Arsonval movement

The Y-shaped member shown in Fig. 2.3 is the zero adjust control, and is connected to the fixed end of the front control spring. An eccentric pin through the instrument case engages the Y-shaped member so that the zero position of the pointer can be adjusted from outside. The calibrated force opposing the moving torque is provided by two phosphor-bronze conductive springs, normally equal in strength. (This also provides the necessary torque to bring the pointer back to its original position after the measurement is over.)

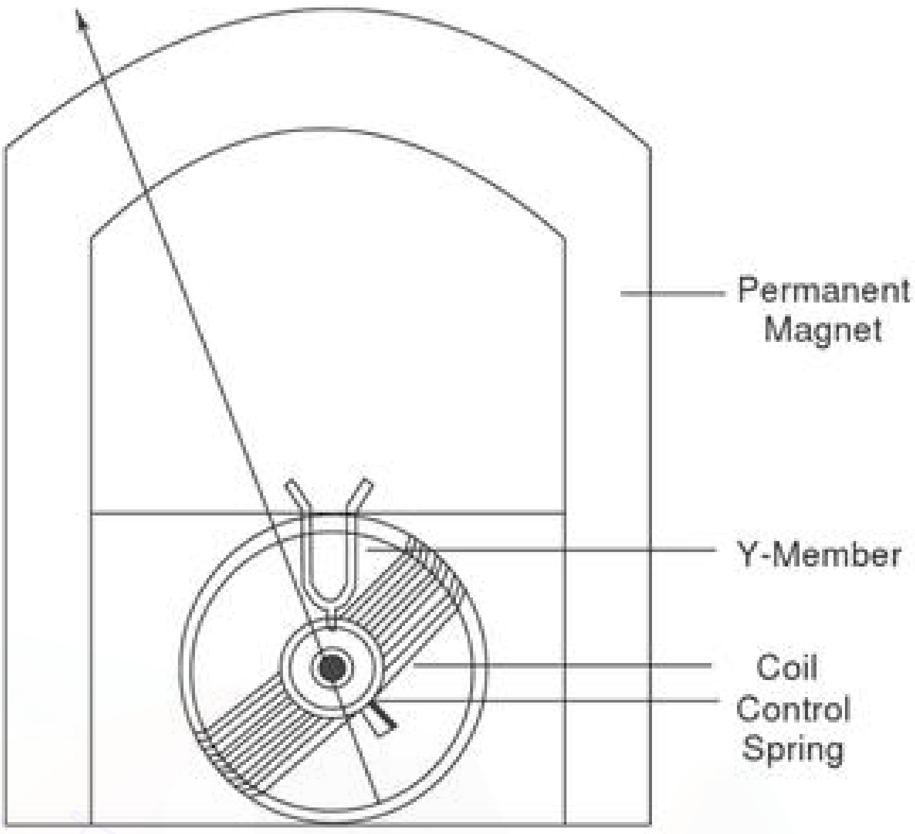


Fig. 2.3 Simplified diagram of a PMMC movement showing the Y-member

The accuracy of the instrument can be maintained by keeping spring performance constant. The entire moving system is statically balanced at all positions by three (counterweights) balance weights. The pointer, springs, and pivots are fixed to the coil assembly by means of pivot bases and the entire movable coil element is supported by jewel bearings.

PMMC instruments are constructed to produce as little viscious damping as possible and the required degree of damping is added.

In Fig. 2.4, Curve 2 is the underdamped case; the pointer attached to the movable coil oscillates back and forth several times before coming to rest. As in curve 1, the overdamped case, the pointer tends to approach the steady state position in a sluggish manner. In Curve 3, the critically damped case, the pointer moves up to its steady state position without oscillations. Critical damping is the ideal behaviour for a PMMC movement.

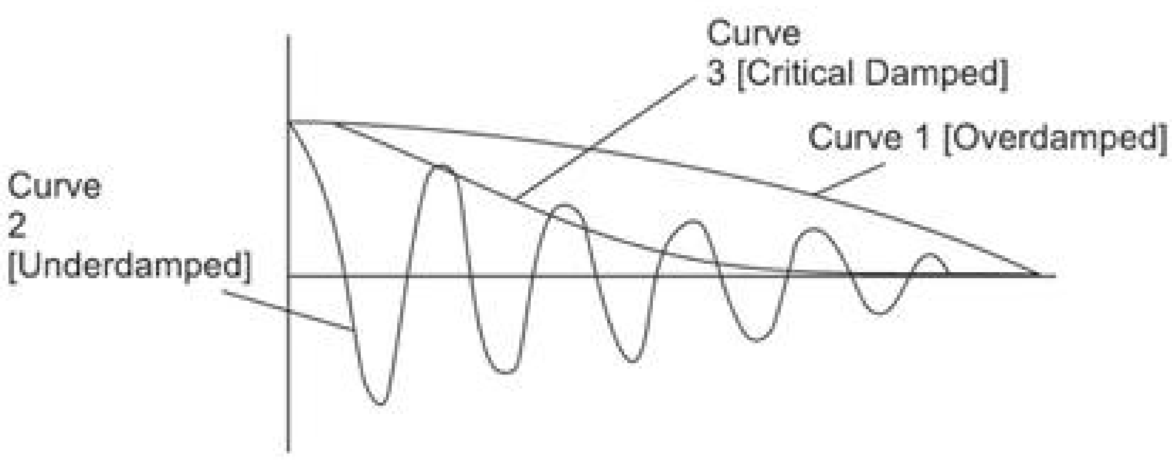


Fig. 2.4 Degree of damping

In practice, however, the instrument is usually slightly underdamped, causing the pointer to overshoot a little before coming to rest.

The various methods of damping are as follows.

One of the simplest methods is to attach an aluminium vane to the shaft of the moving coil. As the coil rotates, the vane moves in an air chamber, the amount of clearance between the chamber walls and the air vane effectively controls the degree of damping.

Some instruments use the principle of electromagnetic damping (Lenz's law), where the movable coil is wound on a light aluminium frame. The rotation of the coil in the magnetic field sets up a circulating current in the conductive frame, causing a retarding torque that opposes the motion of the coil.

A PMMC movement may also be damped by a resistor across the coil. When the coil rotates in the magnetic field, a voltage is generated in the coil, which circulates a current through it and the external resistance. This produces an opposing or retarding torque that damps the motion. In any galvanometer, the value of the external resistance that produces critical damping can be found. This resistance is called critically damping external resistance (CDRX). Most voltmeter coils are wound on metal frames to provide Electro-Magnetic damping. The metal frames constitute a short-circuit turn in a magnetic field.

Ammeters coils, are however wound in a non-conductive frame, because the coil turns are effectively shorted by the ammeter shunt. The coil itself provides the EM damping.

If low frequency alternating current is applied to the movable coil, the deflection of the pointer would be upscale for half the cycle of the input waveform and downscale (in the opposite direction) for the next half. At power line frequency (50 Hz) and above, the pointer cannot follow the rapid variations in direction and quivers slightly around the zero mark, seeking the average value of the ac (which equals zero). The PMMC instrument is therefore unsuitable for ac measurements, unless the current is rectified before reaching the coil.

Practical coil areas generally range from 0.5 – 2.5 cm^2.

The flux density for modern instruments usually ranges from 1500 – 5000 Wb/cm^2.

The power requirements of D'Arsonval movements are quite small, typically from 25 – 200 μW.

The accuracy of the instrument is generally of the order of 2 – 5% of full scale deflection.

The permanent magnet is made up of Alnico material.

Scale markings of basic dc PMMC instruments are usually linearly spaced, because the torque (and hence the pointer deflection) is directly proportional to the coil current. The basic PMMC instrument is therefore a linear-reading device.

The advantages and disadvantages of PMMC are as follows.

Advantages

1. They can be modified with the help of shunts and resistance to cover a wide range of currents and voltages.
2. They display no hysteresis.
3. Since operating fields of such instruments are very strong, they are not significantly affected by stray magnetic fields.

Disadvantages

1. Some errors may set in due to ageing of control springs and the permanent magnet.
2. Friction due to jewel-pivot suspension.

TAUT BAND INSTRUMENT 2.3

The taut band movement utilises the same principle as the D'Arsonval movable coil and fixed magnet. The primary difference between the two is the method of mounting the movable coil.

The taut band movement has the advantage of eliminating the friction caused by a jewel-pivot suspension. The meter has a coil mounted in a cradle and surrounded by a ring-bar magnet, as shown in Fig. 2.5. The cradle is secured to a support bracket, which in turn is suspended between two steel taut bands (ribbon), i.e. the movable coil is suspended by means of two taut torsion ribbons. The ribbons are placed under sufficient tension to eliminate any sag. This tension is provided by the tension spring, so that the instrument can be used in any position.

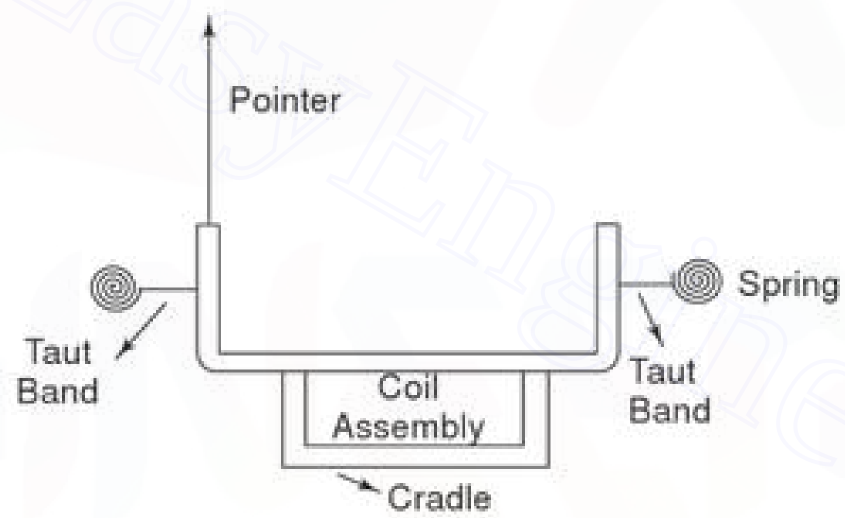


Fig. 2.5 (a) Taut band instrument (Side view)

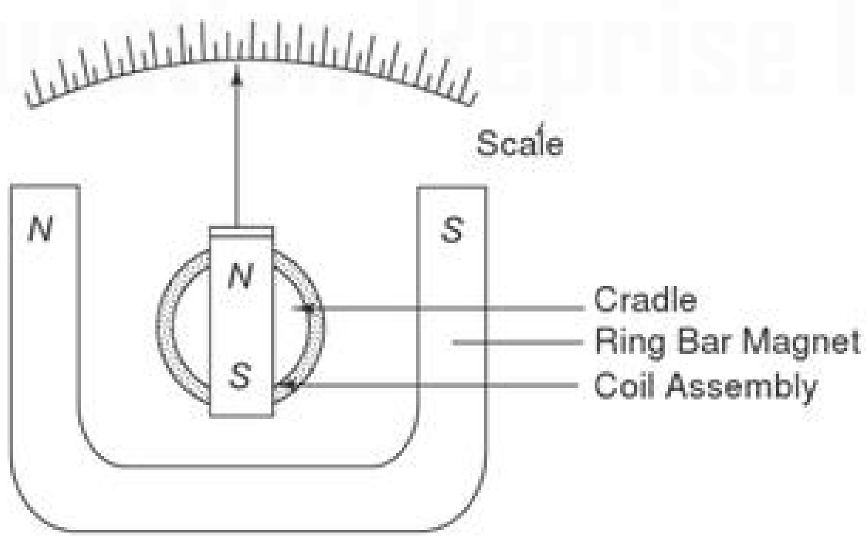


Fig. 2.5 (b) Taut band instrument (Top view)

The current to be measured is passed through the coil, thereby energising it. The interaction of the magnetic fields deflects the cradle to one side and moves the pointer along the scale.

The movement of the cradle exerts a twisting force on the steel bands. These twisted bands supply the torque to return the pointer to zero, when no current flows. There are no bearings, and there is a constant level of sensitivity throughout the range of movement.

Taut band instruments have a higher sensitivity than those using pivots and jewels. In addition taut band instruments are relatively insensitive to shock and temperature and are capable of withstanding greater overloads than PMMC or other types.

ELECTRODYNAMOMETER 2.4

The D'Arsonval movement responds to the average or dc value of the current flowing through the coil.

If ac current is sought to be measured, the current would flow through the coil with positive and negative half cycles, and hence the driving torque would be positive in one direction and negative in the other. If the frequency of the ac is very low, the pointer would swing back and forth around the zero point on the meter scale.

At higher frequencies, the inertia of the coil is so great that the pointer does not follow the rapid variations of the driving torque and vibrates around the zero mark.

Therefore, to measure ac on a D'Arsonval movement, a rectifier has to be used to produce a unidirectional torque. This rectifier converts ac into dc and the rectified current deflects the coil. Another method is to use the heating effect of ac current to produce an indication of its magnitude. This is done using an electrodynamometer (EDM).

An electrodynamometer is often used in accurate voltmeter and ammeters not only at power line frequency but also at low AF range. The electrodynamometer can be used by slightly modifying the PMMC movement. It may also serve as a transfer instrument, because it can be calibrated on dc and then used directly on ac thereby equating ac and dc measurements of voltage and current directly.

A movable coil is used to provide the magnetic field in an electrodynamometer, instead of a permanent magnet, as in the D'Arsonval movement. This movable coil rotates within the magnetic field. The EDM uses the current under measurement to produce the required field flux. A fixed coil, split into two equal halves provides the magnetic field in which the movable coil rotates, as shown in Fig. 2.6 (a). The coil halves are connected in series with the moving coil and are fed by the current being measured. The fixed coils are spaced far apart to allow passage for the shaft of the movable coil. The movable coil carries a pointer, which is balanced by counterweights. Its rotation is controlled by springs, similar to those in a D'Arsonval movement.

The complete assembly is surrounded by a laminated shield to protect the instrument from stray magnetic field which may affect its operation.

Damping is provided by aluminium air vanes moving in a sector shaped chamber. (The entire movement is very solid and rigidly constructed in order to keep its mechanical dimensions stable, and calibration intact.)

The operation of the instrument may be understood from the expression for the torque developed by a coil suspended in a magnetic field, i.e.

$$\tau = B \times A \times N \times I$$

indicating that the torque which deflects the movable coil is directly proportional to the coil constants (A and N), the strength of the magnetic field in which the coil moves (B), and the current (I) flowing through the coil.

In an EDM the flux density (B) depends on the current through the fixed coil and is therefore proportional to the deflection current (I). Since the coil constants are fixed quantities for any given meter, the developed torque becomes a function of the current squared (I^2).

If the EDM is used for dc measurement, the square law can be noticed by the crowding of the scale markings at low current values, progressively spreading at higher current values.

For ac measurement, the developed torque at any instant is proportional to the instantaneous current squared (i^2). The instantaneous values of i^2 are always positive and torque pulsations are therefore produced.

The meter movement, however, cannot follow rapid variations of the torque and take up a position in which the average torque is balanced by the torque of the control springs. The meter deflection is therefore a function of the mean of the squared current. The scale of the EDM is usually calibrated in terms of the square root of the average current squared, and therefore reads the effective or rms value of the ac.

The transfer properties of the EDM become apparent when we compare the effective value of the alternating current and the direct current in terms of their heating effect, or transfer of power.

(If the EDM is calibrated with a direct current of 500 mA and a mark is placed on the scale to indicate this value, then that ac current which causes the pointer to deflect to the same mark on the scale must have an rms value of 500 mA.)

The EDM has the disadvantage of high power consumption, due to its construction. The current under measurement must not only pass through the movable coil, but also provide the necessary field flux to get a sufficiently strong magnetic field. Hence high mmf is required and the source must have a high current and power.

In spite of this high power consumption the magnetic field is still weaker than that of the D'Arsonval movement because there is no iron in the path, the entire flux path consisting of air.

The EDM can be used to measure ac or dc voltage or current, as shown in Figs. 2.6 (a) and (b).

Typical values of EDM flux density are in the range of approximately 60 gauss as compared to the high flux densities (1000 – 4000 guass) of a good D'Arsonval movement. The low flux density of the EDM affects the developed torque and therefore the sensitivity of the instrument.

The addition of a series multiplier converts the basic EDM into a voltmeter [Fig. 2.6 (b)] which can be used for ac and dc measurements. The sensitivity of the EDM voltmeter is low, approximately 10 – 30 Ω/V, compared to 20 kΩ/V of the D'Arsonval movement. It is however very accurate at power line frequency and can be considered as a secondary standard.

The basic EDM shown in Fig. 2.6 (a) can be converted into an ammeter (even without a shunt), because it is difficult to design a moving coil which can carry more than approximately 100 mA.

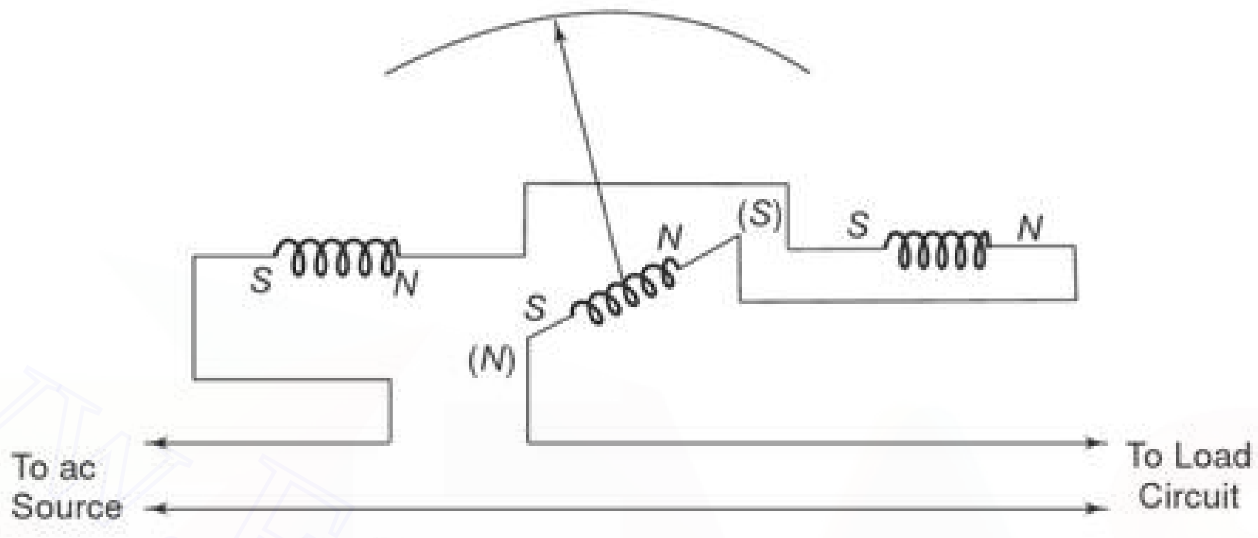


Fig. 2.6 (a) Basic EDM as an ammeter

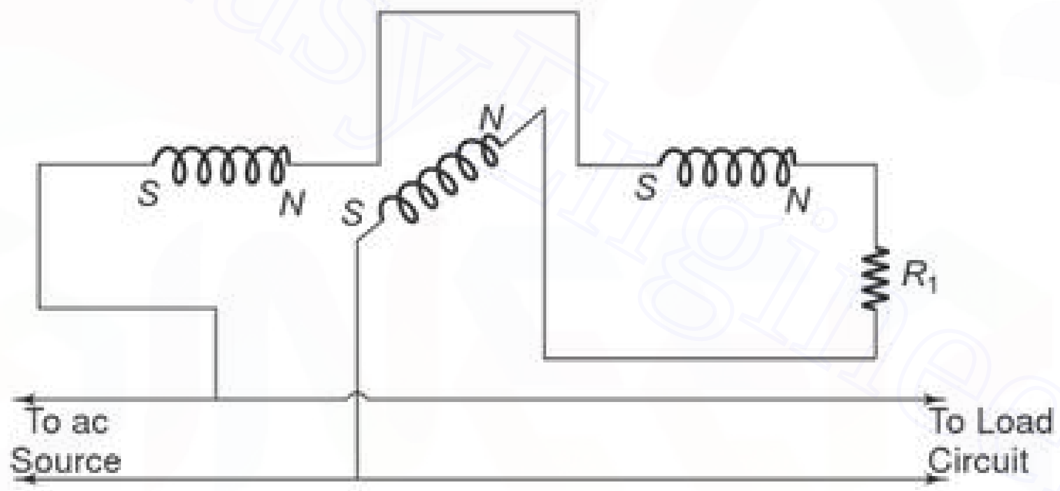


Fig. 2.6 (b) Basic EDM as a voltmeter

The EDM movement is extensively used to measure power, both dc and ac, for any waveform of voltage and current.

An EDM used as a voltmeter or ammeter has the fixed coils and movable coil connected in series, thereby reacting to I^2.

When an EDM is used as a single phase wattmeter, the coil arrangement is different, as shown in Fig. 2.7.

The fixed coils, shown in Fig. 2.7 as separate elements, are connected in series and carries the total line current. The movable coil located in the magnetic field of the fixed coils is connected in series with a current-limiting resistor across the power line, and carries a small current.

The deflection of the movable coil is proportional to the product of the instantaneous value of current in the movable coil and the total line current. The EDM wattmeter consumes some power for the maintenance of its magnetic field, but this is usually small compared to the load power.

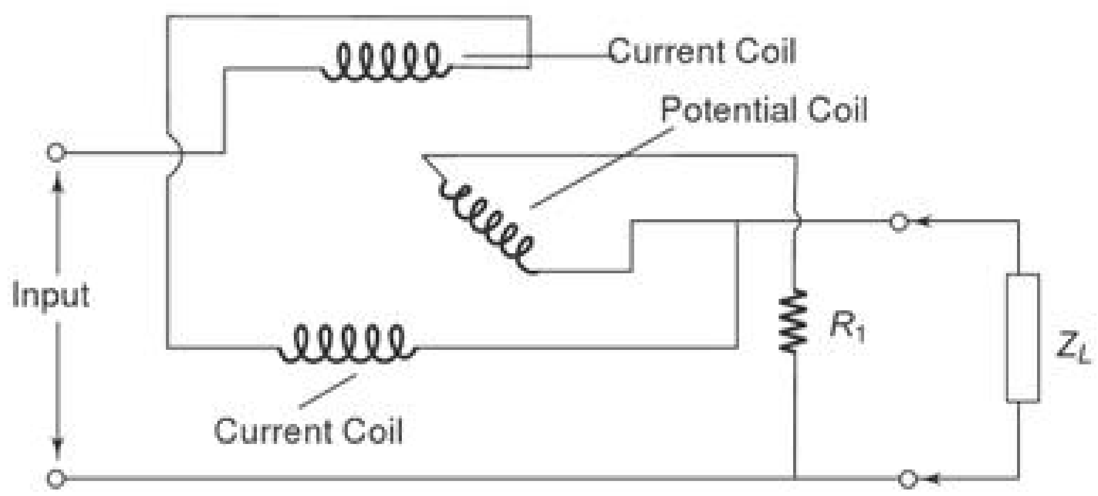


Fig. 2.7 EDM as a wattmeter

MOVING IRON TYPES INSTRUMENT 2.5

Moving iron instruments can be classified into attraction and repulsion types. Repulsion type instruments are the most commonly used.

Iron vane ammeters and voltmeters depend for their operations on the repulsion that exists between two like magnetic poles.

The movement consists of a stationary coil of many turns which carries the current to be measured. Two iron vanes are placed inside the coil. One vane is rigidly attached to the coil frame, while the other is connected to the instrument shaft which rotates freely. The current through the coil magnetises both the vanes with the same polarity, regardless of the instantaneous direction of current. The two magnetised vanes experience a repelling force, and since only one vane can move, its displacement is an indicator of the magnitude of the coil current. The repelling force is proportional to the current squared, but the effects of frequency and hysteresis tend to produce a pointer deflection that is not linear and that does not have a perfect square law relationship.

Figure 2.8 shows a radial vane repulsion instrument which is the most sensitive of the moving iron mechanisms and has the most linear scale. One of these like poles is created by the instrument coil and appears as an iron vane fixed in its position within the coil, as shown in Fig. 2.8. The other like pole is induced on the movable iron piece or vane, which is suspended in the induction field of the coil and to which the needle of the instrument is attached. Since the instrument is used on ac, the magnetic polarity of the coil changes with every half cycle and induces a corresponding amount of repulsion of the movable vane against the spring tension. The deflection of the instrument pointer is therefore always in the same direction, since there is always repulsion between the like poles of the fixed and the movable vane, even though the current in the inducing coil alternates.

The deflection of the pointer thus produced is effectively proportional to the actual current through the instrument. It can therefore be calibrated directly in amperes and volts.

The calibrations of a given instrument will however only be accurate for the ac frequency for which it is designed, because the impedance will be different at a new frequency.

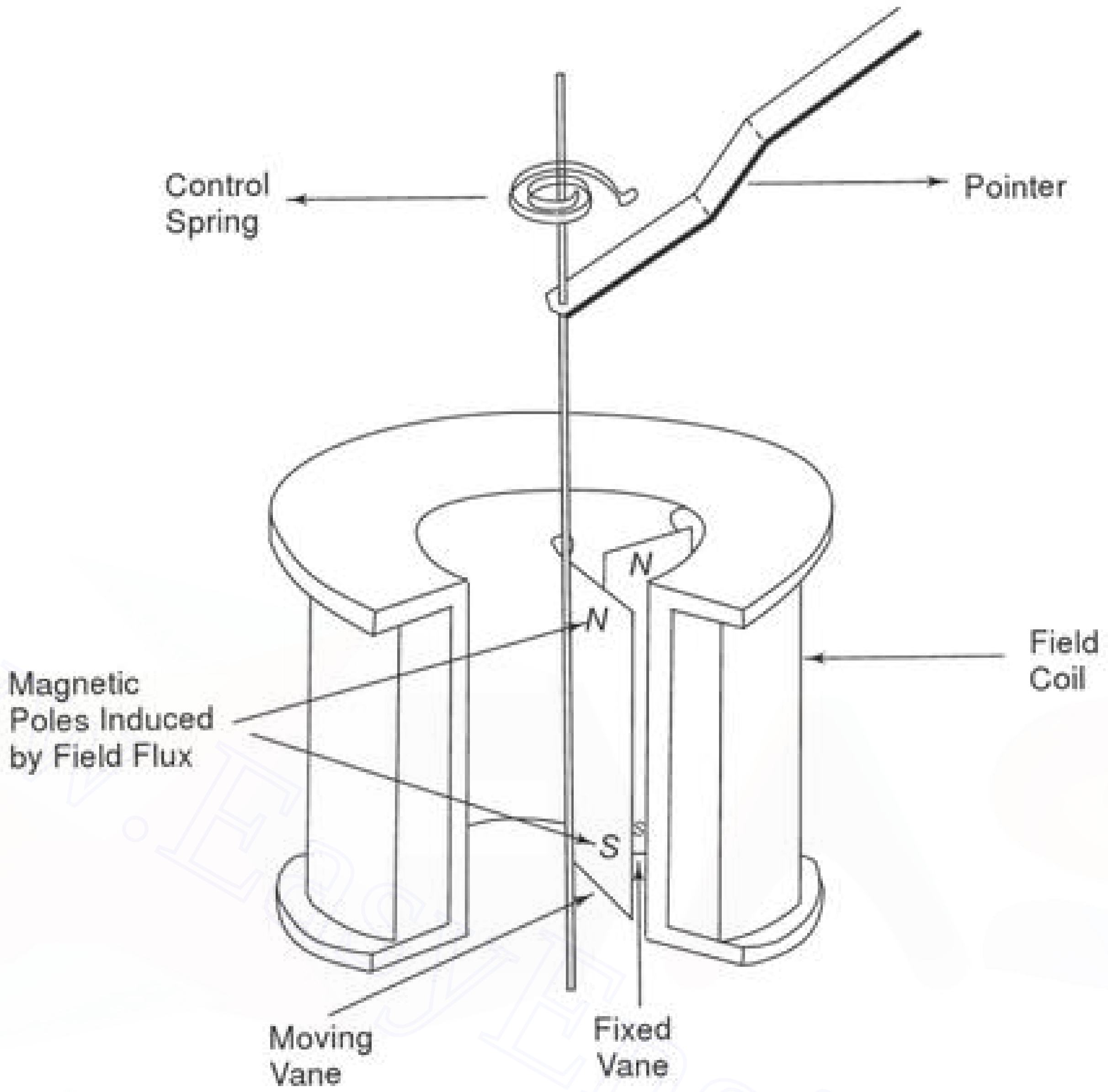


Fig. 2.8 Repulsion type AC meter (Radial vane type)

The moving coil or repulsion type of instrument is usually calibrated to read the effective value of amperes and volts, and is used primarily for rugged and inexpensive meters.

The iron vane or radial type is forced to turn within the fixed current carrying coil by the repulsion between like poles. The aluminium vanes, attached to the lower end of the pointer, acts as a damping vane, in its close fitting chamber, to bring the pointer quickly to rest.

CONCENTRIC VANE REPULSION TYPE (MOVING IRON TYPE) INSTRUMENT 2.6

A variation of the radial vane instrument is the concentric vane repulsion movement. The instrument has two concentric vanes.

One vane is rigidly attached to the coil frame while the other can rotate coaxially inside the stationary vane, as shown in Fig. 2.9. Both vanes are magnetised by the current in the coil to the same polarity, causing the vanes to slip laterally under repulsion. Because the moving vane is attached to a pivoted shaft, this repulsion results in a rotational force that is a function of the current in the coil. As in other mechanisms the final pointer position is a measure of the coil current. Since this movement, like all iron vane instruments, does not distinguish polarity, the concentric vane may be used on dc and ac, but it is most commonly used for the latter.

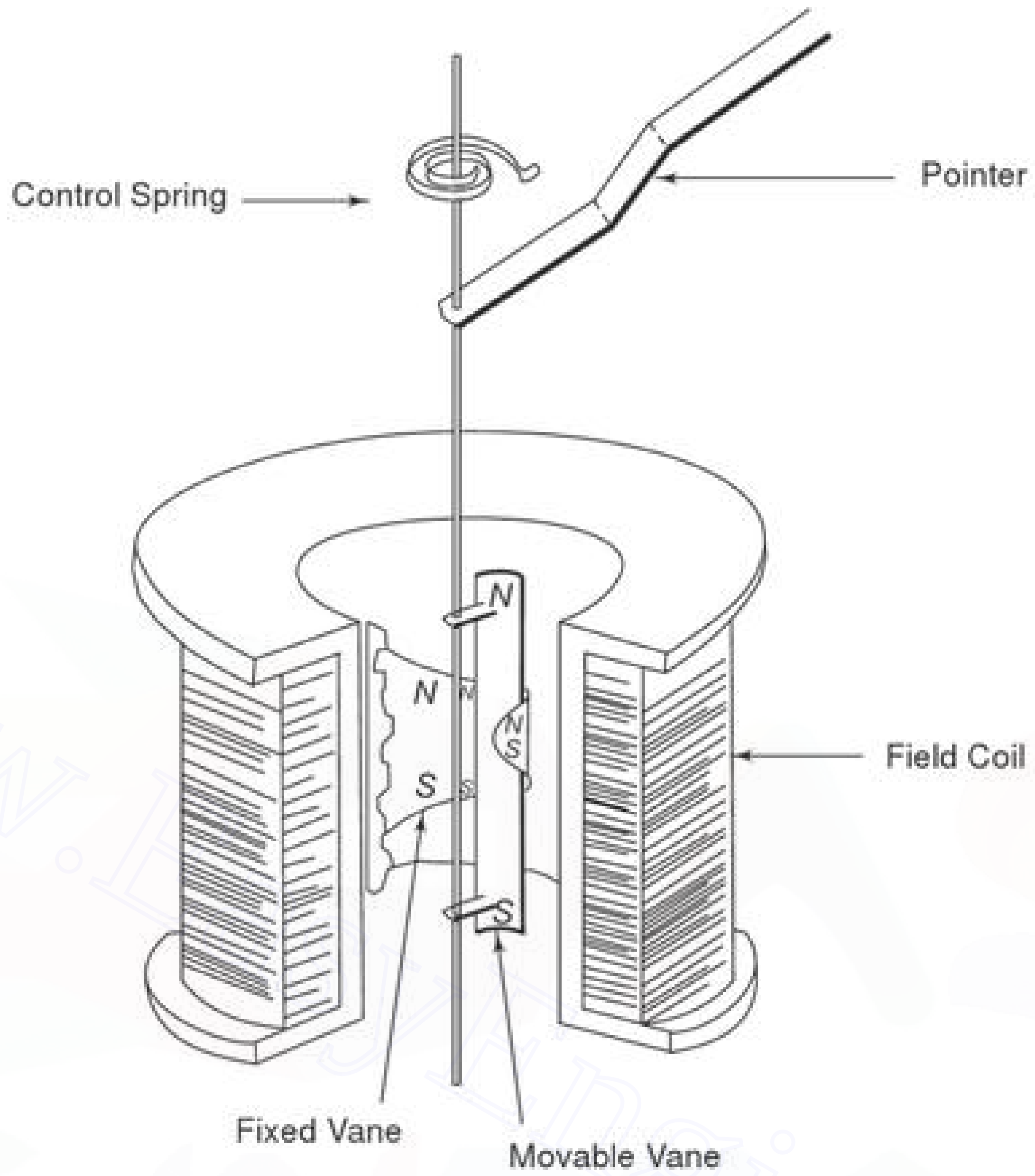


Fig. 2.9 Concentric iron vane (Repulsion type)

Damping is obtained by a light aluminium damping vane, rotating with small clearance in a closed air chamber. When used on ac, the actual operating torque is pulsating and this may cause vibration of the pointer. Rigid (trussed) pointer construction effectively eliminates such vibration and prevents bending of the pointer on heavy overloads. The concentric vane moving iron instrument is only moderately sensitive and has square law scale characteristics. The accuracy of the instrument is limited by several factors: (i) the magnetisation curve of the iron vane is non-linear. (ii) at low current values, the peak to peak of the ac produces a greater displacement per unit current than the average value, resulting in an ac reading that may be appreciably higher than the equivalent dc reading at the lower end of the scale. Similarly, at the higher end of the scale, the knee of the magnetisation curve is approached and the peak value of the ac produces less deflection per unit current than the average value, so that the ac reading is lower than the equivalent dc value.

(Hysteresis in iron and eddy currents in the vanes and other metal parts of the instrument further affect the accuracy of the reading.) The flux density is very small even at full scale values of current, so that the instrument has a low current sensitivity. There are no current carrying parts in the moving system, hence the iron vane meter is extremely rugged and reliable. It is not easily damaged even under severe overload conditions.

Adding a suitable multiplier converts the iron vane movement into a voltmeter; adding a shunt produces different current ranges. When an iron vane movement is used as an ac voltmeter, the frequency increases the impedance of the instrument and therefore a lower reading is obtained for a given applied voltage. An iron vane voltmeter should therefore always be calibrated at the frequency at which it is to be used. The usual commercial instrument may be used within its accuracy tolerance from 25–125 Hz.

DIGITAL DISPLAY SYSTEM AND INDICATORS 2.7

The rapid growth of electronic handling of numerical data has bought with it a great demand for simple systems to display the data in a readily understandable form. Display devices provide a visual display of numbers, letters, and symbols in response to electrical input, and serve as constituents of an electronic display system.

CLASSIFICATION OF DISPLAYS 2.8

Commonly used displays in the digital electronic field are as follows.

1. Cathode Ray Tube (CRT)
2. Light Emitting Diode (LED)
3. Liquid Crystal Display (LCD)
4. Gas discharge plasma displays (Cold cathode displays or Nixies)
5. Electro-Luminescent (EL) displays
6. Incandescent display
7. ElectroPhoretic Image Displays (EPID)
8. Liquid Vapour Display (LVD)

In general, displays are classified in a number of ways, as follows.

1. On methods of conversion of electrical data into visible light
   (a) Active displays
   (Light emitters – Incandescent, i.e. due to temperature, luminescence, i.e. due to non-thermal means or physio-thermal, and gas discharge-glow of light around the cathode.)
   — CRTs, Gas discharge plasma, LEDs, etc.
   (b) Passive displays
   Light controllers, LCDs, EPIDs, etc.
2. On the applications
   (a) Analog displays — Bar graph displays (CRT)
   (b) Digital displays — Nixies, Alphanumeric, LEDs, etc.
3. According to the display size and physical dimensions
   (a) Symbolic displays — Alphanumeric, Nixie tubes, LEDs, etc.
   (b) Console displays — CRTs, LEDs, etc.
   (c) Large screen display — Enlarged projection system
4. According to the display format
   (a) Direct view type (Flat panel planar) — Segmental, dotmatrix — CRTs

   (b) Stacked electrode non-planar type — Nixie
5. In terms of resolution and legibility of characters
   (a) Simple single element indicator
   (b) Multi-element displays

DISPLAY DEVICES 2.9

When displaying large quantities of alphanumeric data, the read out system employed most commonly is a familiar CRT. Conventionally, CRTs form the basis of CROs and TV systems. To generate characters on the CRT, the generation system of characters on CRTs requires relatively simple electronic circuitry.

A typical CRT display has easy facilities for the control of digit size by controlling the deflection sensitivity of the system (either electromagnetic or electrostatic deflection). The number of characters displayed can be changed with the help of time shared deflection and modulator circuits.

Importantly, the intensity and brightness can be realised. with different gray scales, and the display can have different colour depending on the phosphor used in the screen. Generally the phosphor is chosen to be white or green.

Storage type CRTs facilitate storing a stationary pattern on the screen without flickering display and it is possible to retain the pattern for a long time, independent of the phosphor persistence.

LIGHT EMITTING DIODES (LED) 2.10

The LED, Fig. 2.10 (a) is basically a semiconductor PN junction diode capable of emitting electromagnetic radiation under forward conductions. The radiation emitted by LEDs can be either in the visible spectrum or in the infrared region, depending on the type of the semiconductor material used. Generally, infra-red emitting LED's are coated with Phosphor so that, by the excitation of phosphor visible light can be produced. LEDs are useful for electronics display and instrumentation. Figure 2.10 (b) shows the symbol of an LED.

The advantage of using LEDs in electronic displays are as follows.

1. LEDs are very small devices, and can be considered as point sources of light. They can therefore be stacked in a high-density matrix to serve as a numeric and alphanumeric display. (They can have a character density of several thousand per square metre).
2. The light output from an LED is function of the current flowing through it. An LED can therefore, be smoothly controlled by varying the current. This is particularly useful for operating LED displays under different ambient lighting conditions.
3. LEDs are highly efficient emitters of EM radiation. LEDs with light output of different colours, i.e. red, amber, green and yellow are commonly available.
4. LEDs are very fast devices, having a turn ON-OFF time of less than 1 ns.

5. The low supply voltage and current requirements of LEDs make them compatible with DTL and TTL, ICs.

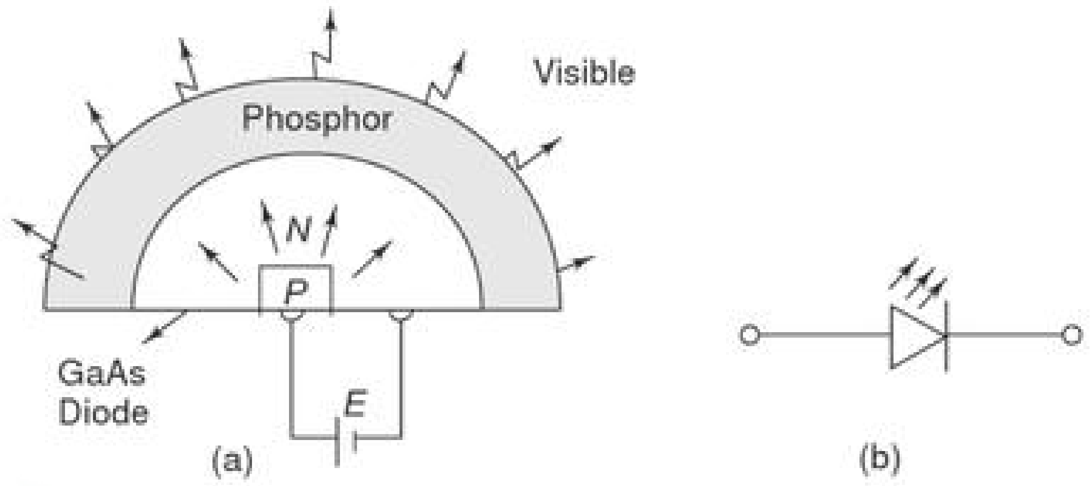


Fig. 2.10 (a) Structure of a visible emitter using GaAs PN junction (b) Symbol of LED

In germanium and silicon semiconductors, most of the energy is released in the form of heat. In Gallium Phosphide (GaP) and Gallium Arsenide Phosphide (GaAsP) most of the emitted photons have their wavelengths in the visible regions, and therefore these semiconductors are used for the construction of LEDs. The colour of light emitted depends upon the semiconductor material and doping level.

Different materials used for doping give out different colours.

1. Gallium Arsenide (GaAs) — red
2. Gallium Arsenide Phosphide (GaAsP) — red or yellow
3. Gallium Phosphide (GaP) — red or green

Alphanumeric displays using LEDs employ a number of square and oblong emitting areas, arranged either as dotmatrix or segmented bar matrix.

Alphanumeric LEDs are normally laid out on a single slice of semiconductor material, all the chips being enclosed in a package, similar to an IC, except that the packaging compound is transparent rather than opaque. Figure 2.10 (c) and (d) gives typical LED packages for single element LEDs.

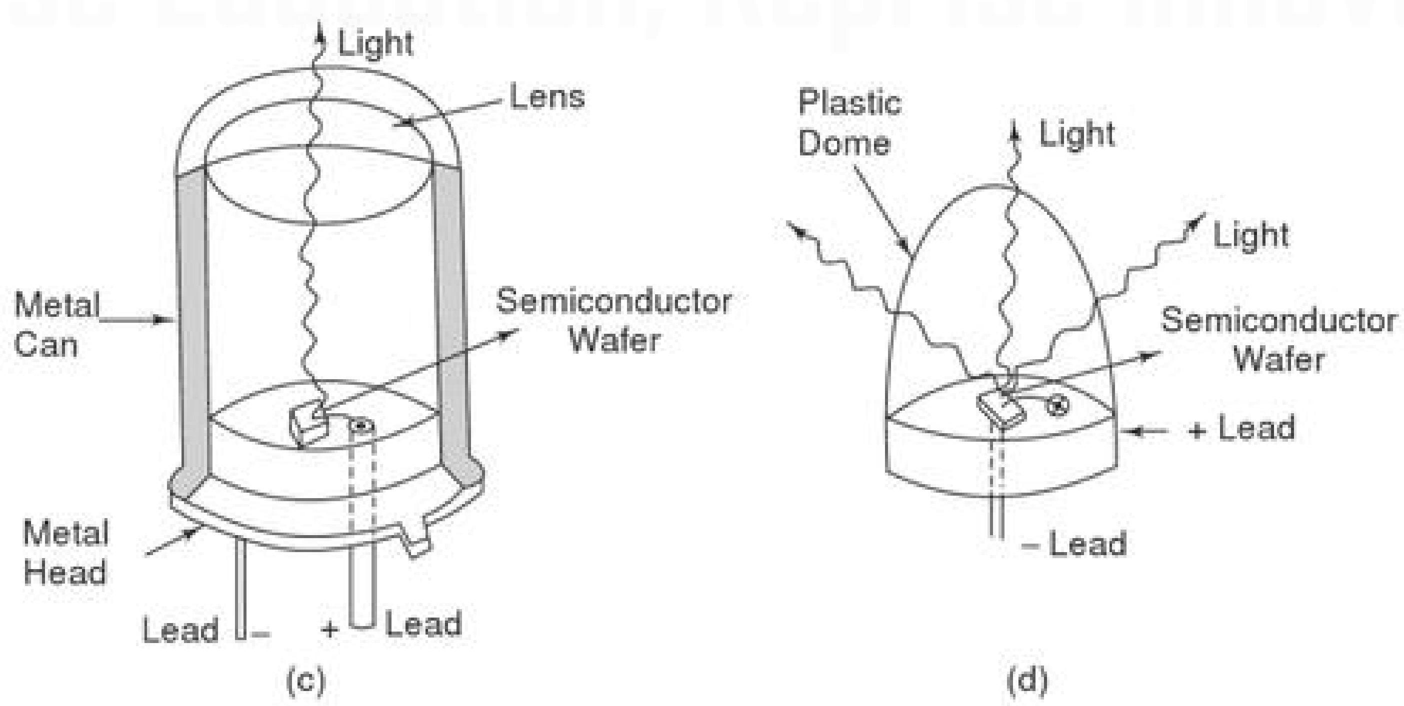


Fig. 2.10 (c) Metal can Tθ-5 type (d) Epoxy type

LIQUID CRYSTAL DISPLAY (LCD) 2.11

LCDs are passive displays characterised by very low power consumption and good contrast ratio. They have the following characteristics in common.

1. They are light scattering.
2. They can operate in a reflective or transmissive configuration.
3. They do not actively generate light and depend for their operation on ambient or back lighting.

A transmissive LCD has a better visual characteristic than a reflective LCD. The power required by an LCD to scatter or absorb light is extremely small, of the order of a few µW/cm. LCDs operate at low voltages, ranging from 1–15 V.

The operation of liquid crystals is based on the utilisation of a class of organic materials which remain a regular crystal-like structure even when they have melted. Two liquid crystal materials which are important in display technology are nematic and cholesteric, as shown in Fig. 2.11.

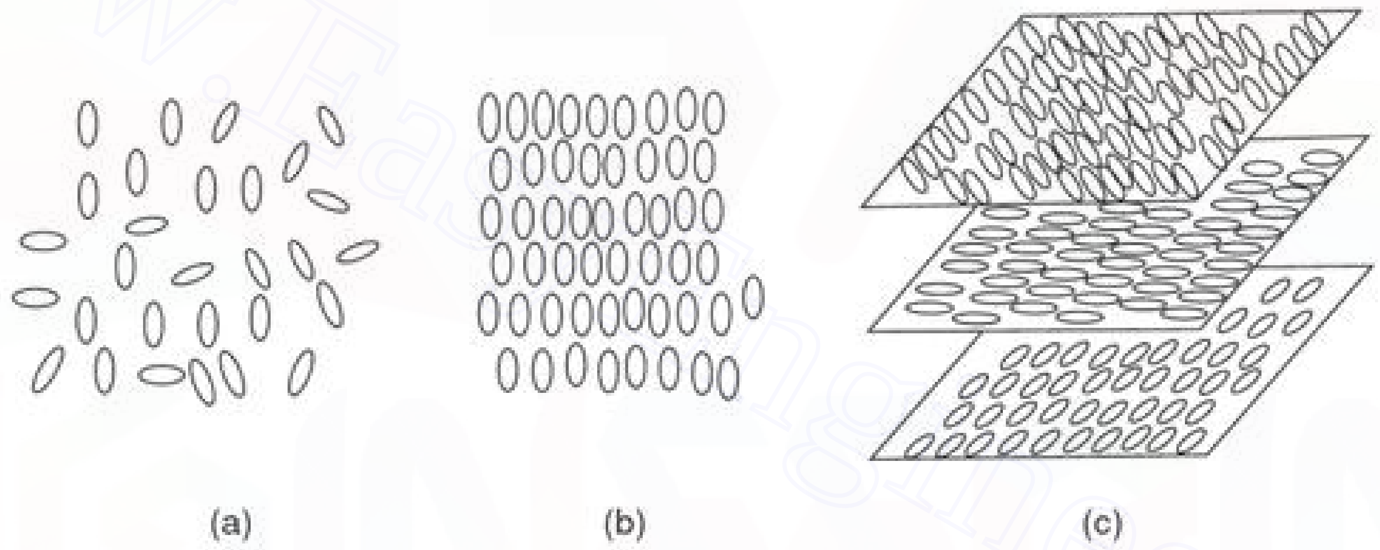


Fig. 2.11 Liquid crystal materials (a) Ordinary liquids (b) Nematic liquid crystal (c) Cholesteric liquid crystal

The most popular liquid crystal structure is the nematic liquid crystal (NLC). The liquid is normally transparent, but if it is subjected to a strong electric field, ions move through it and disrupt the well ordered crystal structure, causing the liquid to polarise and hence turn opaque. The removal of the applied field allows the crystals structure to reform and the material regains its transparency.

Basically, the LCD comprises of a thin layer of NLC fluid, about 10 µ thick, sandwiched between two glass plates having electrodes, at least one of which is transparent.

(If both are transparent, the LCD is of the transmissive type, whereas a reflective LCD has only one electrode transparent.)

The structure of a typical reflective LCD is shown in Fig. 2.12.

The NLC material in Fig. 2.12 has a homogeneous alignment of molecules. While the glass substrate supports the LCD and provides the required transparency, the electrode facilitates electrical connections for the display. The insulating spacers are the hermetic seal.

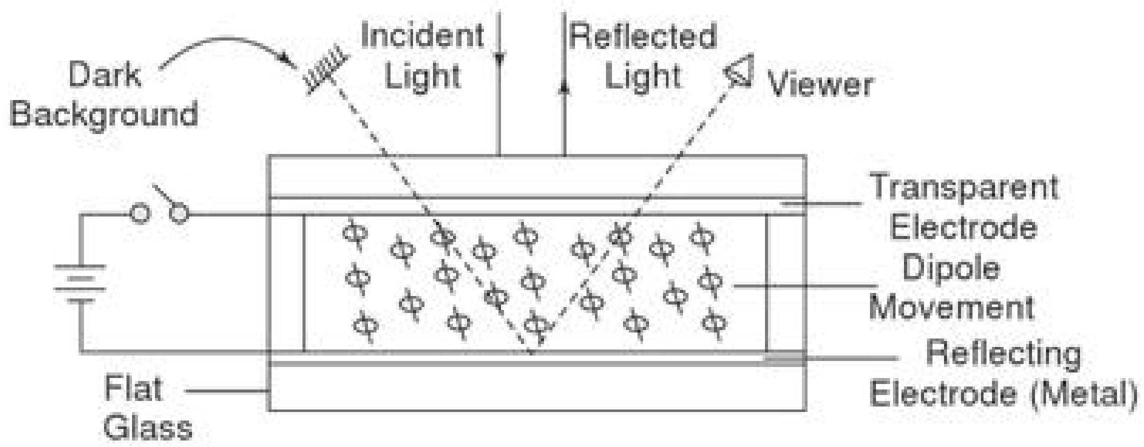


Fig. 2.12 Reflective display using NLC

The LCD material is held in the centre cell of a glass sandwich, the inner surface of which is coated with a very thin conducting layer of tin-oxide, which can be either transparent or reflective. The oxide coating on the front sheet of the indicator is etched to produce a single or multisegment pattern of characters and each segment of character is properly insulated from each other.

LCDs can be read easily in any situation, even when the ambient light is strong. If the read electrode is made transparent instead of reflective, back illumination is possible by a standard indicator lamp. Extending back illumination a step further by adding a lens arrangement. LCDs can be used as the slide in a projection system, to obtain an enlarged image.

Important Features of LCDs

1. The electric field required to activate LCDs is typically of the order of 10^4 V/cm. This is equivalent to an LCD terminal voltage of 10 V when the NLC layer is 10 μ thick.
2. NLC materials possess high resistivity > 10^{10} Ω. Therefore the current required for scattering light in an NLC is very marginal (typically 0.1 $\mu A/cm^2$).
3. Since the light source for a reflective LCD is the ambient light itself, the only power required is that needed to cause turbulence in the cell, which is very small, typically 1 μW/cm.
4. LCDs are very slow devices. They have a turn-on time of a few milli-seconds, and a turn-off time of tens of milliseconds.

To sum up, LCDs are characterised by low power dissipation, low cost, large area and low operating speed.

LCDs are usually of the seven segment type for numeric use and have one common back electrode and seven transparent front electrodes characters, as shown in Fig. 2.13.

The back electrode may be reflective or transmissive, depending on the mode of operation of the display device.

Generally arrays of such characters are simultaneously fabricated using thin-film or hybrid IC technology for segments and conductors on glass plates, and then filled in with NLC material, followed by hermetic sealing.

LCD arrays utilising a dot-matrix are also possible, but they are not popular because of their slow operation.

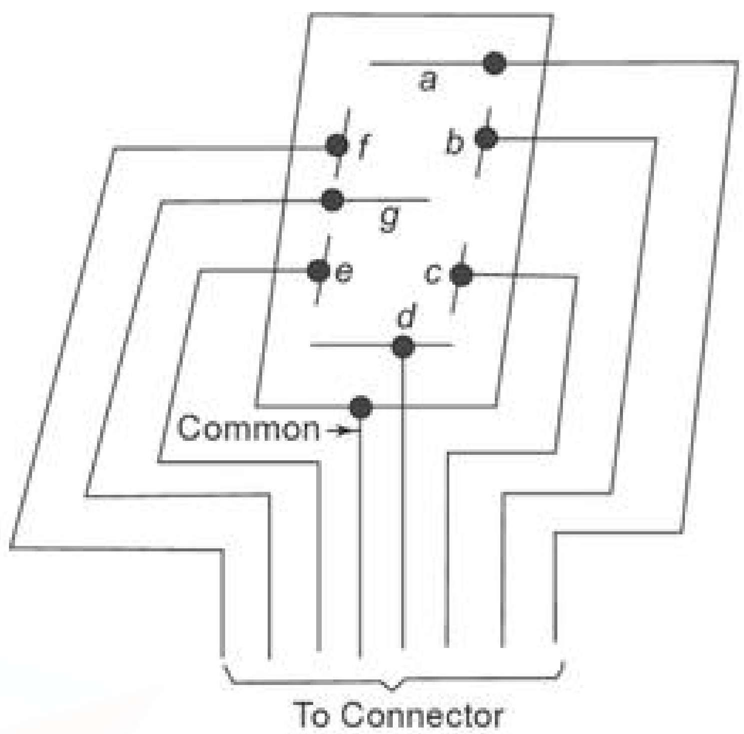


Fig. 2.13 Seven segment LCD character

OTHER DISPLAYS 2.12

Other important displays for use in electronic instrumentation are gas discharge plasma, electroluminescent, incandescent, electrophoretic, and liquid vapour display.

2.12.1 Gas Discharge Plasma Displays

These are the most well-known type of alphanumeric displays. Their operation is based on the emission of light in a cold cathode gas filled tube under breakdown condition.

These cold cathode numerical indicators are called Nixies (Numicators and Numbertrons).

This Nixie tube is a numeric indicator based on glow discharge in cold cathode gas filled tubes. It is essentially a multicathode tube filled with a gas such as neon and having a single anode, as shown in Fig. 2.14.

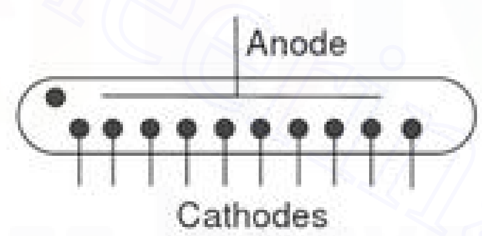


Fig. 2.14 Nixie tube—Symbolic representation

Each of the cathodes is made of a thin wire and is shaped in the form of characters to be displayed, for example, numerals 0 to 9. The anode is also in the form of a thin frame.

In its normal operation, the anode is returned to positive supply through a suitable current limiting resistor, the value of the supply being greater than the worst-case breakdown voltage of the gas within the tube. The gas in the vicinity of the appropriate cathode glows when the cathode is switched to ground potential.

(The characteristic orange red glow in the case of neon covers the selected cathode completely, thereby illuminating the character brightly.)

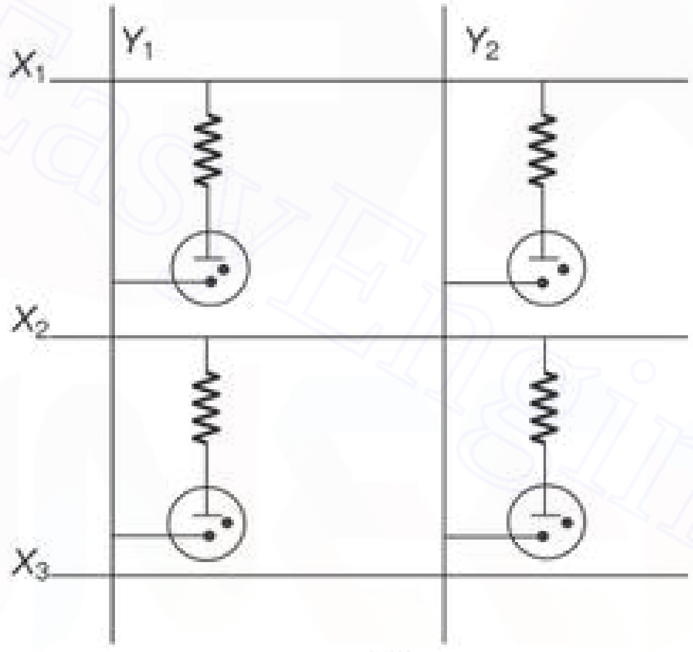
Since 10 cathodes have to be associated with a single anode inside the glass bulb, they have necessarily to be stacked in different planes. This requires different voltages for different cathodes to enable the glow discharge.

Many Nixie tubes also possess dot-cathodes either on the left or right of the character to serve as decimal points.

The standard Nixie is not the only format used with cold cathode technology—both bar and dot matrix versions are available. The bar types have a cathode which forms the segment and operates in a fashion similar to the standard neon tube. Identical supply voltage and drivers are required. In the dot type display, each dot is in matrix fashion and operates as an individual glow discharge light source. The required dots are selected by an *X-Y* addressing array of thin film metal lines, as shown in Fig. 2.15 (a).

Nixie tubes have the following important characteristics.

1. The numerals are usually large, typically 15–30 mm high, and appear in the same base line for in-line read-out.
2. Nixie tubes are single digit devices with or without a decimal point.
3. They are either side viewing or top viewing (as shown in Figs 2.15 (b) and (c)).



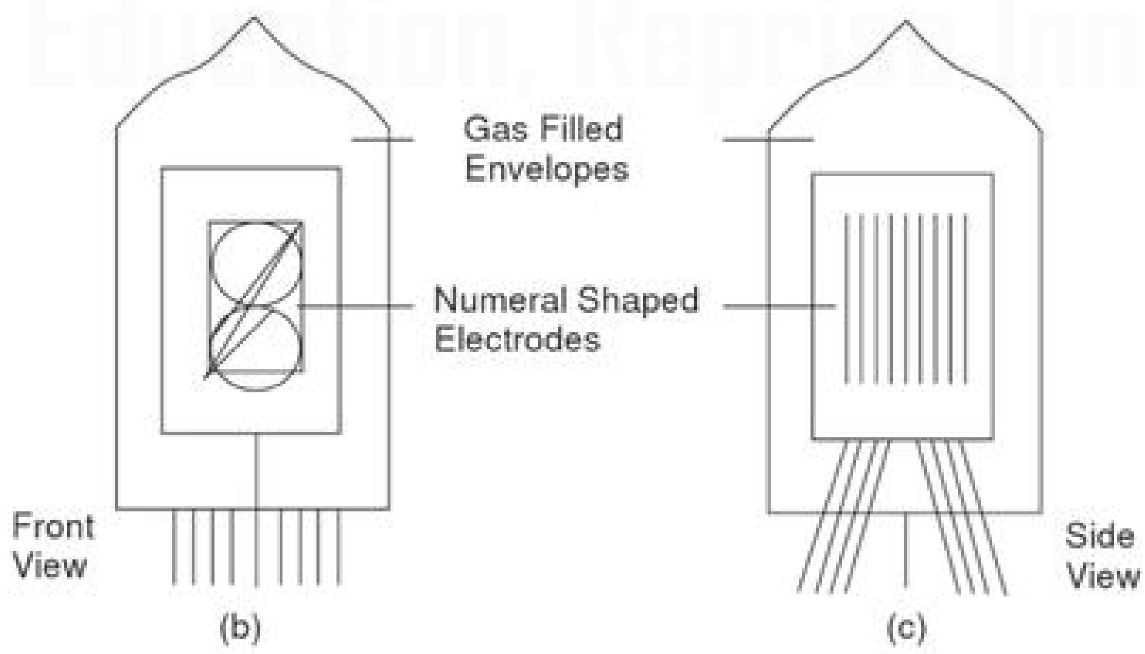


Fig. 2.15 (a) Matrix operation of display panel using gas filled devices (b) and (c) nixie tube

4. Most Nixie tubes require dc supply of 150–220 V, and the selected cathode carries current in the range of 1–5 mA.

5. The Nixie tube can be pulse operated and hence can be used in multiplexed displays.
6. Alphabetical symbols can also be introduced in the Nixie tube.

2.12.2 Segmented Gas Discharge Displays

Segmented gas discharge displays work on the principle of gas discharge glow, similar to the case of Nixie tubes. They are mostly available in 7 segment or 14 segment form, to display numeric and alphanumeric characters.

Since these devices require high voltages, special ICs are developed to drive them. The construction of a 7 segment Display is shown in Fig. 2.16. Each segment (decimal point) of the 7 segment display formed on a base has a separate cathode. The anode is common to each member of the 7 segment group which is deposited on the covering face plate. The space between the anodes and cathodes contains the gas. For each group of segments, a 'keep alive' cathode is also provided. For improving the switching speeds of the display a small constant current (a few micro amps) is passed through this keep alive cathode, which acts as a source of ions. Pins are connected to the electrodes at the rear of the base plate, with the help of which external connections can be made.

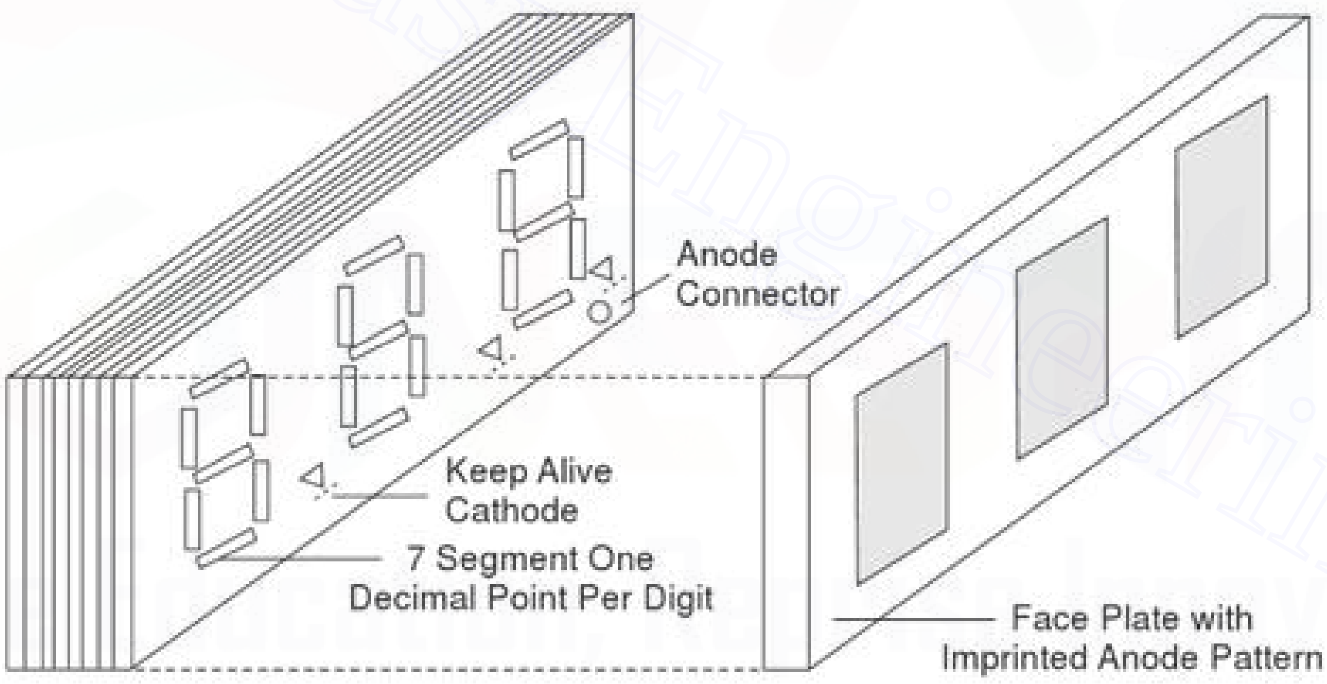


Fig. 2.16 Seven segment display using gaseous discharge

The major disadvantage of this gas discharge tube is that high voltage is required for operating it. Therefore, high voltage transistors, in the range of 150 – 200 V, are required as switches for the cathodes. A major advantage is that the power consumed is extremely small, because a bright display can be obtained even for currents as low as 200 μA.

This display follows a simple construction. Figure 2.17 gives the structure of a typical 7 segment display making use of a gas discharge plasma.

The device uses a glass substrate, shown in Fig. 2.17. Back electrodes of the thick film type serve as cathode segments, and front electrodes of the thin film type serve as transparent anodes. A gas, typically neon, is filled in the discharge space between the cathode and anode segment. The gas is struck between the cathode and anode of a chosen segment so that the cathode glow provides the illumination. All numeric characters can be displayed by activating the appropriate segment.

Display panels of rows or columns of such characters can be easily constructed by extending a single character. The power requirements of such devices are more or less in the same range as those for Nixie tubes.

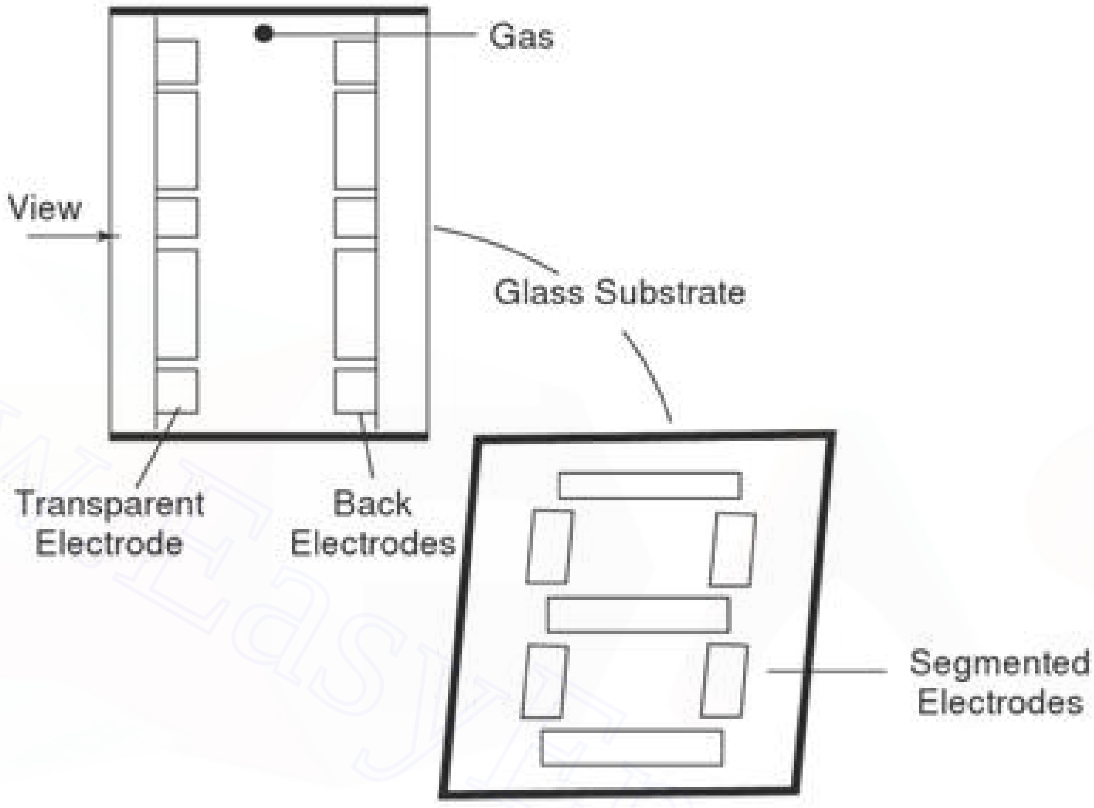


Fig. 2.17 Seven segment gas filled character

2.12.3 Segmental Displays using LEDs

In segmental displays, it is usual to employ a single LED for each segment.

For conventional 7 segment LED displays (including the decimal point, i.e. the 8th segment), the wiring pattern is simplified by making one terminal common to all LEDs and other terminals corresponding to different segments. The terminals can be either of the common anode (CA) form or common cathode (CC) form, shown in Figs 2.18 (b) and (c).

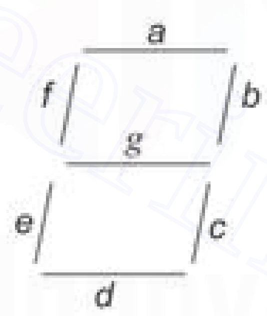


Fig. 2.18 (a) LED 7 segment format

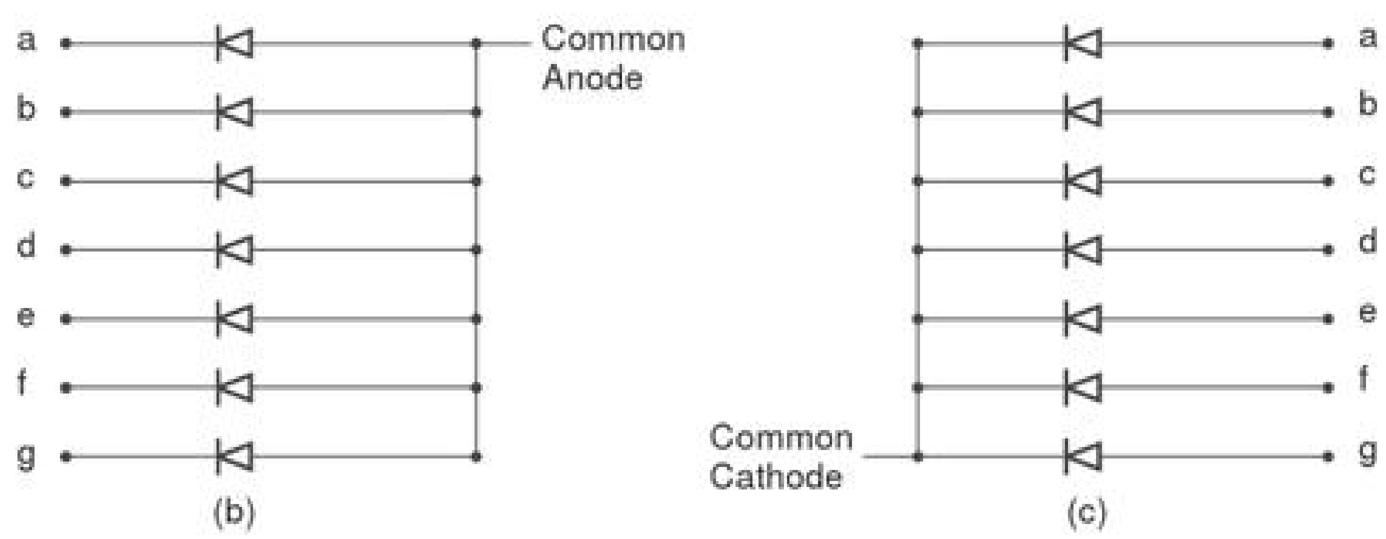


Fig. 2.18 (b) Common anode connections (c) Common cathode connections

A typical static single digit 7 segment LED display system and multi-digit are shown in Figs. 2.18 (a) and (d).

Multi-digit display system may be static or dynamic.

Common anode type displays require an active low (or current sinking) configuration for code converter circuitry, whereas an active high (or current sourcing) output circuit is necessary for common-cathode LED type display.

Both multi-digit and segmental displays require a code converter; one code converter per character for static display systems and a single code converter for time shared and multiplexed dynamic display systems, which are illuminated one at a time.

The typical circuit schemes described in the figures are only of the decimal numeric character. An 8 digit display system, operating on this principle and suitable for digital instrumentation is given in Fig. 2.18 (d).

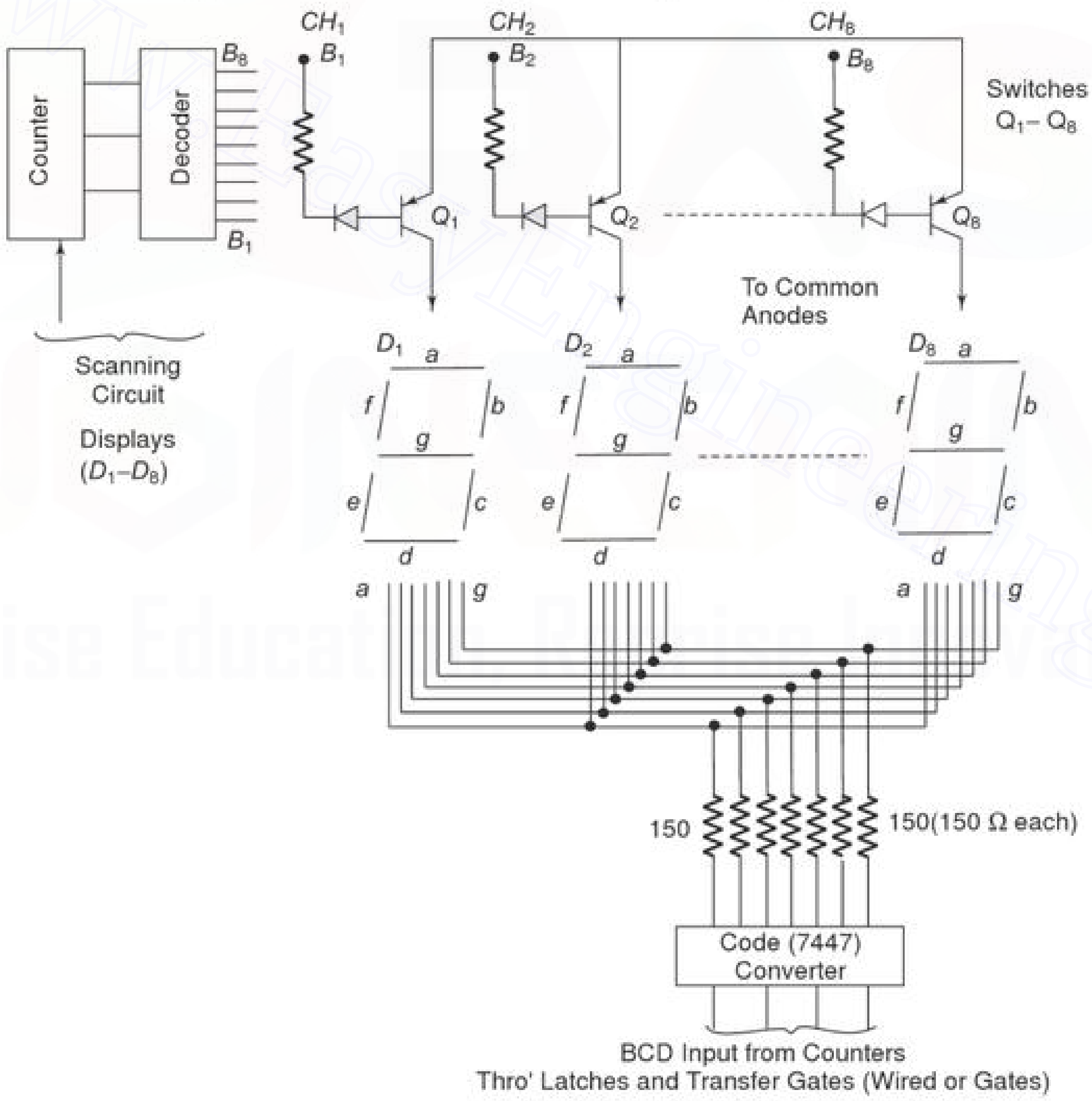


Fig. 2.18 (d) Multi-digit display system (8 digit) using LED 7 segment characters

It is also possible to generate hexadecimal numeric characters and conventional alphanumeric characters using 7 segment and 14 or 16 segment LED display units respectively, with a proper code converter. Both static and dynamic displays can be realised using LCDs, either in a common format (7 segment) or in single or multi character.

A chopped dc supply may be used, for simplicity, but conventionally an ac voltage is applied either to the common electrode or to the segment. Various segmental LCD driver circuits are displayed in Fig. 2.19.

Referring to Figs 2.19 (a) and (b), it is seen that an ac voltage (V_{ac}) is applied to either the common electrode or to the segment. High value resistances ($R > 1M$) are included in the circuit, as shown. The code converter controls the switches (S). V_{ac} is present across the selected segment and the common electrode when S is ON, and the voltage between any other segment (S-OFF) and the common electrode is zero. Hence the desired segments are energised, provided V_{ac} has a magnitude greater than or equal to the operating voltage of the LCD.

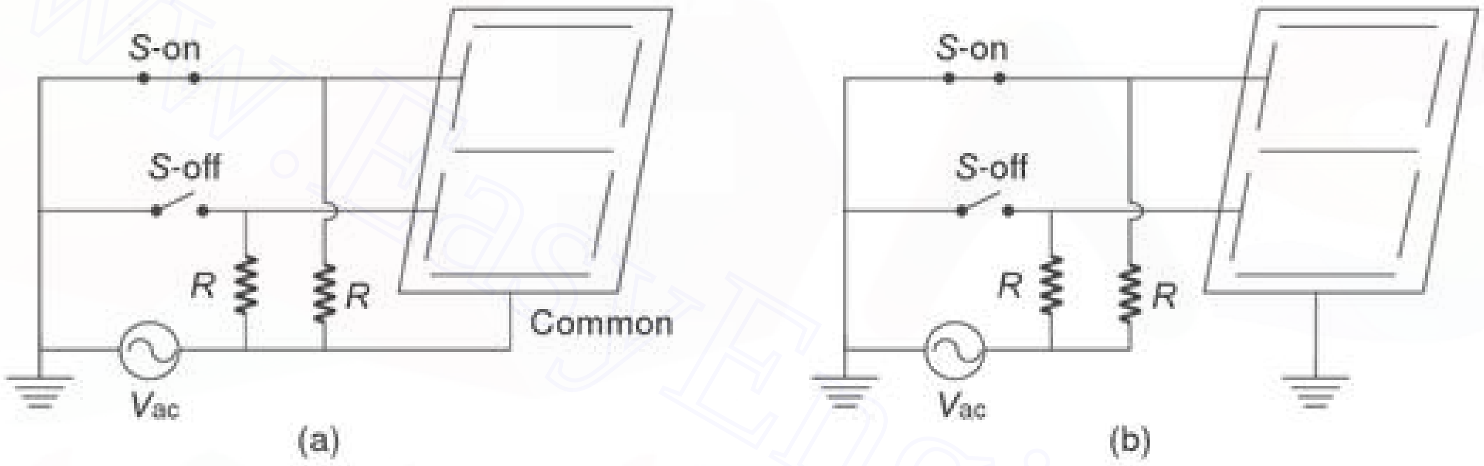


Fig. 2.19 (a) Segments driving circuits for LCD, switching method common electrode (b) Segments Driving circuits for LCD, switching method

The basic operation of the phase shift method for driving the segment is shown in Fig. 2.19 (c). In this circuit, ac voltages of the same amplitude and frequency (not necessarily same phase) are supplied to the common electrode as well as the segments.

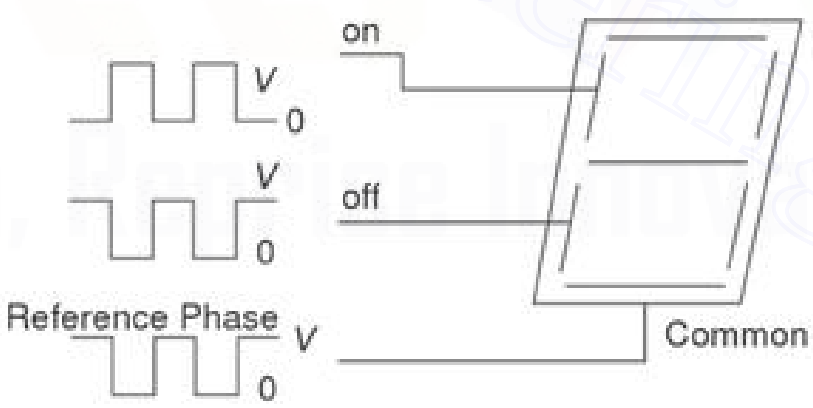


Fig. 2.19 (c) Segments driving circuits for LCD, using phase shift method

There will be a finite voltage drop between a segment and the common electrode only when the ac voltages applied are out of phase, and thus the selected segment is energised. On the other hand, when in-phase voltages are present, the voltage drop between a segment and the common electrode is zero, leading to the off state.

2.12.4 Dot Matrix Displays

Excellent alphanumeric characters can be displayed by using dot matrix LEDs with an LED at each dot location. Commonly used dot matrices for the display of prominent characters are 5×7, 5×8, and 7×9, of which 5×7 shown in

Fig. 2.20 (a), is very popular due to economic considerations. The two wiring patterns of dotmatrix displays are as follows.

1. Common anode or common cathode connection (uneconomical).
2. $X - Y$ array connection (economical and can be extended vertically or horizontally using a minimum number of wires, Fig. 2.20 (b)).

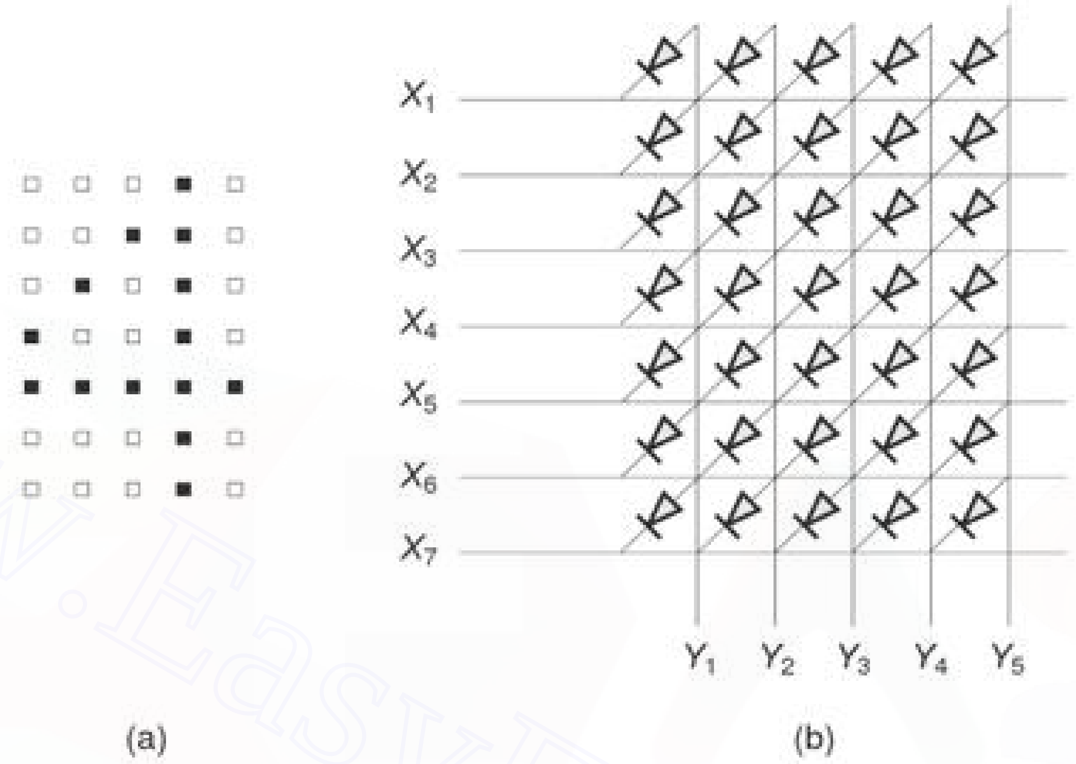


Fig. 2.20 (a) 5 × 7 dot matrix character using LED (b) Wiring pattern for 5 × 7 LED character

A typical 3 digit alphanumeric character display system using 5 × 7 dot matrix LEDs is shown in Fig. 2.21.

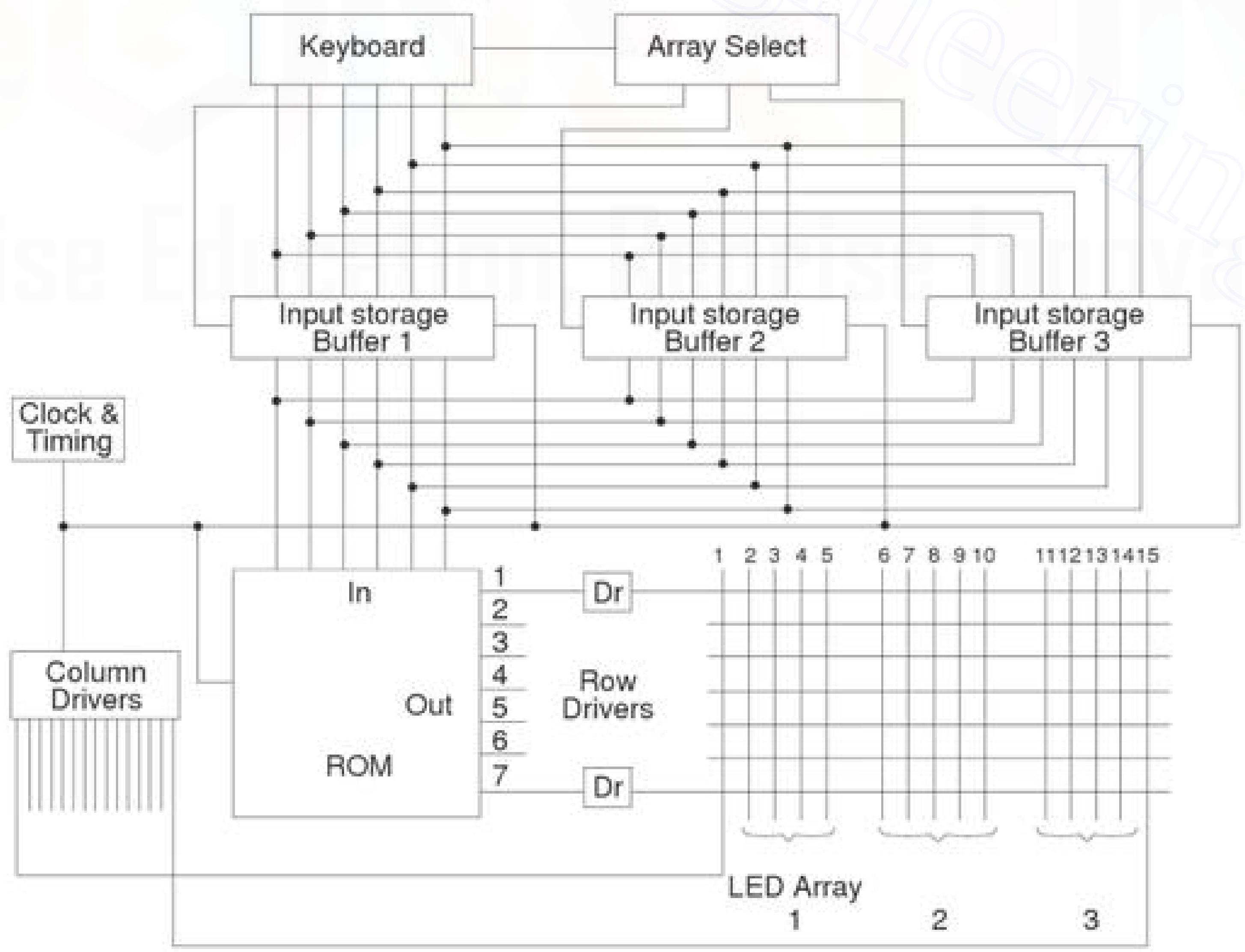


Fig. 2.21 A 3 digit alphanumeric display system using 5 × 7 characters

2.12.5 Bar Graph Displays

Bar graph displays are analogue displays which are an alternative to conventional D'Arsonval moving coil meters. They use a closely packed linear array or column of display elements, i.e. "DOT-LED'S", which are independently driven so that the length of the array (or the height of the column) corresponds to the voltage or current being measured. These displays are generally used in the panel meters to accept analog input signals and produce an equivalent display of the input signal level by illuminating the corresponding LEDs, as shown in Fig. 2.22.

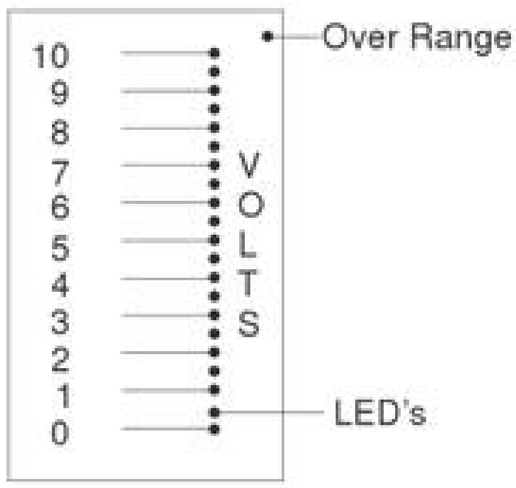


Fig. 2.22 Analog meter using bar graph of LEDs

2.12.6 Electro Luminescent (EL) Displays

Electro luminescent displays are an important means of light generation. They can be fabricated using polycrystalline semiconductors, and in view of their simple technology, brightness of display and possibility of different colours, are rapidly gaining in popularity.

The semiconductors used for EL displays are essentially phosphor powder or film type structures.

The powder type consist of powder phosphor with some binding material e.g. organic liquids deposited on a sheet of glass. The glass has transparent conductive segments (e.g. 7 segment displays) or dots (dot matrix display) along with the required conductive leads on the side on which phosphor is coated for electrical connections.

A metallic electrode, usually aluminium, is placed over the phosphor in a pressure cell by vacuum evaporation, so as to form an electrical connection on the other side of the phosphor. The resulting device is capacitive, because of poor conduction paths in phosphor. An ac field applied across the chosen segment (or dot) and aluminium electrode excites the phosphor, resulting in emission of light. In film type structures the EL powder structure is replaced by a polycrystalline phosphor film which is deposited on a glass substrate using a vacuum or pressure cell. These devices can be operated by ac as well as dc.

2.12.7 Incandescent Display

Incandescence has been a basic process of light generation for several decades. This process is now down in fully integrated electronic displays.

Incandescent displays using 16 segment as well as 5 × 7 dot matrix formats fabricated using thin film micro electronics are now available for alphanumeric characters. Such displays are characterised by simple technology, bright output and compatibility with ICs, but at very low operating speeds.

A thin film of tungsten can be made to emit light if its temperature is raised to about 1200°C by electrical excitation. A 5 × 7 character array is formed on a ceramic substrate employing such films in a matrix form and is used as an integrated electronic display unit. Figure 2.23 gives a typical tungsten film or filament suitable for a dot location in the display.

An array of such filaments can be formed on ceramic substrates using conventional thin film technology commonly used in semiconductor fabrication.

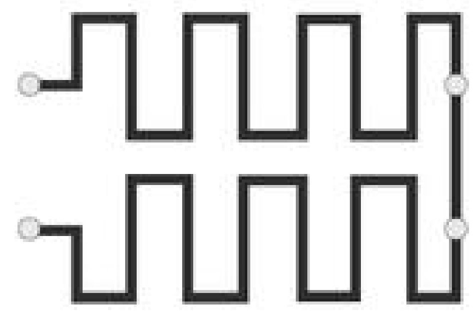


Fig. 2.23 Tungsten filament suitable for incandescent display

Considering the filament dimensions and the dimensions of commonly available substrates, an array of three characters can be located on a 2.5 cm ceramic substrate.

16 segment incandescent displays are also available, but their display is slow, because of the large thermal time constant associated with the filaments.

2.12.8 Electrophoretic Image Display (EPID)

Electrophoresis is the movement of charged pigment particles suspended in a liquid under the influence of an electric field. This pheonomenon has been utilised in electrophoretic image displays, as shown in Fig. 2.24.

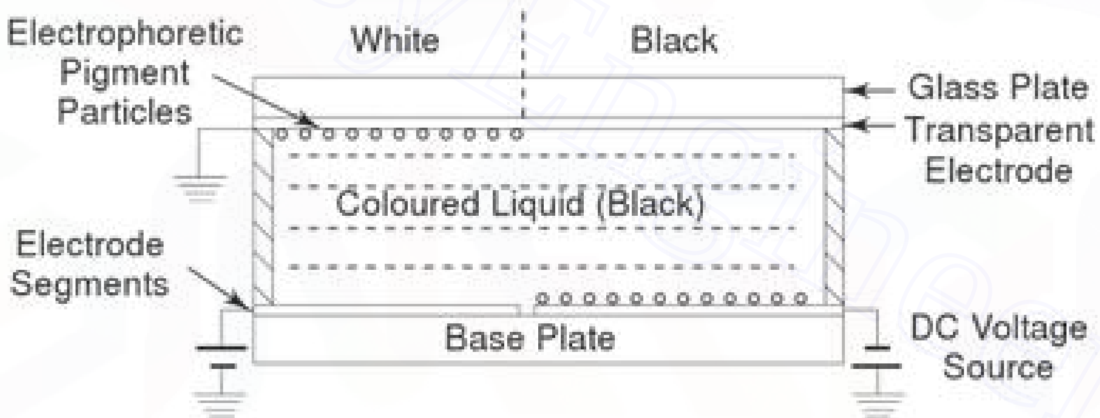


Fig. 2.24 Structure of an EPID

The basic principle; fabrication and operating characteristics of a reflective type Electrophoretic Image Display (EPID) panel are as follows. These displays are characterised by large character size, low power dissipation and internal memory.

The relatively slow speed of these displays is a major limitation, particularly for use as a dynamic display. The life span of an EPID is a few thousand hours only.

The EPID panel makes use of the electrophoretic migration of charged pigment particles in a supension. The suspension, 25 – 100 μ thick, which largely contains the pigment particles and a suspending liquid, is sandwiched between a pair of electrodes, one of which is transparent.

The application of a dc electric field, across the electrodes, as shown in Fig. 2.24 moves the particles electrophoretically towards either electrode, the movement depending mainly on the polarity of the charge on the particles. The reflective colour of the suspension layer changes on account of this migration.

EPID panels generally follow a segmented character format – typically 7 segment for numeric characters.

It is usual to have the transparent electrode as a common electrode. The back electrodes are generally segmented. Two such segments are shown in Fig. 2.24.

During the normal operation of the display, the transparent electrode is maintained at ground potential and the segmented electrodes at the back are given different potentials.

If the pigment particles are white and positively charged in the black suspending liquid, the application of a positive voltage to the chosen segment moves the pigment particles away from it and towards the transparent electrode. This is shown on the left side of Fig. 2.24. Pigment particles appear white in reflective colour as viewed through the transparent electrodes.

On the other hand, when a segment has a negative voltage with reference to the transparent electrode, the white pigment particles go towards it and get immersed in the black suspension. In this case, the viewer sees the reflection from the black liquid itself.

Colour combinations of both the pigment particles and the suspending liquid can be used to achieve a desired colour display.

Moreover, the colours between the displayed pattern and its background can be reversed, by changing the polarities of segment voltages.

In addition, the EPID panel has a memory, because the pigment particles deposited on an electrode surface remain there even after the applied voltage is removed.

2.12.9 Liquid Vapour Display (LVD)

LVDs are the latest in economical display technology. They employ a new reflective passive display principle and depend on the presence of ambient lights for their operation. Figure 2.25 gives the structure of a typical LVD cell.

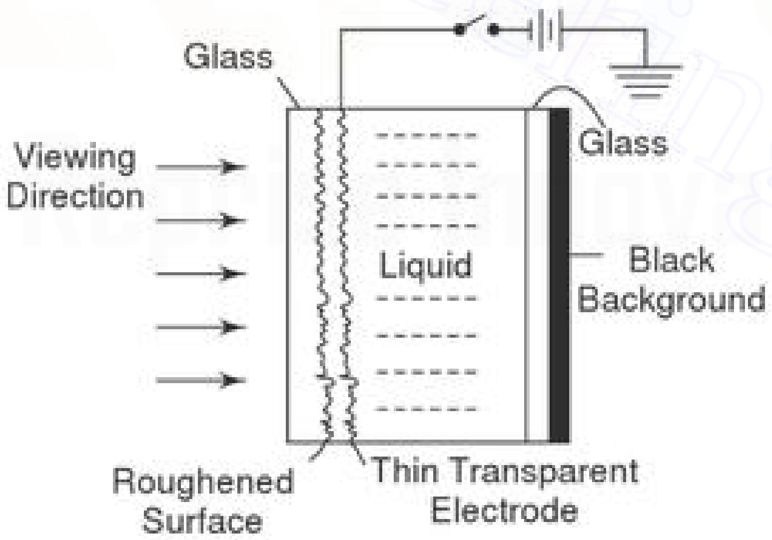


Fig. 2.25 Structure of an LVD Cell

It consists of a transparent volatile liquid encased between two glass plates and side spacers. The rear glass plate has a black background and the front glass surface in contact with the liquid is roughened, so that the liquid wets it, i.e. in its simplest form, an LVD consists of a roughened glass surface wetted with a transparent volatile liquid of the same refractive index as that of the glass. The rear surface is blackened.

The transparent electrode is heated by using a voltage drive, which is the basis for the display function.

In the OFF condition of display with no voltage applied across the transparent electrode, the viewer sees the black background through the front transparent glass electrode and the liquid.

To achieve an ON condition of the display, a voltage is applied to the transparent electrode. This causes sufficient heat in the electrode, which evaporates the liquid in contact with it, and a combination of vapour film and vapour bubbles is formed around the roughened glass surface. As the refractive index of vapour is approximately 1, there is a discontinuity established at the interface between the front glass plate and the liquid, which gives rise to light scattering. This makes it a simple display device.

The organic liquid selected for LVD should have the following features.

1. Refractive index close to that of the glass plate.
2. Minimum energy for vapourising the liquid in contact with the roughened surface.

The electrical heating of a thin film of liquid adjacent to the roughened surface using transparent electrodes and the applied voltage, makes it an unusually good display with a better contrast ratio than an LCD. The speed of operation of LVDs is low.

A summary of some important display devices is given in Tables 2.1 and 2.2.

Table 2.1 Some Popular Display Devices

Display devices	*Applications*	*Advantages*	*Disadvantages*
1. CRTs	Large display, small and large group viewing, console display.	Bright, efficient, uniform, planar display—all colours, high reliability	Bulky, high voltage, non-digital address, high initial cost.
2. LEDs	Indicators and small displays, individual viewing, flat-panel.	Bright, efficient, red, yellow, amber, green colours, compatible with ICs, small size	High cost per element, limited reliability, low switching speed
3. LCDs	do	Good contrast in bright ambient light, low power, compatible with ICs, low cost element	Limited temperature range (0 – 60°C) Limited reliability, ac operation necessary, low switching speed.
4. NIXIEs	Indicators, small, medium and large displays, small group viewing.	Bright, range of colours, low cost element, compatible with ICs	High drive power
5. ELs	Indicator and small display, flat panel	Low cost element, many columns	Not compatible with ICs

Table 2.2 Typical applications of digital display

Field of applications	*Displays*
1. *Industrial Electronics*	
Meters, positioner and instrumentation, test equipment, guages and counters	Incandescent, LED, LCD, CRT, Nixie
2. *Medical*	
Digital thermometer, Pulse rate meter, manometer, patient monitoring	CRT, LED's
3. *Computers, Commerce and Business*	
Peripheral and ALU status, calculators and cash register	LED, CRT, EL, Nixie, LCD
4. *Domestic*	
Electronic Oven, telephone, dial indicator, TV channel indicators, clock and calendars, video games	LED, CRT, LCD, Nixie
5. *Military and Space Research*	
Situation indicators	Traditional

PRINTERS 2.13

Character printers and graphic plotters are the two devices used to prepare a permanent (or hard copy) record of computer output.

The basic difference between printers and plotters is that the former are devices whose purpose is to print letters, numbers and similar characters in text readable form, while the latter print diagrams with continuous lines.

CLASSIFICATION OF PRINTERS 2.14

Printers used in computers are classified in the following three broad categories.

1. Impact and Non-impact Printers

Impact printers form characters on a paper by striking the paper with a print head and squeezing an inked ribbon between the print head and the paper.

Non-impact printers form characters without engaging the print mechanism with the print surface, e.g. by heating sensitised paper or by spraying ink from a jet.

2. Fully Formed Character and Dot Matrix Printer

Fully formed characters are like those made by a standard typewriter—all parts of characters are embossed in the reverse on the type bars of the typewriter. When printed, all type elements appear connected or fully formed.

Dot matrix characters are shaped by combinations of dots that form a group representing a letter or number when viewed together.

3. Character at a Time and Line at a Time Printer

Character at a time printers (character printers or serial printers), print each character serially, and virtually instantaneously.

Line at a time printers (line printers), print each line virtually instantaneously.

(Some advanced printers, e.g. those using lasers and xerographic methods, print lines so rapidly that they virtually print a page at a time, and are therefore called page printers. They are rarely used in mini computers and microcomputers, for special purposes like phototype setting.)

PRINTER CHARACTER SET 2.15

Most printers used with mini or micro computers use ASCII codes. Printers are specified as using the 48 character set, the 64 character set, the 96 character set or the 128 character set.

The 48 and 64 character sets include commonly used special symbols, numbers, a space, and upper case (capital) English alphabets.

The 96 ASCII character set includes the lower case English alphabet and several additional special symbols. Of the 96 characters, 'space' and 'delete' do not print, leaving only 94 printable characters.

The entire 128 character ASCII set contains 32 characters normally used for communication and control. These characters usually do not print, but correspond to expandable functions, such as communication and control.

CHARACTER AT A TIME IMPACT PRINTERS FOR FULLY FORMED CHARACTERS (DRUM WHEEL) 2.16

The typewriter is the classic example of this printer, with characters fully formed because they are embossed on each type bar.

Ordinary type bar typewriters cannot be used with computers, because they lack a computer coding interface for easy communications.

(The classic printer used with mini and micro computers in the past was the Teletype Model 33 printer. The ready availability and low cost of these printers, plus their relatively easy interfacing, made them natural for use in small computers. The model 33 prints at a rate of 10 characters per second which is slow compared to today's printer of 55 characters per second for similar printers.) The print mechanism is a vertical cylinder. Characters are embossed in several rows and columns around the cylinder, as shown in Fig. 2.26 (a).

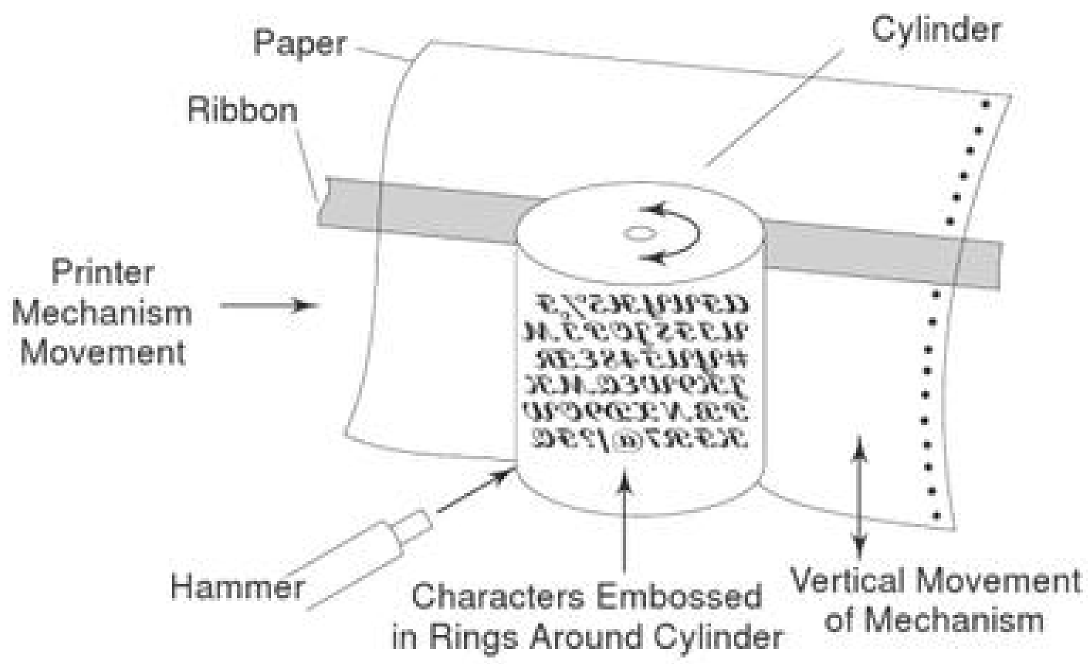


Fig. 2.26 (a) Drum wheel printer

The ASCII character code sent to the printer, is translated into motion that rotates the cylinder, so that the column containing the desired character faces the paper. The cylinder is then raised or lowered (depending on the ASCII code) to present the column containing the desired character to be printed directly to the paper. A hammer mechanism propels (hits) the cylinder towards the paper, where only the positioned character strikes the ribbon, creating the printed impression of the character on the paper.

These printers are interfaced with small computers by a 20 – 60 mA current used to transmit ASCII coded bits serially.

Another type of fully formed character printer, designed for computer use, has characters mounted on the periphery of a spinning print head, known as a daisy wheel printer, and is shown in Fig. 2.26 (b).

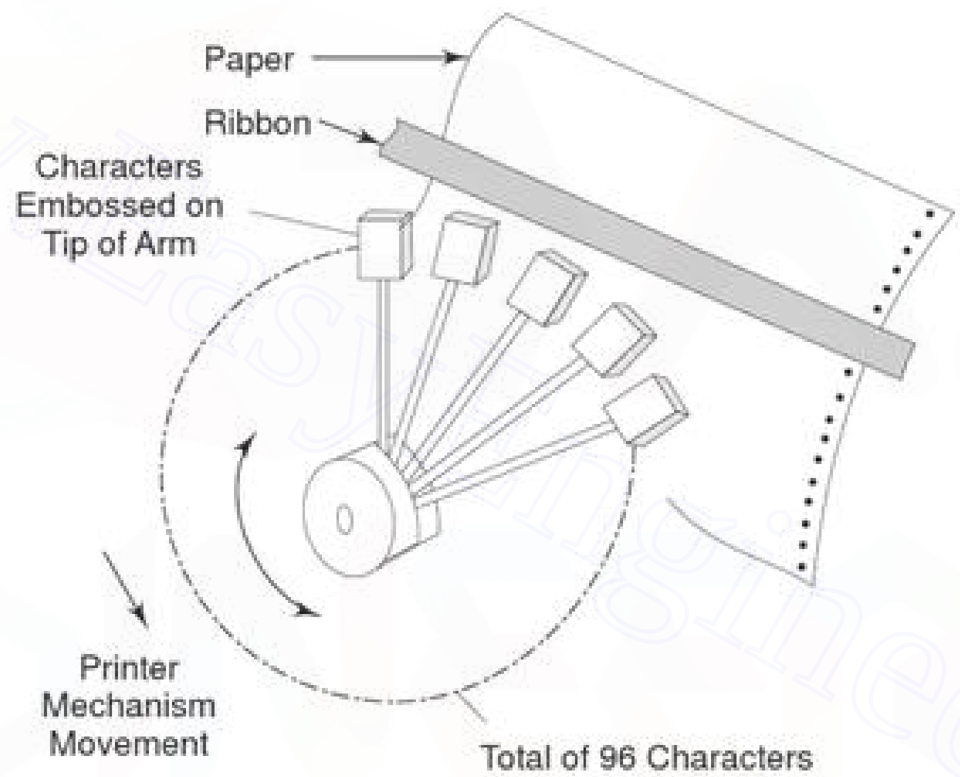


Fig. 2.26 (b) Daisy wheel printer

A daisy wheel print head is mounted on a rotating disk with flexible flower like petals similar to a daisy flower. Each petal contains the embossed character in reverse. As the daisy wheel spins, a hammer strikes the desired flexible petal containing the character, in turn impacting the paper with the embossed character through an inked ribbon.

To print a letter, the wheel is rotated until the desired letter is in position over the paper. A solenoid driven hammer then hits the petal against the ribbon to print the letter.

Daisy wheel printers are slow, with a speed of about 50 characters per second (cps). The advantage of the daisy wheel mechanism is high print quality, and interchangeable fonts.

Character at a time printing follows the following sequence of steps; left to right printing to the end of the line, stop, return carriage and start a second line, and again print left to right. It is unidirectional.

Spinning wheel printers are capable of bidirectional printing. The second line is stored in a buffer memory within the printer control circuitry and can be printed in either direction, depending on which takes the least printer time.

LINE AT A TIME IMPACT PRINTERS FOR FULLY FORMED CHARACTERS (LINE PRINTERS) 2.17

In line printers, characters or spaces constituting printable lines (typically 132 character positions wide) are printed simultaneously across the entire line. Paper is spaced up and the next line is printed. Speeds for line printers range from several hundreds to thousands of lines per minute.

Line printers are used for high volumes of printed output and less frequently in micro computers, because of their high equipment cost relative to character at a time printers.

An embossed type font is positioned across a line for printing by using embossed type, either on a carrier consisting of a chain, train or band moving horizontally across the paper and print line, or a drum rotating in front of the paper with characters embossed. Typically, there are 132 columns on the drum. As the drum rotates, the column of characters pan vertically across the paper and the print line (shown in Fig. 2.27). In both methods, hammers (one for each of 132 print positions) strikes when the correct character is positioned, imprinting the character on the paper with an inked ribbon.

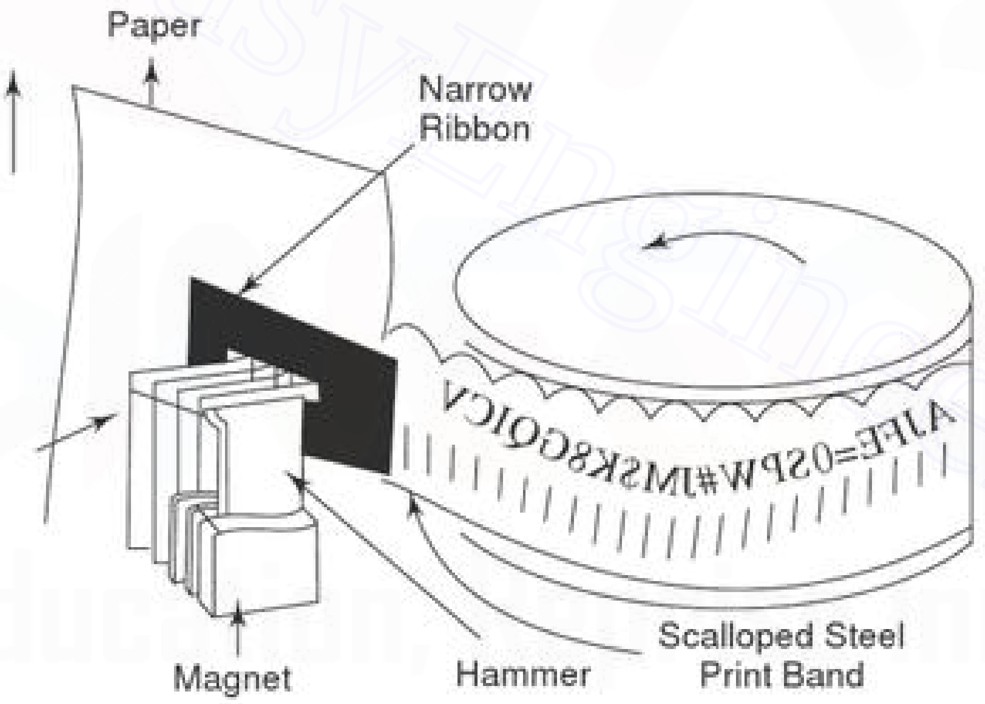


Fig. 2.27 Band printers (Line printer)

Print characters are embossed on the band. The band revolves between two capstans, passing in front of the paper. An inked ribbon is positioned between the moving band and the paper. As the print characters on the band move by 132 horizontal print positions, the 132 corresponding print hammers behind the paper strike the band at the appropriate time, causing the line of characters to print each desired character in 132 print positions.

In band printers, a metallic or plastic band has a fully formed etched character on it. The band rotates at high speed. There is one hammer for one print position, because several hammers can strike simultaneously for many print positions. These printers are faster than dot matrix printers. These line printers have speeds varying from 75 to 4000 lines per minute (1 pm). These printers are both noisier and costlier than dot-matrix printers.

A band always contains more than one character set. This reduces access time needed to match the characters, thereby reducing the printing time. Below the characters are the timing marks which are sensed by the printers electronic circuitry. It compares the character to be printed with the character corresponding to the timing mark, senses it and if a match occurs, fires the corresponding hammer.

A chain printer is similar to a band printer, except that in the former the characters sets are held in a metal or rubber chain and rotated across the paper along a print line.

A chain revolves in front of the ribbon and paper. Each link in the chain is designed to hold a pallet on which type characters are embossed. Hammers are located behind the paper and each of 132 hammers strikes the moving type pallet when the desired character passes the position in which it is timed to print.

DRUM PRINTER 2.18

Figure 2.28 illustrates a drum printer. Each of the 64 or 96 characters used is embossed in 132 columns around the drum, corresponding to the print positions. The drum rotates in front of the paper and ribbon. Print hammers strike the paper, imprinting characters from the drum through the ribbon and forming an impression on the paper.

The drum printer uses a cylindrical drum which contains characters embossed around it. There is one complete character set for each print position. To print characters, magnetically driven hammers in each character position strike the paper and ribbon against the spinning drum. An entire line of characters can be printed during each rotation of the drum. Printing speeds of drum printers vary from 200 – 300 lpm. The drawbacks of drum printers are that the fonts are not easily changeable, and the print lines may be wavy.

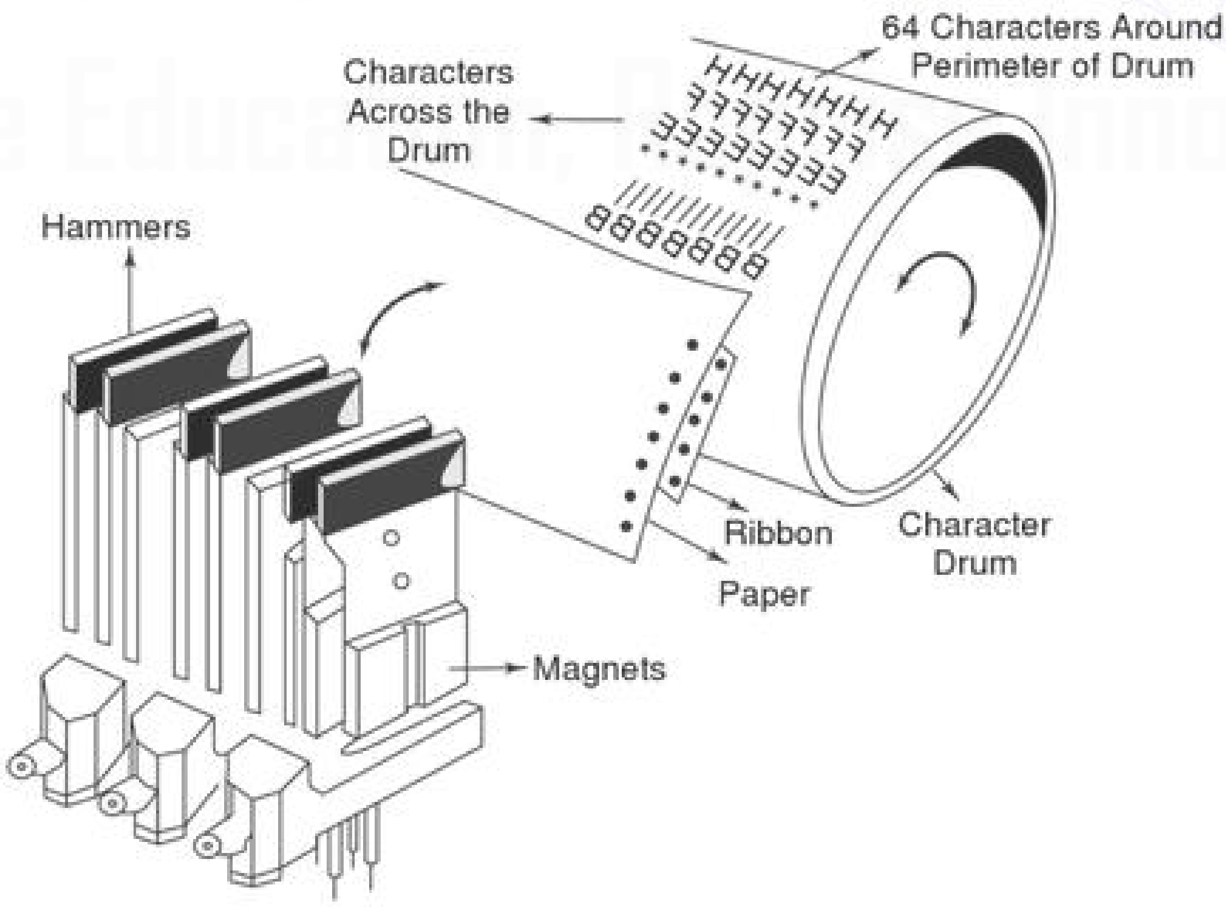


Fig. 2.28 Drum printers

DOT-MATRIX PRINTERS 2.19

Dot matrix characters are formed by printing a group of dots to form a letter, number or other symbol. This method is widely used with mini and micro computers.

Dots are formed both by impact and non impact print methods and are both character at a time and line at a time printers.

Figure 2.29 shows the letter 'A' formed by a dot-matrix, five dots wide and seven dots high (5×7) and in a 9×7 matrix. A 5×7 dot-matrix is frequently used when all letters are acceptable, in upper case.

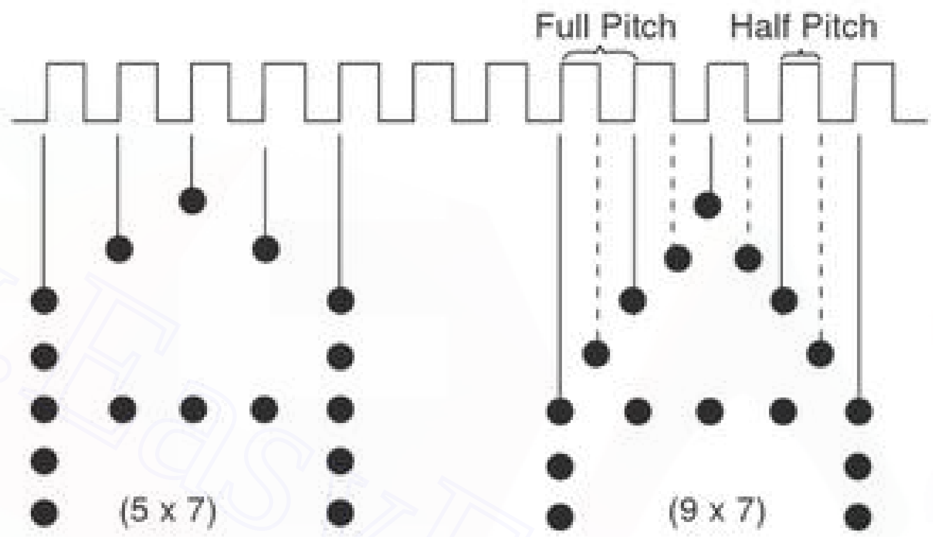


Fig. 2.29 Dot matrix sizes

Dot-matrix printers can print any combination of dots with all available print positions in the matrix. The character is printed when one of 128 ASCII codes is signalled and controlled by the ROM (read only memory) chip, which in turn controls the patterns of the dots. By changing the ROM chip a character set for any language or graphic character set can be used by the printer.

CHARACTER AT A TIME DOT-MATRIX IMPACT PRINTER 2.20

The print head for an impact dot matrix character is usually composed for an array of wires (or pins) arranged in a tabular form, that impact the character through an inked ribbon, as shown in Fig. 2.30. For this reason, these printers are sometimes also called wire printers.

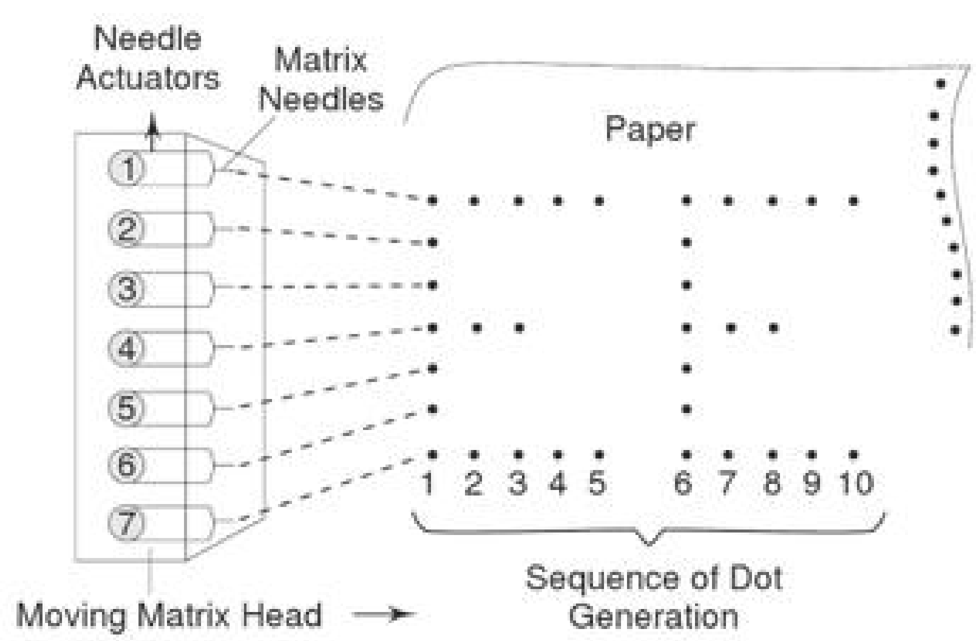


Fig. 2.30 Impact dot matrix print head

The print head often contains a single column seven wires high, though it may be two or more columns wide (Fig. 2.31 (a)).

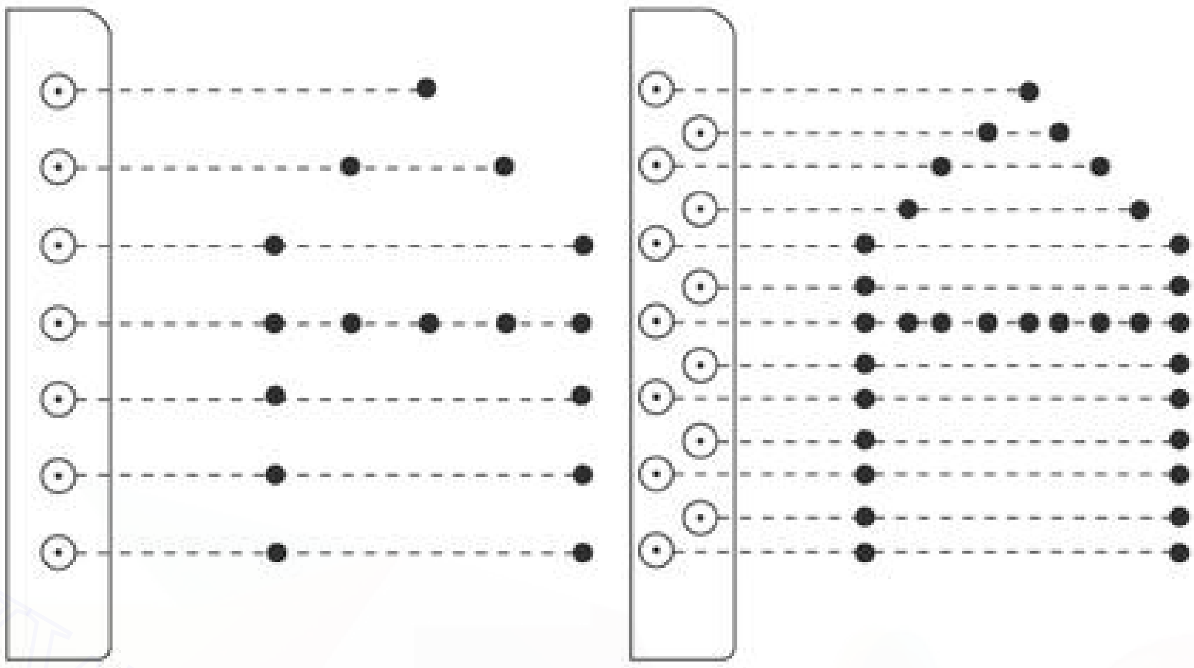


Fig. 2.31 (a) 5 × 7 single element (b) 5 × 7 double element

For purpose of illustration, assume that the print head contains a single column seven wires high. The seven wires are thrust from the print head (usually electromagnetically) in whatever combination the print controller requires to create a character. The wire strikes the ribbon and in turn impacts the paper, printing one vertical column of a single character.

The dot-matrix print head contains wires (or pins) arranged in tabular form. Characters are printed as a matrix of dots. The thin wire, driven by solenoids at the rear of the print head, strikes the ribbon against the paper to produce dots. The print wires are arranged in a vertical column, so that characters are printed out one dot column at a time as the print head moves on a line.

For a 5 × 7 full step dot-matrix character, the print head spaces one step, prints the second column of dots and repeats the pricess until all five columns are printed.

If the printer is designed to print dots in half steps, the same process is used, except that five horizontal print steps are used to form the characters (the five normal steps, plus four intervening half steps), thereby forming a 9 × 7 half step dot matrix character.

The dot-matrix character printer, strictly speaking, does not actually print a character at a time, but one column of a dot-matrix character at a time. However, the print speeds of a dot-matrix printer are very high, up to 180 characters per second.

Early dot-matrix print heads had only seven print wires, and consequently poor print quality. Currently available dot-matrix printers use 9, 14, 18 or even 24 print wires in the print head. Using a large number of print wires and/or printing a line twice with the dots for the second printing offset slightly from those of the first, ensures a better quality of print (Fig. 2.31 b).

Common speeds of dot-matrix printers range from 50 – 200 cps, but printers with speed as high as 300 cps are also available.

The dot-matrix codes of the characters are stored in EPROM. The fonts or print graphics can be changed under program control. This is the main advantage of dot-matrix printers.

The font of dot-matrix printers can be changed during printing by including the desired formats in RAM or ROM. Hence, it is possible to include standard ASCII characters, italics, subscripts, etc. on the same line. Special graphics can also be programmed into the printer.

NON-IMPACT DOT-MATRIX (NIDM) PRINTERS 2.21

Non-impact dot-matrix printers cause a mark without directly touching the paper. They are therefore quiet compared to impact printers.

They cannot make carbon copies, however, as there is no force to impress the character through multiple carbon copies. NIDM printers are useful for printing single copies of computer output, for recording the output of printing calculators and video displays, and for logging industrial data.

There are four types of NIDM printers thermal, electrosensitive, electrostatic, and ink jet.

Review Questions

1. Explain the basic principle of a D'Arsonval movement.
2. Draw and explain the construction of a PMMC movement.
3. State the functions of counterweights in a PMMC movement.
4. Describe the operation of a practical PMMC movement.
5. Explain the basic construction of a taut band movement.
6. Compare a PMMC movement with a taut band movement.
7. State the operating principle of an electrodynamometer (EDM).
8. Describe the operation of an electrodynamometer.
9. Why is an electrodynamometer called a square law device?
10. What is a transfer instrument? Why is an electrodynamometer referred to as a transfer instrument?
11. State the principle of a moving iron type instrument.
12. Describe with a diagram the construction of a radial vane type movement.
13. Explain the operation of a repulsion type ac meter.
14. Describe with a diagram the construction of a concentric vane repulsion type movement. Explain the operation of a concentric vane repulsion type movement.
15. Differentiate between moving iron and moving coil movement.
16. State the difference between radial and concentric vane movement
17. How can an electrodynamometer be converted into an ammeter? How can an electrodynamometer be converted into a voltmeter? How can an electrodynamometer be converted into a wattmeter?
18. State the difference between analog and digital indicators.
19. How are the displays classified. List different types of display devices.

20. Draw the structure of an LED and explain its operation.
21. What are the conditions to be satisfied by the device for emission of visible light?
22. State the advantages and disadvantages of using LED in electronic display.
23. List different materials used to radiate different colours.
24. Explain the construction and operation of a seven-segment display.
25. Discuss with a neat diagram, a method of realizing a 7-segment numeric display using LEDs.
26. Bring out the important differences between the common anode and common cathode type circuit arrangements for a 7-segment numeric display using LEDs.
27. State the operating principle of LCD display.
28. State different types of liquid crystal used for LCD display.
29. Explain with diagram the operation of a Nematic Liquid Crystal (NLC).
30. Explain the basic differences between transmissive and reflective type LCD.
31. Explain with a diagram the operation of a reflective display using NLC.
32. State the important features of LCDs.
33. State the advantages of LCD display over LED display.
34. Compare LCD and LED display.
35. State the principle of a gas discharge plasma display.
36. What do you understand by Nixie?
37. Explain with a diagram the operation of a seven-segment display using gaseous discharge.
38. Give reasons for the following:
    (i) Dot matrix presentation is more popular than bar matrix in character generation in CRT.
    (ii) Reflective LCDs have many advantages over transmissive LCDs.
    (iii) Bar graphs have unique role in electronic display system.
39. What is an electro-luminscent display? Explain its operation.
40. Compare the relative performance of the following displays in numeric display application:
    (i) Electrophoretic image display
    (ii) Liquid vapour display
    (iii) Nixie tube
    (iv) Flat panel alphanumeric CRT
41. Explain with a diagram the construction and working of an electrophoretic image display.
42. Describe with diagram the operation of a liquid vapour tube.
43. What are printers? Where are they used? Describe different types of printers.
44. How is character-at-a-time printing done?
45. How is line at a time printing done?
46. What do you mean by impact and non-impact printers?
47. State the different methods of character-at-a-time printing.
48. Explain with a diagram how printing is done using a drum wheel.
49. Explain with a diagram the operation of a band printer.
50. Explain the principle of operation of a dot matrix printer.
51. Differentiate between (5×7) and (9×7) matrix.
52. Which matrix is most commonly used? Why?
53. Describe with a diagram the operation of an impact dot matrix printer.
54. Explain in brief the working of a non-impact dot matrix printer.
55. What is a daisy wheel? Explain with a diagram the operation of a daisy wheel.
56. What are dot matrix printers? How is printing done by them? How can the quality of printing be improved.
57. What are the main advantages of a dot matrix printer over other printers.
58. What are half steps in a Dot matrix? Why are they used?

Multiple Choice Questions

1. A D'Arsonval movement is
   (a) taut band
   (b) PMMC
   (c) electrodynamometer
   (d) moving iron type
2. A PMMC uses a
   (a) taut band
   (b) moving coil
   (c) electrodynamometer
   (d) moving iron type.
3. A taut band movement uses a/an
   (a) ribbon
   (b) moving coil
   (c) electrodynamometer
   (d) moving iron type
4. A moving iron movement uses
   (a) ribbon
   (b) moving coil
   (c) electrodynamometer
   (d) radial vane
5. Less power is consumed by the following devices:
   (a) LED (b) LCD
   (c) neon lamps (d) nixie tube
6. LED is based on the principle of
   (a) scattering (b) illumination
   (c) absorption (d) transmission
7. The liquid used in LCDs are
   (a) nematic (b) tantalum
   (c) oil (d) electrolytic

Further Reading

1. B.S. Sonde, *Transducers and Display Systems*, Tata McGraw-Hill, 1979.
2. Philco Technological Centre, *Electronic Precision Measurement Techniques and Experiment.*
3. C. Louis Hohenstein, 'Computer Peripherals for Mini Computer', *Micro-processor and P.C.*, McGraw-Hill, 1980.
4. A.K. Sawhney, *Electronic and Electrical Measurements*, Khanna Publishers.

Chapter 3

Ammeters

DC AMMETER 3.1

The PMMC galvanometer constitutes the basic movement of a dc ammeter. Since the coil winding of a basic movement is small and light, it can carry only very small currents. When large currents are to be measured, it is necessary to bypass a major part of the current through a resistance called a shunt, as shown in Fig. 3.1. The resistance of shunt can be calculated using conventional circuit analysis.

Referring to Fig. 3.1

R_m = internal resistance of the movement.

I_{sh} = shunt current

I_m = full scale deflection current of the movement

I = full scale current of the ammeter + shunt (i.e. total current)

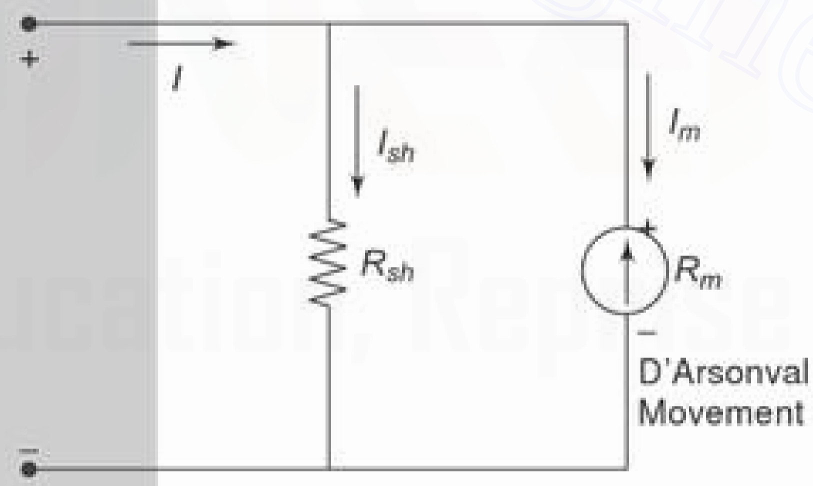


Fig. 3.1 Basic dc Ammeter

Since the shunt resistance is in parallel with the meter movement, the voltage drop across the shunt and movement must be the same.

Therefore $V_{sh} = V_m$

$\therefore$ $I_{sh} R_{sh} = I_m R_m$, $R_{sh} = \dfrac{I_m R_m}{I_{sh}}$

But $I_{sh} = I - I_m$

hence $R_{sh} = \dfrac{I_m R_m}{I - I_m}$

For each required value of full scale meter current, we can determine the value of shunt resistance.

Example 3.1 (a) *A 1 mA meter movement with an internal resistance of 100 Ω is to be converted into a 0 – 100 mA. Calculate the value of shunt resistance required.*

Solution Given $R_m = 100\ \Omega$, $I_m = 1$ mA, $I = 100$ mA

$$R_{sh} = \frac{I_m R_m}{I - I_m} = \frac{1\text{ mA} \times 100\ \Omega}{99\text{ mA}} = \frac{100\text{ m}A\Omega}{99\text{ mA}} = \frac{100\ \Omega}{99} = 1.01\ \Omega$$

The shunt resistance used with a basic movement may consist of a length of constant temperature resistance wire within the case of the instrument. Alternatively, there may be an external (manganin or constantan) shunt having very low resistance.

The general requirements of a shunt are as follows.

1. The temperature coefficients of the shunt and instrument should be low and nearly identical.
2. The resistance of the shunt should not vary with time.
3. It should carry the current without excessive temperature rise.
4. It should have a low thermal emf.

Manganin is usually used as a shunt for dc instruments, since it gives a low value of thermal emf with copper.

Constantan is a useful material for ac circuits, since it's comparatively high thermal emf, being unidirectional, is ineffective on the these circuits.

Shunt for low current are enclosed in the meter casing, while for currents above 200 A, they are mounted separately.

Example 3.1 (b) *A 100 μA meter movement with an internal resistance of 500 Ω is to be used in a 0 – 100 mA Ammeter. Find the value of the required shunt.*

Solution The shunt can also be determined by considering current I to be 'n' times larger than I_m. This is called a multiplying factor and relates the total current and meter current.

Therefore $\quad I = n\,I_m$

Therefore the equation for

$$R_{sh} = \frac{I_m R_m}{I - I_m} = \frac{I_m R_m}{nI_m - I_m} = \frac{I_m R_m}{I_m(n-1)} = \frac{R_m}{(n-1)}$$

Given: $I_m = 100\ \mu$A and $R_m = 500\ \Omega$

Step 1: $$n = \frac{I}{I_m} = \frac{100\text{ mA}}{100\ \mu\text{A}} = 1000$$

Step 2: $$R_{sh} = \frac{R_m}{(n-1)} = \frac{500\ \Omega}{1000-1} = \frac{500}{999} = 0.50\ \Omega$$

MULTIRANGE AMMETERS 3.2

The current range of the dc ammeter may be further extended by a number of shunts, selected by a range switch. Such a meter is called a multirange ammeter, shown in Fig. 3.2.

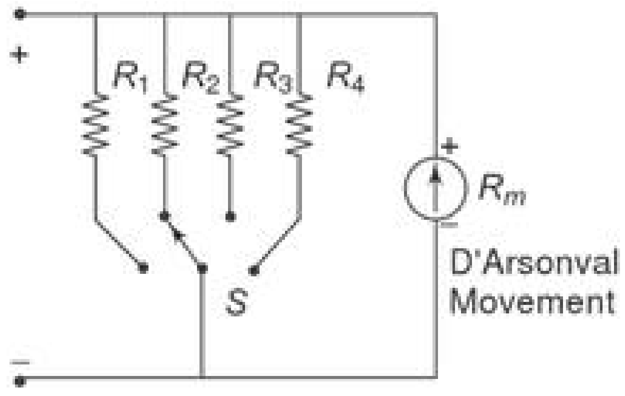


Fig. 3.2 Multirange ammeter

The circuit has four shunts R_1, R_2, R_3 and R_4, which can be placed in parallel with the movement to give four different current ranges. Switch S is a multiposition switch, (having low contact resistance and high current carrying capacity, since its contacts are in series with low resistance shunts). Make before break type switch is used for range changing. This switch protects the meter movement from being damaged without a shunt during range changing.

If we use an ordinary switch for range changing, the meter does not have any shunt in parallel while the range is being changed, and hence full current passes through the meter movement, damaging the movement. Hence a make before break type switch is used. The switch is so designed that when the switch position is changed, it makes contact with the next terminal (range) before breaking contact with the previous terminal. Therefore the meter movement is never left unprotected. Multirange ammeters are used for ranges up to 50A. When using a multirange ammeter, first use the highest current range, then decrease the range until good upscale reading is obtained. The resistance used for the various ranges are of very high precision values, hence the cost of the meter increases.

Example 3.2 *A 1 mA meter movement having an internal resistance of 100 Ω is used to convert into a multirange ammeter having the range 0–10 mA, 0–20 mA and 0–50 mA. Determine the value of the shunt resistance required.*

Solution Given $I_m = 1$ mA and $R_m = 100\ \Omega$

Case 1: For the range 0 – 10 mA

$$\text{Given } R_{sh1} = \frac{I_m \cdot R_m}{I - I_m} = \frac{1\text{ mA} \times 100}{10\text{ mA} - 1\text{ mA}} = \frac{100}{9} = 11.11\ \Omega$$

Case 2: For the range 0 – 20 mA

$$\text{Given } R_{sh2} = \frac{I_m \cdot R_m}{I - I_m} = \frac{1\text{ mA} \times 100}{20\text{ mA} - 1\text{ mA}} = \frac{100}{19} = 5.2\ \Omega$$

Case 3: For the range 0 – 50 mA

$$\text{Given } R_{sh3} = \frac{I_m \cdot R_m}{I - I_m} = \frac{1\text{ mA} \times 100}{50\text{ mA} - 1\text{ mA}} = \frac{100}{49} = 2.041\ \Omega$$

Example 3.3 *Design a multirange ammeter with range of 0–1 A, 5 A and 10 A employing individual shunt in each A D'Arsonval movement with an internal resistance of 500 Ω and a full scale deflection of 10 mA is available.*

Solution

Given I_m = 10 mA and R_m = 500 Ω

Case 1 : For the range 0 – 1A, i.e, 1000 mA

$$\text{Given } R_{sh1} = \frac{I_m \cdot R_m}{I - I_m} = \frac{10 \text{ mA} \times 500}{1000 \text{ mA} - 10 \text{ mA}} = \frac{5000}{990} = 5.05\ \Omega$$

Case 2 : For the range 0 – 5A, i.e, 5000 mA

$$\text{Given } R_{sh2} = \frac{I_m \cdot R_m}{I - I_m} = \frac{10 \text{ mA} \times 500}{5000 \text{ mA} - 10 \text{ mA}} = \frac{5000}{4990} = 1.002\ \Omega$$

Case 3 : For the range 0 – 10A, i.e, 10000 mA

$$\text{Given } R_{sh3} = \frac{I_m \cdot R_m}{I - I_m} = \frac{10 \text{ mA} \times 500}{10000 \text{ mA} - 10 \text{ mA}} = \frac{5000}{99990} = 0.050\ \Omega$$

Hence the values of shunt resistances are 5.05 Ω , 1.002 Ω and 0.050 Ω.

THE ARYTON SHUNT OR UNIVERSAL SHUNT 3.3

The Aryton shunt eliminates the possibility of having the meter in the circuit without a shunt. This advantage is gained at the price of slightly higher overall resistance. Figure 3.3 shows a circuit of an Aryton shunt ammeter. In this circuit, when the switch is in position "1", resistance R_a is in parallel with the series combination of R_b, R_c and the meter movement. Hence the current through the shunt is more than the current through the meter movement, thereby protecting the meter movement and reducing its sensitivity. If the switch is connected to position "2", resistance R_a and R_b are together in parallel with the series combination of R_c and the meter movement. Now the current through the meter is more than the current through the shunt resistance.

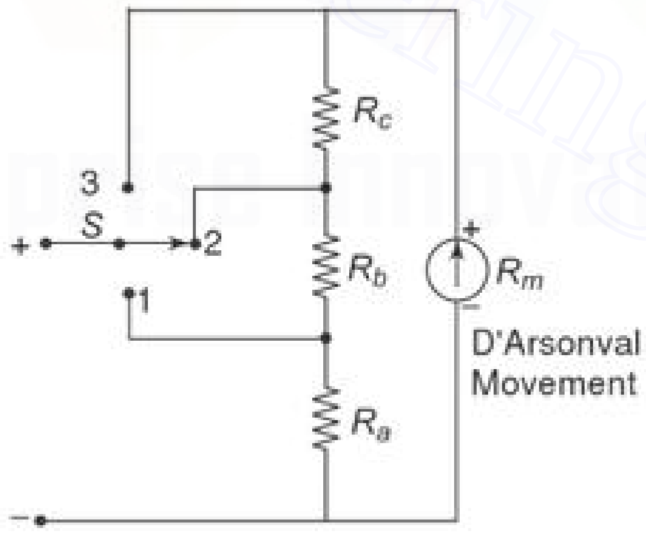


Fig. 3.3 Aryton shunt

If the switch is connected to position "3" R_a, R_b and R_c are together in parallel with the meter. Hence maximum current flows through the meter movement and very little through the shunt. This increases the sensitivity.

Example 3.4 (a) *Design an Aryton shunt (Fig. 3.4) to provide an ammeter with a current range of 0 – 1 mA, 10 mA, 50 mA and 100 mA. A D'Arsonval movement with an internal resistance of 100 Ω and full scale current of 50 μA is used.*

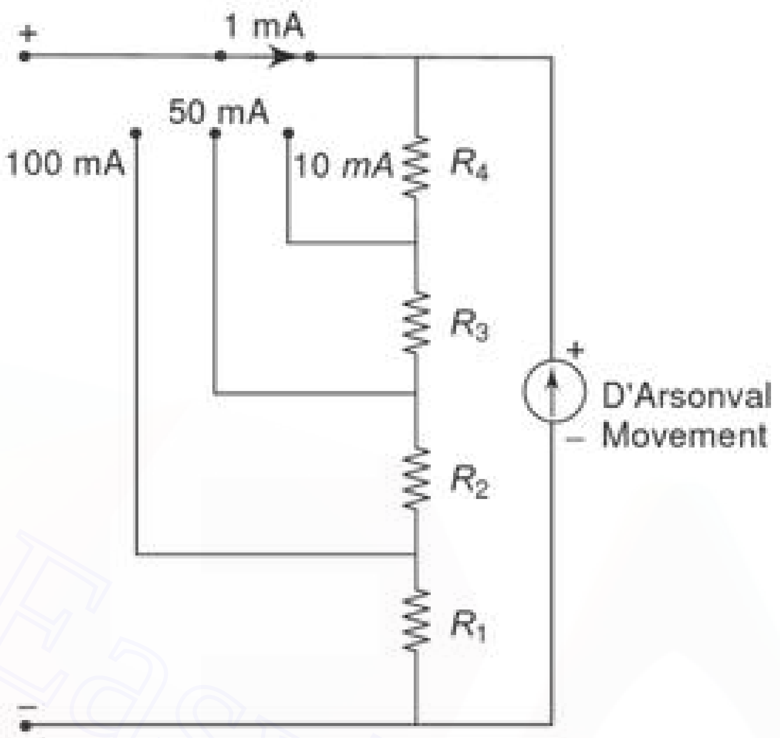


Fig. 3.4(a) For Example 3.4(a)

Solution Given $R_m = 100\ \Omega$, $I_m = 50\ \mu A$.

For 0 – 1 mA range

$$I_{sh} R_{sh} = I_m R_m$$

$$\therefore \quad 950\ \mu A\ (R_1 + R_2 + R_3 + R_4) = 50\ \mu A \times 100.$$

$$\therefore \quad R_1 + R_2 + R_3 + R_4 = \frac{50\ \mu A \times 100}{950\ \mu A} = \frac{5000}{950} = 5.26\ \Omega \tag{3.1}$$

For 0 – 10 mA

$$9950\ \mu A\ (R_1 + R_2 + R_3) = 50\ \mu A \cdot (100 + R_4) \tag{3.2}$$

For 0 – 50 mA

$$49950\ \mu A\ (R_1 + R_2) = 50\ \mu A \cdot (100 + R_3 + R_4) \tag{3.3}$$

For 0 – 100 mA

$$99950\ \mu A\ (R_1) = 50\ \mu A\ (100 + R_2 + R_3 + R_4) \tag{3.4}$$

But $R_1 + R_2 + R_3 = 5.26 - R_4$. Substituting in Eq. 3.2, we have

$$9950\ \mu A\ (5.26 - R_4) = 50\ \mu A\ (100 + R_4)$$

$$9950\ \mu A \times 5.26 - 9950\ \mu A \times R_4 = 5000\ \mu A + 50\ \mu A\ R_4$$

$$(9950\ \mu A \times 5.26 - 5000\ \mu A) = 9950\ \mu A\ R_4 + 50\ \mu A\ R_4$$

Therefore $$R_4 = \frac{9950\ \mu A \times 5.26 - 5000\ \mu A}{10\ mA} = \frac{47377\ \mu A}{10\ mA} = 4.737\ \Omega$$

$R_4 = 4.74\ \Omega$

In Eq. 3.1, substituting for R_4 we get

$$R_1 + R_2 + R_3 = 5.26 - 4.74 = 0.52$$

$$\therefore \quad R_1 + R_2 = 0.52 - R_3$$

Substituting in Eq. 3.3, we have

$$49950\ \mu A\ (0.52 - R_3) = 50\ \mu A\ (R_3 + 4.74 + 100)$$

$$49950\ \mu A \times 0.52 - 49950\ \mu A \times R_3 = 50\ \mu A \times R_3 + 50\ \mu A \times 4.74 + 50\ \mu A \times 100$$

$$49950\ \mu A \times 0.52 - 50\ \mu A \times 4.74 = 49950\ \mu A \times R_3 + 50\ \mu A \times R_3 + 5000\ \mu A$$

$$(25974 - 237)\ \mu A = 50\ mA \times R_3 + 5000\ \mu A$$

$$25737\ \mu A = 50\ mA \times R_3 + 5000\ \mu A$$

$$R_3 = \frac{25737\ \mu A - 5000\ \mu A}{50\ mA} = \frac{20737\ \mu A}{50\ mA}$$

$$R_3 = 0.4147 = 0.42\ \Omega$$

But $\quad R_1 + R_2 = 0.52 - R_3$

$\therefore \quad R_1 + R_2 = 0.52 - 0.4147 = 0.10526$

Therefore $\quad R_2 = 0.10526 - R_1 \qquad (3.5)$

From Eq. 3.4

$$99950\ \mu A\ (R_1) = 50\ \mu A \times (100 + R_2 + R_3 + R_4)$$

But $\quad R_2 + R_3 + R_4 = 5.26 - R_1 \qquad$ (from Eq. 3.1)

Substituting in Eq. 3.4

$$99950\ \mu A \times R_1 = 50\ \mu A \times (100 + 5.26 - R_1)$$

$$99950\ \mu A \times R_1 = 5000\ \mu A + (50\ \mu A \times 5.26) - (R_1 \times 50\ \mu A)$$

$$99950\ \mu A \times R_1 + 50\ \mu A \times R_1 = 5000\ \mu A + 50\ \mu A \times 5.26$$

$$(99950\ \mu A + 50\ \mu A)\ R_1 = 5000\ \mu A + 263\ \mu A$$

$$100\ mA \times R_1 = 5263\ \mu A$$

$$R_1 = \frac{5263\ \mu A}{100\ mA} = 0.05263$$

Therefore $\quad R_1 = 0.05263\ \Omega$

From Eq. 3.5, we have

$$R_2 = 0.10526 - R_1 = 0.10526 - 0.05263 = 0.05263\ \Omega$$

Hence the value of shunts are

$$R_1 = 0.05263\ \Omega\ ; R_2 = 0.05263\ \Omega$$

$$R_3 = 0.4147\ \Omega\ ;\ R_4 = 4.74\ \Omega$$

Example 3.4 (b) *Calculate the value of the shunt resistors for the circuit shown below.*

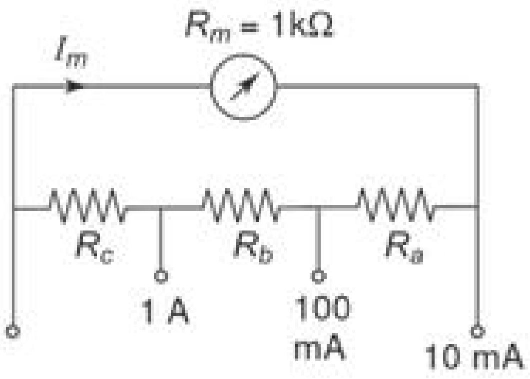


Fig. 3.4(b) For Example 3.4(b)

Solution The total shunt resistance R_{sh} is determined by

$$R_{sh} = \frac{R_m}{(n-1)} \quad \text{where } n = I/I_m$$

Given $I_m = 100\ \mu A$ and $R_m = 1000\ \Omega$

Step 1: For 10 mA range:

$$n = \frac{I}{I_m} = \frac{10\text{ mA}}{100\ \mu\text{A}} = 100$$

$$R_{sh} = \frac{R_m}{(n-1)} = \frac{1000\ \Omega}{100-1} = \frac{1000}{99} = 10.1\ \Omega$$

Step 2: When the meter is set on the 100 mA range, the resistance R_b and R_c provides the shunt.

The shunt can be found from the equation

$$R_{sh_2} = (R_b + R_c) = \frac{I_m(R_m + R_{sh})}{I} = \frac{100\ \mu\text{A}\ (10.1 + 1000)}{100\text{ mA}} = 1.01\ \Omega$$

Step 3: The resistor which provides the shunt resistance on the 1A range can be found from the equation

$$R_c = \frac{I_m(R_m + R_{sh})}{I} = \frac{100\ \mu\text{A}\ (10.1 + 1000)}{1000\text{ mA}} = 0.101\ \Omega$$

Step 4: But $R_b + R_c = 1.01\ \Omega$

$$R_b = 1.01 - R_c = 1.01 - 0.101\ \Omega = 0.909\ \Omega$$

Step 5: Resistor R_a is found by

$$R_a = R_{sh} - (R_b + R_c) = 10.1 - (0.909 + .101)\ \Omega$$
$$= 10.1 - 1.01\ \Omega$$

$= 9.09\Omega$

Hence $R_a = 9.09\ \Omega$, $R_b = 0.909\ \Omega$ and $R_c = 0.101\ \Omega$

REQUIREMENTS OF A SHUNT 3.4

The type of material that should be used to join the shunts should have two main properties.

1. Minimum Thermo Dielectric Voltage Drop

Soldering of joint should not cause a voltage drop.

2. Solderability

Resistance of different sizes and values must be soldered with minimum change in value.

The following precautions should be observed when using an ammeter for measurement.

1. Never connect an ammeter across a source of emf. Because of its low resistance it would draw a high current and destroy the movement. Always connect an ammeter in series with a load capable of limiting the current.
2. Observe the correct polarity. Reverse polarity causes the meter to deflect against the mechanical stopper, which may damage the pointer.
3. When using a multirange meter, first use the highest current range, then decrease the current range until substantial deflection is obtained. To increase the accuracy use the range that will give a reading as near full scale as possible.

EXTENDING OF AMMETER RANGES 3.5

The range of an ammeter can be extended to measure high current values by using external shunts connected to the basic meter movement (usually the lowest current range), as given in Fig. 3.5.

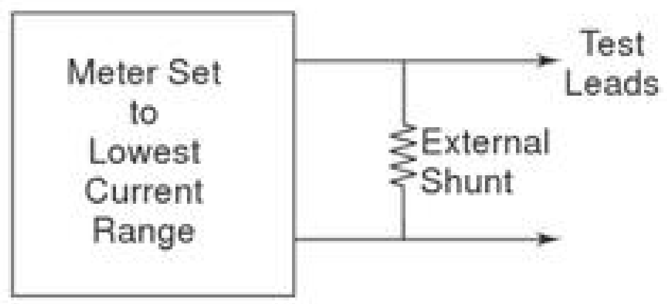


Fig. 3.5 Extending of ammeters

Note that the range of the basic meter movement cannot be lowered. (For example, if a 100 µA movement with 100 scale division is used to measure 1 µA, the meter will deflect by only one division. Hence ranges lower than the basic range are not practically possible.)

RF AMMETER (THERMOCOUPLE) 3.6

3.6.1 Thermocouple Instruments

Thermocouples consists of a junction of two dissimilar wires, so chosen that a voltage is generated by heating the junction. The output of a thermocouple is delivered to a sensitive dc microammeter.

(Calibration is made with dc or with a low frequency, such as 50 cycles, and applies for all frequencies for which the skin effect in the heater is not appreciable. Thermocouple instruments are the standard means for measuring current at radio frequencies.)

The generation of dc voltage by heating the junction is called thermoelectric action and the device is called a thermocouple.

3.6.2 Different Types of Thermocouples

In a thermocouple instrument, the current to be measured is used to heat the junction of two metals. These two metals form a thermocouple and they have the property that when the junction is heated it produces a voltage proportional to the heating effect. This output voltage drives a sensitive dc microammeter, giving a reading proportional to the magnitude of the ac input.

The alternating current heats the junction; the heating effect is the same for both half cycles of the ac, because the direction of potential drop (or polarity) is always be the same. The various types of thermocouples are as follows.

Mutual Type (Fig. 3.6 (a)) In this type, the alternating current passes through the thermocouple itself and not through a heater wire. It has the disadvantages that the meter shunts the thermocouple.

Contact Type (Fig. 3.6 (b)) This is less sensitive than the mutual type. In the contact type there are separate thermocouple leads which conduct away the heat from the heater wire.

Separate Heater Type (Fig. 3.6 (c)) In this arrangement, the thermocouple is held near the heater, but insulated from it by a glass bead. This makes the instrument sluggish and also less sensitive because of temperature drop in the glass bead. The separate type is useful for certain applications, like RF current measurements. To avoid loss of heat by radiation, the thermocouple arrangement is placed in a vacuum in order to increase its sensitivity.

Bridge Type (Fig. 3.6 (d)) This has the high sensitivity of the mutual type and yet avoids the shunting effect of the microammeter.

The sensitivity of a thermocouple is increased by placing it in a vacuum since loss of heat by conduction is avoided, and the absence of oxygen permits operation at a much higher temperature. A vacuum thermocouple can be designed to give a full scale deflection of approximately 1 mA. A similar bridge arrangement in air would require about 100 mA for full scale deflection.

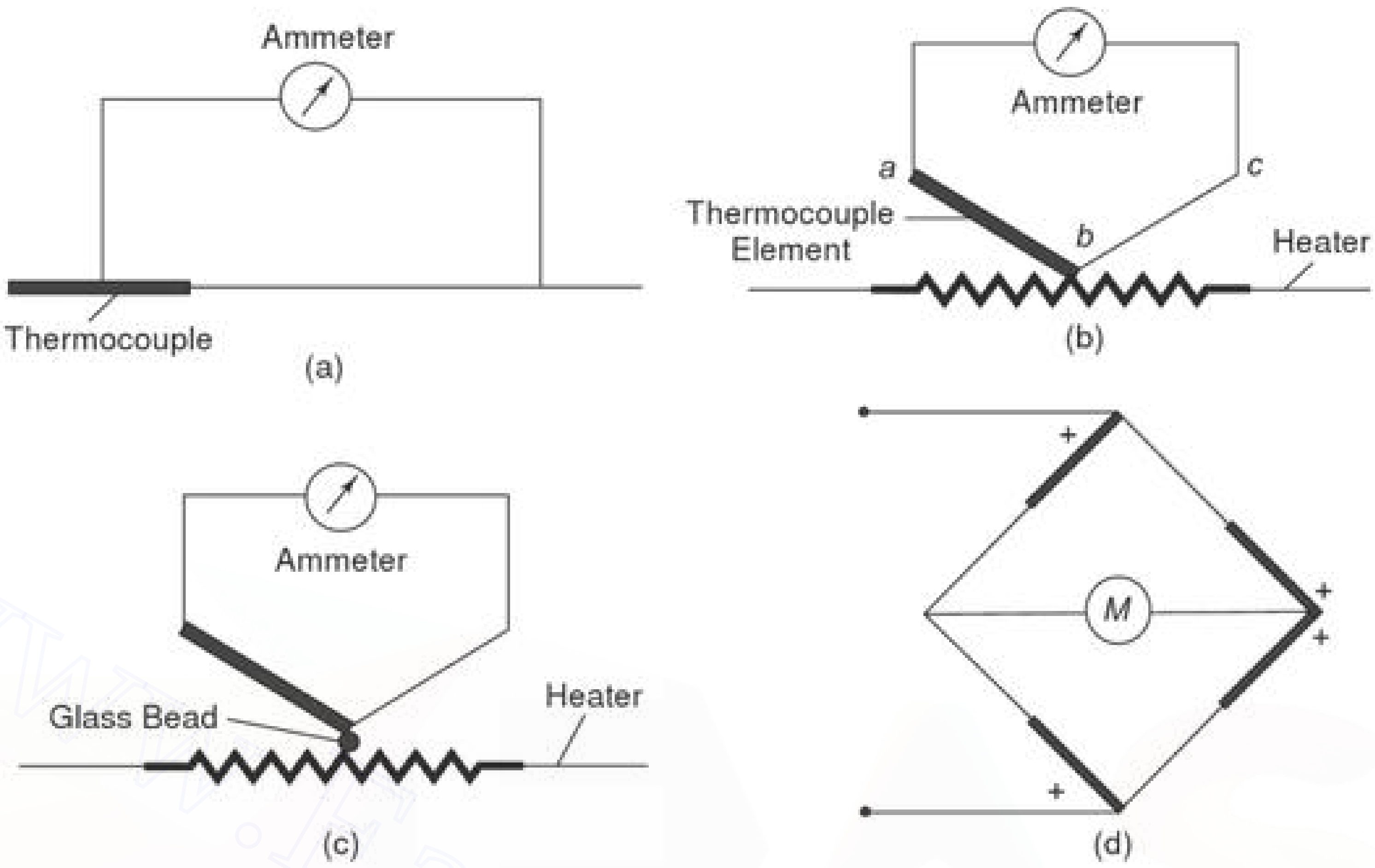


Fig. 3.6 (a) Mutual type (b) Contact type (c) Separate heater type (d) Bridge type thermocouple

Material commonly used to form a thermocouple are constantan against copper, manganin or a platinum alloy. Such a junction gives a thermal emf of approximately 45 μV/°C.

The heating element of open air heaters is typically a non-corroding platinum alloy. Carbon filament heaters are used in vacuum type.

Thermocouple heaters operate so close to the burnout point under normal conditions, that they can withstand only small overloads without damage, commonly up to 50%. This is one of the limitations of the thermocouple instrument.

(Commonly used metal combinations are copper-constantan, iron-constantan, chromel-constantan, chromel-alumel, and platinum-rhodium. Tables are available that show the voltages produced by each of the various metal combination at specific temperatures.)

LIMITATIONS OF THERMOCOUPLES 3.7

Following are the limitations of thermocouples

1. Heaters can stand only small overload.
2. A rise in temperature (higher operating temperatures) causes a change in the resistance of the heater.
3. Presence of harmonics changes meter reading, because the heating effect is proportional to the square of current.

This can be understood by the following example.

The effective value of input wave is

$$= \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots}$$

where I_1 is the fundamental
I_2 is second harmonic
I_3 is third harmonic

If 20% harmonics are present, then $I_2 = \dfrac{I_1}{5}$.

Therefore, the error in the current reading if 20% harmonics is present, is calculated as follows. Therefore, effective value of input wave

$$= \sqrt{I_1^2 + I_2^2} = \sqrt{I_1^2 + \left(\frac{I_1}{5}\right)^2}$$

$$= \sqrt{I_1^2 + \frac{I_1^2}{25}} = \sqrt{\frac{26}{25} I_1^2} = \sqrt{1.04\, I_1^2}$$

$$= 1.02\, I_1 = I_1 + 0.02\, I_1$$

But 0.02 = 2%. Hence 20% harmonics increase the error by 2%.

EFFECT OF FREQUENCY ON CALIBRATION 3.8

The frequency effect arises because of various factors such as:

1. Skin effect
2. Non uniform distribution of current along the heater wires
3. Spurious capacitive currents

1. Skin Effect The skin effect causes a higher reading at higher frequencies, especially if the heater wire is small. A low current instrument with a circular cross-section, used in vacuum, may have a skin effect error of less than 1% at frequencies up to 30,000 MHz. Ribbon heaters are often used for large currents, but they have larger skin effects. Solid wire, and better still hollow conductors are ideal with a view to minimising the skin effect.

Calibration done with dc or low frequency as such as 50 Hz for which the skin effect of the heater is not appreciable. Accuracy can be as high as 1% for frequencies up to 50 MHz. For this reason, thermocouple instruments are classified as RF instruments.

Above 50 MHz the skin effect forces the current to the outer surface of the conductor, increasing the effective resistance of the heating wire and reducing the instrument's accuracy. For small currents of up to 3 A, the heating wire should be solid and very thin. Above 3 A the heating element should be hollow and tubular in design to reduce the skin effect.

2. Non-uniform Distribution of Current This occurs at frequencies where the heater length is of the order of a fraction of a wavelength (magnitude of one wavelength).

The current distribution along the heater is not uniform and the meter indication is uncertain. Hence to avoid this the heater length and its associated leads should be less than 1/10th of a wavelength.

3. Spurious Capacitive Currents These occur when the thermocouple instrument is connected in such a manner that both terminals are at a potential above ground. As the frequency is increased, a large current flows through the capacitance formed by the thermocouple leads, with the meter acting as one electrode and the ground as the other. To avoid this, proper shielding of the instrument should be provided.

The calibration of a thermocouple is reasonably permanent. When calibrating Contact and Mutual with dc, it is always necessary to reverse the polarity to take the average reading. This is because of the resistance drop in the heater at the contact may cause a small amount of dc-current to flow; reversing the calibrating current averages out this effect.

MEASUREMENTS OF VERY LARGE CURRENTS BY THERMOCOUPLES 3.9

Thermocouples instruments with heaters large enough to carry very large currents may have an excessive skin effect. Ordinary shunts cannot be used because the shunting ratio will be affected by the relative inductance and resistance, resulting in a frequency effect.

One solution to this problem consists of minimising the skin effect by employing a heater, which is a tube of large diameter, but with very thin walls.

Another consists of employing an array of shunts of identical resistance arranged symmetrically as shown in Fig. 3.7 (a).

In Fig. 3.7 (a) each filament of wire has the same inductance, so that the inductance causes the current to divide at high frequencies, in the same way as does the resistance at low frequencies. In Fig. 3.7 (b) the condensor shunt is used such that the current divides between the two parallel capacitors proportional to their capacitance, and maintains this ratio independent of frequency, as long as the capacitor that is in series with the thermocouple has a higher impedance than the thermocouple heater and the lead inductance is inversely proportional to the capacitances.

In Fig. 3.7 (c) the current transformer is used to measure very large RF currents at low and moderate frequencies using a thermocouple instrument of ordinary range. Such transformers generally use a magnetic dust core. The current ratio is given by

$$\frac{\text{Primary Current}}{\text{Secondary Current}} = \frac{1}{K}\sqrt{\frac{L_s}{L_p}}\sqrt{1+\frac{1}{Q_s}}$$

where L_s = secondary inductance
L_p = primary inductance
K = coefficient of coupling between Lp and Ls
r_s = resistance of secondary, including meter resistance

$Q_s = \omega L_s / r_s = Q$ of the secondary circuit taking into account meter resistance

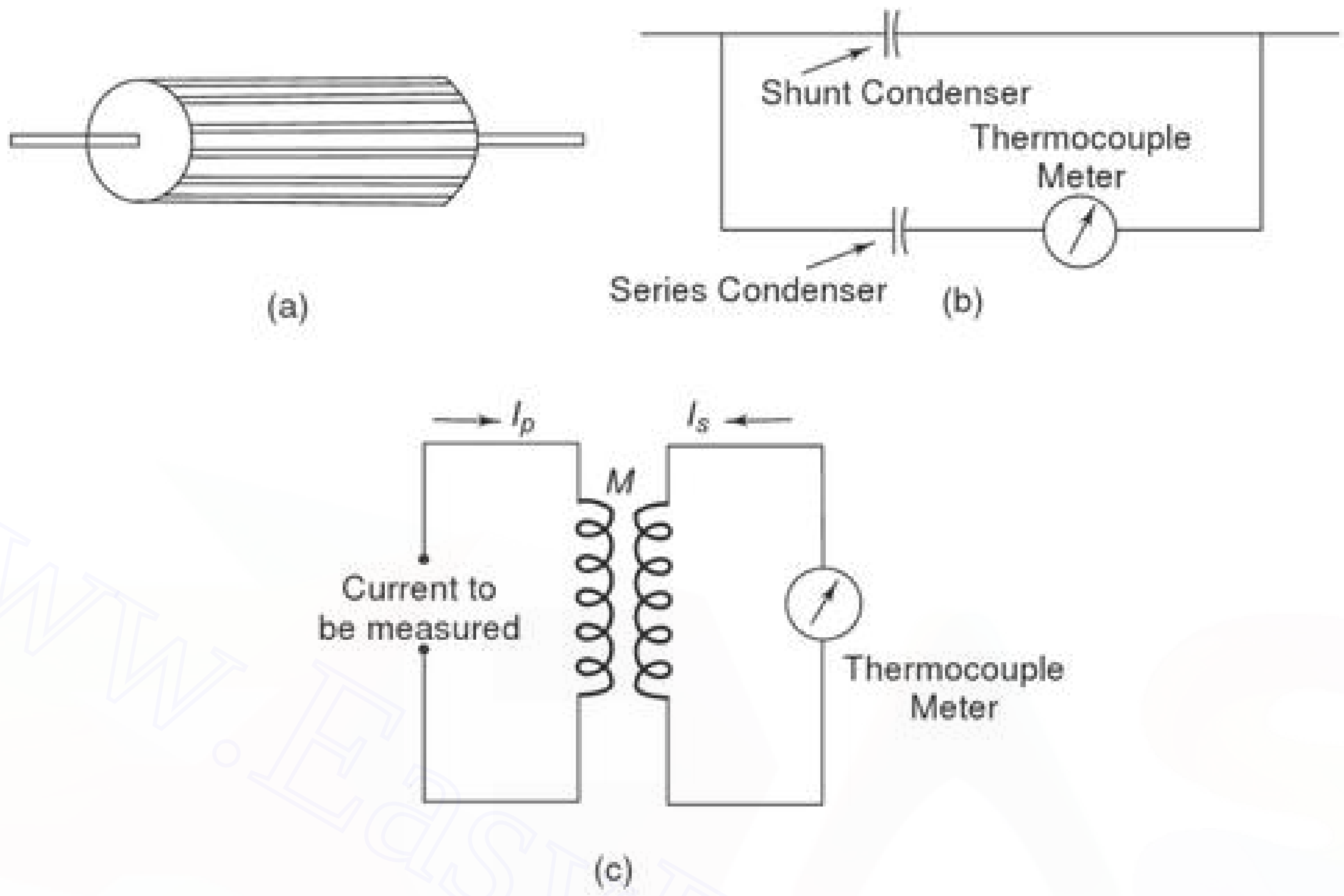


Fig. 3.7 (a) Array of shunts (b) Condenser shunt (c) Current transformer

If Q of the secondary winding is appreciable (i.e. greater than 5), the transformation ratio is independent of frequency.

A current ratio of 1000 or more can be obtained at low and moderate RF by using a many turn secondary wound on a toroidal ring.

Review Questions

1. Explain with a diagram how a PMMC can be used as an ammeter.
2. What are the requirements of a shunt? How can a basic ammeter be converted into a multirange ammeter?
3. What are the limitations of a multirange ammeter. How is it overcome?
4. State the precautions to be observed when using an ammeter.
5. Explain with a diagram the operation of an ayrton shunt.
6. State the advantages of an Ayrton shunt ammeter over a multirange ammeter.
7. How is current in the RF range measured?
8. Why is a thermocouple used in RF measurement of current?
9. Explain the construction and working of a thermocouple measuring instrument. State the limitations of a thermocouple instruments.
10. Why is a thermocouple measuring instrument classified as an RF instrument?
11. State different types of thermocouples used for current measurement. Explain each one in brief.
12. How is a large current measured using a thermocouple?
13. What are the effects of frequency on the calibration of a thermocouple?
14. Explain with a diagram how a current transformer can be used to measure large RF currents.

Multiple Choice Questions

1. The instrument required to measure current is a/an
   (a) voltmeter (b) ammeter
   (c) wattmeter (d) ohmmeter
2 A D'Arsonval movement is
   (a) taut band
   (b) p1mmc
   (c) electrodynamometer
   (d) moving iron type
3. To select the range, a multirange ammeter uses a
   (a) double pole double throw switch
   (b) make before break type switch
   (c) single pole double throw switch
   (d) simple switch
4. To select a range , the Aryton shunt uses a
   (a) double pole double throw switch
   (b) make before break type switch
   (c) single pole double throw switch
   (d) simple switch
5. Current in the RF range is measured by
   (a) simple ammeter
   (b) ammeter using thermocouples.
   (c) multirange ammeters.
   (d) aryton shunt.
6. Large current in RF range at low moderate frequencies is measured by
   (a) simple ammeter
   (b) ammeter using thermocouples.
   (c) using a current transformer
   (d) using Aryton shunt.
7. To minimize skin effect at high RF range
   (a) inductance is used
   (b) array of Shunts are used
   (c) dielectric material is used
   (d) aryton shunt is used
8. At low and moderate RF using a secondary wound on a torridal ring, a current ratio is obtained.
   (a) 500 (b) 1000
   (c) 2000 (d) 5000

Practice Problems

1. Calculate the value of shunt resistance required for using a 50 μA meter movement having an internal resistance of 100 Ω for measuring current in the range of 0–250 mA.
2. What value of shunt resistance is required for using 50 μA meter movement having an internal resistance of 250 Ω for measuring current in the range of 0–500 mA?
3. Design a multirange ammeter with ranges of 0–100 mA, 0–200 mA, 0–500 mA, 0–1 A employing individual shunts for each range. A D'Arsonval movement with an internal resistance of 500 Ω and a full scale current of 100 μA is available.
4. Design a multirange ammeter with ranges of 0–1 A, 5 A, 25 A, 125 A employing individual shunts for each range. A D'Arsonval movement with an internal resistance of 730 Ω and a full scale current of 5 mA is available
5. Design an Ayrton shunt to provide an ammeter with current ranges of 0–1 mA, 5 mA, 20 mA and 50 mA, using a D'Arsonval movement having internal resistance of 50 Ω and a full scale current of 100 μA.
6. Design an Ayrton shunt to provide an ammeter with current ranges of 0–1 mA, 10 mA, 50 mA and 100 mA, using a D'Arsonval movement having internal resistance of 100 Ω and a full scale current of 50 μA.
7. Design an Ayrton shunt to provide an ammeter with current ranges of 0–100 mA, 500 mA, 1A, using a D'Arsonval movement having internal resistance of 50 Ω and a full scale current of 1mA.

Further Reading

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2. Sol. D. Prensky, *Electronic Instrumentation*, Prentice-Hall of India, 1963.
3. John. H. Fasal, *Simplified Electronic Measurements*, Hayden Book Co. Inc., Mumbai, 1971.
4. Larry. D. Jones and A. Foster Chin, *Electronic Instruments and Measurements*, John Wiley and Sons, New York, 1987.
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Voltmeters and Multimeters

Chapter 4

INTRODUCTION 4.1

The most commonly used dc meter is based on the fundamental principle of the motor. The motor action is produced by the flow of a small amount of current through a moving coil which is positioned in a permanent magnetic field. This basic moving system, often called the D'Arsonval movement, is also referred to as the basic meter.

Different instrument forms may be obtained by starting with the basic meter movement and adding various elements, as follows.

1. The basic meter movement becomes a dc instrument, measuring
   - (i) dc current, by adding a shunt resistance, forming a microammeter, a milliammeter or an ammeter.
   - (ii) dc voltage, by adding a multiplier resistance, forming a milli voltmeter, voltmeter or kilovoltmeter.
   - (iii) resistance, by adding a battery and resistive network, forming an ohmmeter.
2. The basic meter movement becomes an ac instrument, measuring
   - (i) ac voltage or current, by adding a rectifier, forming a rectifier type meter for power and audio frequencies.
   - (ii) RF voltage or current, by adding a thermocouple-type meter for RF.
   - (iii) Expanded scale for power line voltage, by adding a thermistor in a resistive bridge network, forming an expanded scale (100 – 140 V) ac meter for power line monitoring.

BASIC METER AS A DC VOLTMETER 4.2

To use the basic meter as a dc voltmeter, it is necessary to know the amount of current required to deflect the basic meter to full scale. This current is known as full scale deflection current (I_{fsd}). For example, suppose a 50 μA current is required for full scale deflection.

This full scale value will produce a voltmeter with a sensitivity of 20,000 Ω per V.

The sensitivity is based on the fact that the full scale current of 50 μA results whenever 20,000 Ω of resistance is present in the meter circuit for each voltage applied.

$$\text{Sensitivity} = 1/I_{fsd} = 1/50\ \mu\text{A} = 20\ \text{k}\Omega/\text{V}$$

Hence, a 0 – 1 mA would have a sensitivity of 1 V/1 mA = 1 kΩ/V or 1000 Ω.

Example 4.1 *Calculate the sensitivity of a 200 µA meter movement which is to be used as a dc voltmeter.*

Solution The sensitivity

$$S = \frac{1}{(I_{fsd})} = \frac{1}{200\ \mu\text{A}}$$

Therefore $S = 5\ \text{k}\Omega/\text{V}$

DC VOLTMETER 4.3

A basic D'Arsonval movement can be converted into a dc voltmeter by adding a series resistor known as multiplier, as shown in Fig. 4.1. The function of the multiplier is to limit the current through the movement so that the current does not exceed the full scale deflection value. A dc voltmeter measures the potential difference between two points in a dc circuit or a circuit component.

To measure the potential difference between two points in a dc circuit or a circuit component, a dc voltmeter is always connected across them with the proper polarity.

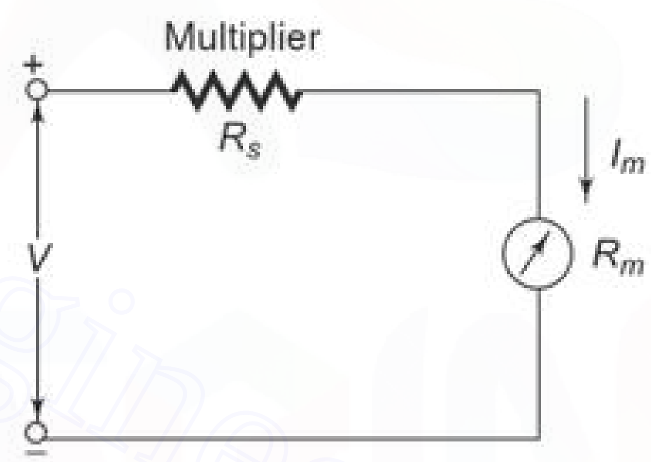


Fig. 4.1 Basic dc voltmeter

The value of the multiplier required is calculated as follows. Referring to Fig. 4.1,

I_m = full scale deflection current of the movement (I_{fsd})
R_m = internal resistance of movement
R_s = multiplier resistance
V = full range voltage of the instrument

From the circuit of Fig. 4.1

$$V = I_m (R_s + R_m)$$

$$R_s = \frac{V - I_m R_m}{I_m} = \frac{V}{I_m} - R_m$$

Therefore $$R_s = \frac{V}{I_m} - R_m$$

The multiplier limits the current through the movement, so as to not exceed the value of the full scale deflection I_{fsd}.

The above equation is also used to further extend the range in DC voltmeter.

Example 4.2 (a) *A basic D'Arsonval movement with a full scale deflection of 50 μA and internal resistance of 500 Ω is used as a voltmeter. Determine the value of the multiplier resistance needed to measure a voltage range of 0 – 10 V.*

Solution Given

$$R_s = \frac{V}{I_m} - R_m = \frac{10}{50\ \mu A} - 500$$
$$= 0.2 \times 10^6 - 500 = 200\ k - 500$$
$$= 199.5\ k\Omega$$

Example 4.2 (b) *Calculate the value of multiplier resistance on the 50V range of a dc voltmeter that uses a 500 μA meter movement with an internal resistance of 1 kΩ.*

Solution

Step 1: The sensitivity of 500 μA meter movement is given by

$$S = 1/I_m = 1/500\ \mu A = 2\ k\Omega/V.$$

Step 2: The value of the multiplier resistance can be calculated by

$$R_s = S \times \text{range} - R_m$$
$$R_s = 2\ k\Omega/V \times 50\ V - 1\ k\Omega$$
$$= 100\ k\Omega - 1\ k\Omega = 99\ k\Omega$$

MULTIRANGE VOLTMETER 4.4

As in the case of an ammeter, to obtain a multirange ammeter, a number of shunts are connected across the movement with a multi-position switch. Similarly, a dc voltmeter can be converted into a multirange voltmeter by connecting a number of resistors (multipliers) along with a range switch to provide a greater number of workable ranges.

Figure 4.2 shows a multirange voltmeter using a three position switch and three multipliers R_1, R_2, and R_3 for voltage values V_1, V_2, and V_3.

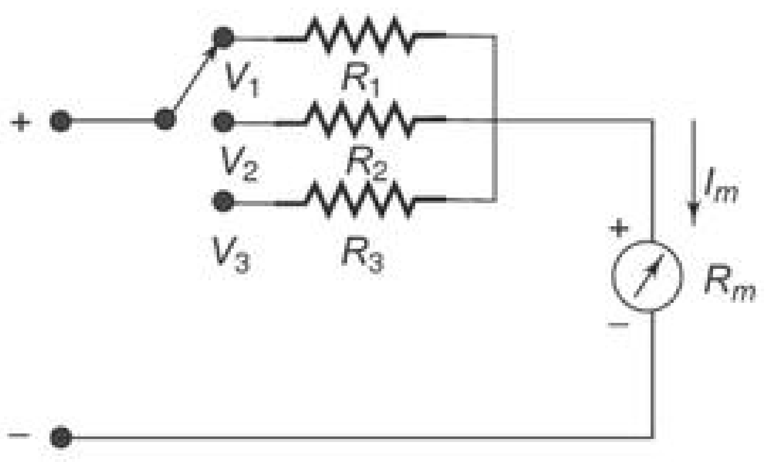


Fig. 4.2 Multirange voltmeter

Figure 4.2 can be further modified to Fig. 4.3, which is a more practical arrangement of the multiplier resistors of a multirange voltmeter.

In this arrangement, the multipliers are connected in a series string, and the range selector selects the appropriate amount of resistance required in series with the movement.

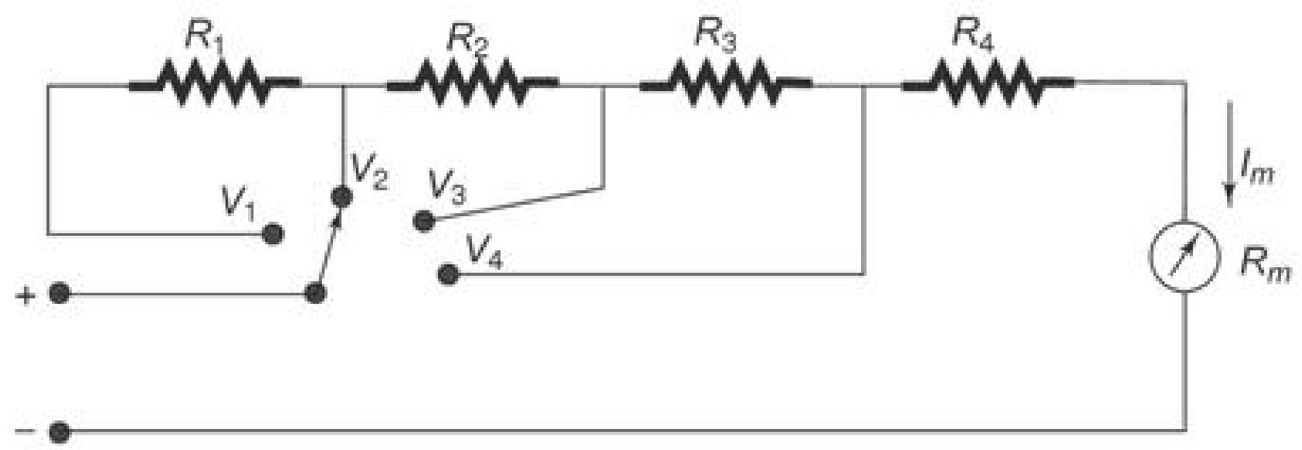


Fig. 4.3 Multipliers connected in series string

This arrangement is advantageous compared to the previous one, because all multiplier resistances except the first have the standard resistance value and are also easily available in precision tolerances.

The first resistor or low range multiplier, R_4, is the only special resistor which has to be specially manufactured to meet the circuit requirements.

Example 4.3 *A D'Arsonval movement with a full scale deflection current of 50 μA and internal resistance of 500 Ω is to be converted into a multirange voltmeter. Determine the value of multiplier required for 0–20 V, 0–50 V and 0–100 V.*

Solution Given $I_m = 50\ \mu\text{A}$ and $R_m = 500\ \Omega$

Case 1: For range 0 – 20V

$$R_s = \frac{V}{I_m} - R_m = \frac{20}{50 \times 10^{-6}} - 500 = 0.4 \times 10^6 - 500 = 400\text{ K} - 500 = 399.5\text{ k}\Omega$$

Case 2: For range 0 – 50 V

$$R_s = \frac{V}{I_m} - R_m = \frac{50}{50 \times 10^{-6}} - 500 = 1 \times 10^6 - 500 = 1000\text{ K} - 500 = 999.5\text{ k}\Omega$$

Case 3: For range 0 – 100 V

$$R_s = \frac{V}{I_m} - R_m = \frac{100}{50 \times 10^{-6}} - 500 = 2 \times 10^6 - 500 = 2000\text{ K} - 500 = 1999.5\text{ k}\Omega$$

Example 4.4 *A D'Arsonval movement with a full scale deflection current of 10 mA and internal resistance of 500 Ω is to be converted into a multirange voltmeter. Determine the value of multiplier required for 0–20 V, 0–50 V and 0–100 V.*

Solution Given $I_m = 10\text{ mA}$ and $R_m = 500\ \Omega$

Case 1: For range 0 – 20V

$$R_s = \frac{V}{I_m} - R_m = \frac{20}{10 \times 10^{-3}} - 500 = 2 \times 10^3 - 500 = 2000 - 500 = 1.5\text{ k}\Omega$$

Case 2: For range 0 – 50V

$$R_s = \frac{V}{I_m} - R_m = \frac{50}{10 \times 10^{-3}} - 500 = 5 \times 10^3 - 500 = 5000 - 500 = 4.5\ \text{k}\Omega$$

Case 3: For range 0 – 100V

$$R_s = \frac{V}{I_m} - R_m = \frac{100}{10 \times 10^{-3}} - 500 = 10 \times 10^3 - 500 = 10\text{K} - 500 = 9.5\ \text{k}\Omega$$

Example 4.5 *Convert a basic D'Arsonval movement with an internal resistance of 100 Ω and a full scale deflection of 10 mA into a multirange dc voltmeter with ranges from 0 – 5 V, 0 – 50 V and 0 – 100 V.*

Solution Given $I_m = 10$ mA, $R_m = 100\ \Omega$

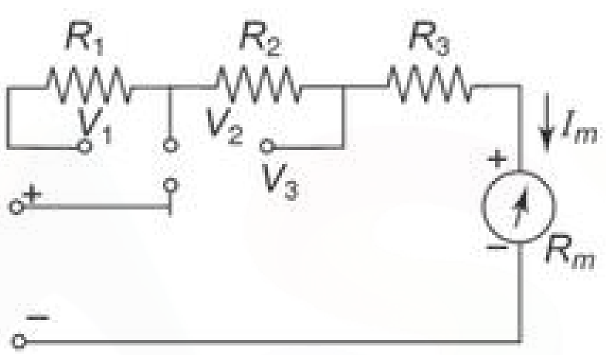


Fig. 4.3(a)

Step 1: For a 5 V (V_3) the total circuit resistance is

$$R_t = \frac{V}{I_{fsd}} = \frac{5}{10\ \text{mA}} = 0.5\ \text{k}\Omega$$

Therefore $R_3 = R_t - R_m = 500\ \Omega - 100\ \Omega$
$= 400\ \Omega$

Step 2: For a 50 V (V_2) position

$$R_t = \frac{V}{I_{fsd}} = \frac{50}{10\ \text{mA}} = 5\ \text{k}\Omega$$

Therefore $R_2 = R_t - (R_3 + R_m) = 5\ \text{k}\Omega - (400\ \Omega + 100\ \Omega)$
$= 5\ \text{k}\Omega - 500\ \Omega = 4.5\ \text{K}\Omega$

Step 3: For a 100 V range (V_1) position

$$R_t = \frac{V}{I_{fsd}} = \frac{100}{10\ \text{mA}} = 10\ \text{k}\Omega$$

Therefore $R_1 = R_t - (R_2 + R_3 + R_m) = 10\ \text{k}\Omega - (4.5\ \text{k}\Omega + 400\ \Omega + 100\ \Omega)$
$= 10\ \text{k}\Omega - 5\ \Omega = 5\ \text{k}\Omega$

Hence it can be seen that R_3 has a non-standard value.

Example 4.6 *Convert a basic D'Arsonval movement with an internal resistance of 50 Ω and a full scale deflection current of 2 mA into a multirange dc voltmeter with voltage ranges of 0 – 10 V, 0 – 50 V, 0 – 100 V and 0 – 250 V. Refer to Fig. 4.3.*

Solution For a 10 V range (V_4 position of switch), the total circuit resistance is

$$R_t = \frac{V}{I_{fsd}} = \frac{10}{2\,\text{mA}} = 5\ \text{k}\Omega$$

Therefore $R_4 = R_t - R_m = 5\ \text{k} - 50 = 4950\ \Omega$.

For 50 V range (V_3 position of switch), the total circuit resistance is

$$R_t = \frac{V}{I_{fsd}} = \frac{50}{2\,\text{mA}} = 25\ \text{k}\Omega$$

Therefore $\quad R_3 = R_t - (R_4 + R_m) = 25\text{ k} - (4950 + 50) = 25\text{ k} - 5\text{ k}$

$\therefore \quad R_3 = 20\ \text{k}\Omega$

For 100 V range (V_2 position of switch), the total circuit resistance is

$$R_t = \frac{V}{I_{fsd}} = \frac{100}{2\,\text{mA}} = 50\ \text{k}\Omega$$

Therefore, $\quad R_2 = R_t - (R_3 + R_4 + R_m)$
$= 50\text{ k} - (20\text{ k} + 4950 + 50)$

$\therefore \quad R_2 = 50\text{ k} - 25\text{ k} = 25\ \text{k}\Omega$

For 250 V range, (V_1 position of switch), the total circuit resistance is

$$R_t = \frac{V}{I_{fsd}} = \frac{250}{2\,\text{mA}} = 125\ \text{k}\Omega$$

Therefore $\quad R_1 = R_t - (R_2 + R_3 + R_4 + R_m)$
$= 125\text{ k} - (25\text{ k} + 20\text{ k} + 4950 + 50)$
$= 125\text{ k} - 50\text{ k}$
$= 75\ \text{k}\Omega$

Only the resistance R_4 (low range multiplier) has a non-standard value.

EXTENDING VOLTMETER RANGES 4.5

The range of a voltmeter can be extended to measure high voltages, by using a high voltage probe or by using an external multiplier resistor, as shown in Fig. 4.4. In most meters the basic movement is used on the lowest current range. Values for multipliers can be determined using the procedure of Section 4.4.

The basic meter movement can be used to measure very low voltages. However, great care must be used not to exceed the voltage drop required for full scale deflection of the basic movement.

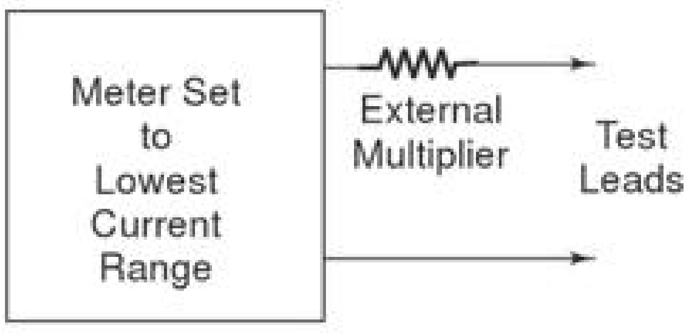


Fig. 4.4 Extending voltage range

Sensitivity The sensitivity or Ohms per Volt rating of a voltmeter is the ratio of the total circuit resistance R_t to the voltage range. Sensitivity is essentially the reciprocal of the full scale deflection current of the basic movement. Therefore, $S = 1/I_{fsd}\ \Omega/V$.

The sensitivity 'S' of the voltmeter has the advantage that it can be used to calculate the value of multiplier resistors in a dc voltmeter. As,

R_t = total circuit resistance [$R_t = R_s + R_m$]
S = sensitivity of voltmeter in ohms per volt
V = voltage range as set by range switch
R_m = internal resistance of the movement

Since $R_s = R_t - R_m$ and $R_t = S \times V$

$\therefore$ $R_s = (S \times V) - R_m$

Example 4.7 *Calculate the value of the multiplier resistance on the 50 V range of a dc voltmeter, that uses a 200 µA meter movement with an internal resistance of 100 Ω.*

Solution As $R_s = S \times$ Range – internal resistance, and $S = 1/I_{fsd}$.

$\therefore$ The sensitivity of the meter movement is

$$S = 1/I_{fsd} = 1/200\ \mu A = 5\ k\Omega/V.$$

The value of multiplier R_s is calculated as

$$R_s = S \times \text{Range} - \text{internal resistance} = S \times V - R_m$$
$$= 5\ k \times 50 - 100$$
$$= 250\ k - 100$$
$$= 249.9\ k\Omega$$

Example 4.8 *Calculate the value of multiplier resistance for the multiple range dc voltmeter circuit shown in Fig. 4.5 (a).*

Solution The sensitivity of the meter movement is given as follows.

$$S = 1/I_{fsd} = 1/50\ \mu A = 20\ k\Omega/V$$

The value of the multiplier resistance can be calculated as follows.

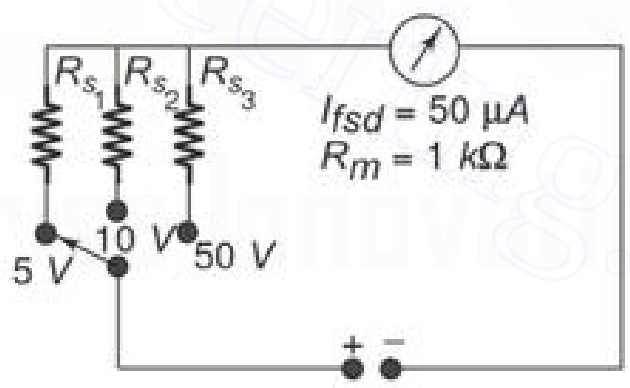


Fig. 4.5 (a)

For 5 V range

$$R_{s_1} = S \times V - R_m$$
$$= 20\ k \times 5 - 1\ k$$
$$= 100\ k - 1\ k = 99\ k\Omega$$

For 10 V range

$$R_{s_2} = S \times V - R_m$$
$$= 20\ k \times 10 - 1\ k$$
$$= 200\ k - 1\ k = 199\ k\Omega$$

For 50 V range

$$R_{s_3} = S \times V - R_m$$
$$= 20\ k \times 50 - 1\ k$$
$$= 1000\ k - 1\ k = 999\ k\Omega$$

Example 4.9 *Calculate the value of multiplier resistance for the multirange dc voltmeter as shown in Fig 4.5(b).*

Solution

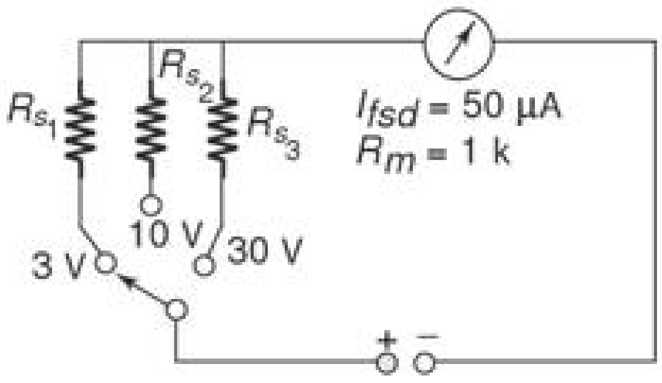


Fig. 4.5 (b)

Step 1: The sensitivity of 50 μA meter movement is given by

$S = 1/I_m = 1/50\ \mu\text{A} = 20\ \text{k}\Omega/\text{V}$.

The value of the multiplier resistance can be calculated by

Step 2: The value of the multiplier for 3 V range

$$R_s = S \times \text{range} - R_m$$
$$R_s = 20\ \text{k}\Omega/\text{V} \times 3\text{V} - 1\ \text{k}\Omega$$
$$= 60\ \text{k}\Omega - 1\ \text{k}\Omega = 59\ \text{k}\Omega.$$

Step 3: The value of the multiplier resistance For 10 V range can be calculated by

$$R_s = S \times \text{range} - R_m$$
$$R_s = 20\ \text{k}\Omega./\text{V} \times 10\ \text{V} - 1\ \text{k}\Omega$$
$$= 200\ \text{k}\Omega - 1\ \text{k}\Omega = 199\ \text{k}\Omega.$$

Step 4: The value of the multiplier resistance For 30V range can be calculated by

$$R_s = S \times \text{range} - R_m$$
$$R_s = 20\ \text{k}\Omega/\text{V} \times 30\ \text{V} - 1\ \text{k}\Omega$$
$$= 600\ \text{k}\Omega - 1\ \text{k}\Omega = 599\ \text{k}\Omega$$

Example 4.10 *A moving coil instrument gives a full scale deflection of 20 mA when the potential difference across its terminals is 100 mV. Calculate*

(a) Shunt resistance for a full scale deflection corresponding of 50 A.

(b) The series resistance for a full scale reading with 500 V. Also calculate the power dissipation in each case.

Solution Given meter current I_m = 20 mA and voltage = 100 mV

Step 1: Meter resistance $R_m = \dfrac{100\ \text{mV}}{20\ \text{mA}} = 5\ \Omega$

Step 2: Shunt resistance is given by

$$R_{sh} = \frac{I_m R_m}{I - I_m} = \frac{20\ \text{mA} \times 5\ \Omega}{50000\ \text{mA} - 20\ \text{mA}} = \frac{100\ \text{mA}}{49980\ \text{mA}} = .002\ \Omega$$

Step 3: Voltage Multiplier

$$R_{sh} = \frac{V}{I_m} - R_m = \frac{500\ \text{V}}{20\ \text{mA}} - 5\ \Omega = 25 \times 10^3 - 5\ \Omega$$
$$= 24995\ \Omega \approx 25\ \text{k}\Omega$$

Power = $V_m \cdot I_m$ = 500 × 20 mA = 10 W

LOADING 4.6

When selecting a meter for a certain voltage measurement, it is important to consider the sensitivity of a dc voltmeter. A low sensitivity meter may give a correct reading when measuring voltages in a low resistance circuit, but it is certain to produce unreliable readings in a high resistance circuit. A Voltmeter when connected across two points in a highly resistive circuits, acts as a shunt for that portion of the circuit, reducing the total equivalent resistance of that portion as shown in Fig. 4.6. The meter then indicates a lower reading than what existed before the meter was connected. This is called the loading effect of an instrument and is caused mainly by low sensitivity instruments.

Example 4.11 *Figure 4.6 shows a simple series circuit of R_1 and R_2 connected to a 100 V dc source. If the voltage across R_2 is to be measured by voltmeters having*

(a) a sensitivity of 1000 Ω/V, and

(b) a sensitivity of 20,000 Ω/V, find which voltmeter will read the accurate value of voltage across R_2. Both the meters are used on the 50 V range.

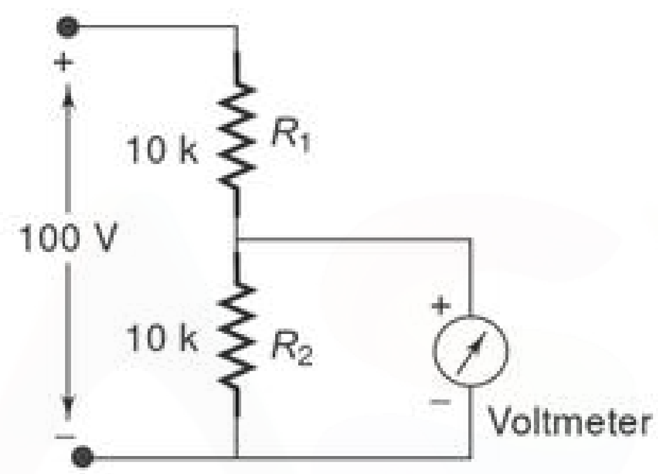


Fig. 4.6 Example on loading effect

Solution Inspection of the circuit indicates that the voltage across the R_2 resistance is

$$\frac{10\text{ k}}{10\text{ k} + 10\text{ k}} \times 100\text{ V} = 50\text{ V}$$

This is the true voltage across R_2.

Case 1

Using a voltmeter having a sensitivity of 1000 Ω/V.

It has a resistance of 1000 × 50 = 50 kΩ on its 50 V range.

Connecting the meter across R_2 causes an equivalent parallel resistance given by

$$R_{eq} = \frac{10\text{ k} \times 50\text{ k}}{10\text{ k} + 50\text{ k}} = \frac{500\text{ M}}{60\text{ k}} = 8.33\text{ k}\Omega$$

Now the voltage across the total combination is given by

$$V_1 = \frac{R_{eq}}{R_1 + R_{eq}} \times V$$

$$V_1 = \frac{8.33\text{ k}}{10\text{ k} + 8.33\text{ k}} \times 100\text{ V} = 45.43\text{ V}$$

Hence this voltmeter indicates 45.43 V.

Case 2

Using a voltmeter having a sensitivity of 20,000 Ω/V. Therefore it has a resistance of

$$20{,}000 \times 50 = 1000\text{ k} = 1\text{ M}\Omega$$

This voltmeter when connected across R_2 produces an equivalent parallel resistance given by

$$R_{eq} = \frac{10\text{ k} \times 1\text{ M}}{10\text{ k} + 1\text{ M}} = \frac{10^9}{1.01\text{ M}} = \frac{10\text{ k}}{1.01} = 9.9\text{ k}\Omega$$

Now the voltage across the total combination is given by

$$V_2 = \frac{9.9\text{ k}}{10\text{ k} + 9.9\text{ k}} \times 100\text{ V} = 49.74\text{ V}$$

Hence this voltmeter will read 49.74 V.

This example shows that a high sensitivity voltmeter should be used to get accurate readings.

Example 4.12 *Two different voltmeters are used to measure the voltage across R_b in the circuit of Fig. 4.7.*

The meters are as follows.

Meter 1: $S = 1$ kΩ/V, $R_m = 0.2$ k, range 10 V

Meter 2: $S = 20$ kΩ/V, $R_m = 1.5$ k, range 10 V

Calculate (i) voltage across R_b without any meter across it, (ii) voltage across R_b when the meter 1 is used (iii) voltage across R_b when the meter 2 is used, and (iv) error in the voltmeters.

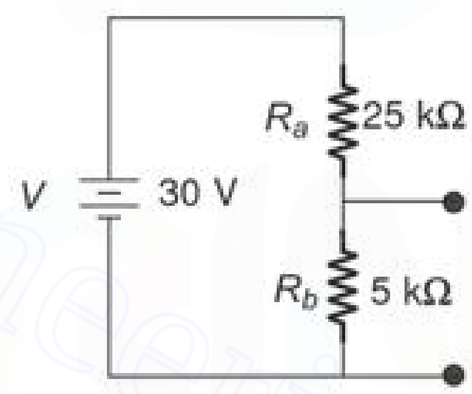


Fig. 4.7

Solution (i) The voltage across the resistance R_b, without either meter connected, is calculated using the voltage divider formula.

Therefore,
$$VR_b = \frac{5\text{ k}}{25\text{ k} + 5\text{ k}} \times 30 = \frac{150\text{ k}}{30\text{ k}} = 5\text{ V}$$

(ii) Starting with meter 1, having sensitivity $S = 1$ kΩ/V

Therefore the total resistance it presents to the circuit

$$R_{m_1} = S \times \text{range} = 1\text{ k}\Omega/\text{V} \times 10 = 10\text{ k}\Omega$$

The total resistance across R_b is, R_b in parallel with meter resistance R_{m1}

$$R_{eq} = \frac{R_b \times R_{m_1}}{R_b + R_{m_1}} = \frac{5\text{ k} \times 10\text{ k}}{5\text{ k} + 10\text{ k}} = 3.33\text{ k}\Omega$$

Therefore, the voltage reading obtained with meter 1 using the voltage divider equation is

$$VR_b = \frac{R_{eq}}{R_{eq} + R_a} \times V = \frac{3.33\text{ k}}{3.33\text{ k} + 25\text{ k}} \times 30 = 3.53\text{ V}$$

(iii) The total resistance that meter 2 presents to the circuit is

$$R_{m_2} = S \times \text{range} = 20\text{ k}\Omega/\text{V} \times 10\text{ V} = 200\text{ k}\Omega$$

The parallel combination of R_b and meter 2 gives

$$R_{eq} = \frac{R_b \times R_{m_2}}{R_b + R_{m_2}} = \frac{5\text{ k} \times 200\text{ k}}{5\text{ k} + 200\text{ k}} = \frac{1000\text{ k} \times 1\text{ k}}{205\text{ k}} = 4.88\text{ k}\Omega$$

Therefore the voltage reading obtained with meter 2, using the voltage divider equation is

$$VR_b = \frac{4.88\text{ k}}{25\text{ k} + 4.88\text{ k}} \times 30 = \frac{4.88\text{ k}}{29.88\text{ k}} \times 30 = 4.9\text{ V}$$

(iv) The error in the reading of the voltmeter is given as:

$$\%\text{ Error} = \frac{\text{Actual voltage} - \text{Voltage reading observed in meter}}{\text{Actual voltage}} \times 100\%$$

$$\therefore \qquad \text{voltmeter 1 error} = \frac{5\text{ V} - 3.33\text{ V}}{5\text{ V}} \times 100\% = 33.4\%$$

Similarly

$$\text{voltmeter 2 error} = \frac{5\text{ V} - 4.9\text{ V}}{5\text{ V}} \times 100\% = 2\%$$

Example 4.13 *Find the voltage reading and % error of each reading obtained with a voltmeter on (i) 5 V range, (ii) 10 V range and (iii) 30 V range, if the instrument has a 20 kΩ/V sensitivity and is connected across R_b of Fig. 4.8 (a).*

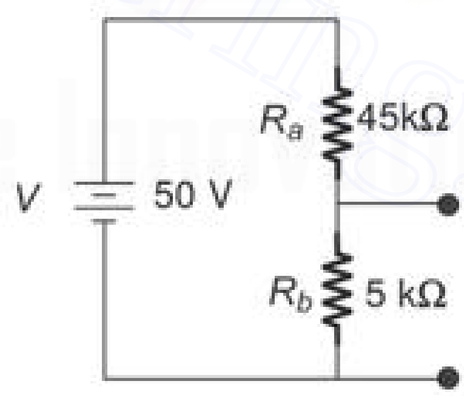


Fig. 4.8 (a)

Solution The voltage drop across R_b without the voltmeter connected is calculated using the voltage equation

$$VR_b = \frac{R_b}{R_a + R_b} \times V = \frac{5\text{ k}}{45\text{ k} + 5\text{ k}} \times 50 = \frac{50 \times 5\text{ k}}{50\text{ k}} = 5\text{ V}$$

On the 5 V range

$$R_m = S \times \text{range} = 20\text{ k}\Omega \times 5\text{ V} = 100\text{ k}\Omega$$

$$\therefore \qquad R_{eq} = \frac{R_m \times R_b}{R_m + R_b} = \frac{100\text{ k} \times 5\text{ k}}{100\text{ k} + 5\text{ k}} = \frac{500\text{ k}}{105\text{ k}} = 4.76\text{ k}\Omega$$

The voltmeter reading is

$$VR_b = \frac{R_{eq}}{R_a + R_{eq}} \times V = \frac{4.76\text{ k}}{45\text{ k} + 4.76\text{ k}} \times 50 = 4.782\text{ V}$$

The % error on the 5 V range is

$$\%\text{ Error} = \frac{\text{Actual voltage} - \text{Voltage reading in meter}}{\text{Actual voltage}}$$

$$= \frac{5\text{ V} - 4.782\text{ V}}{5\text{ V}} \times 100 = \frac{0.217\text{ V}}{5\text{ V}} \times 100 = 4.34\ \%$$

On 10 V range

$$R_m = S \times \text{range} = 20\text{ k}\Omega/\text{V} \times 10\text{ V} = 200\text{ k}\Omega$$

$$\therefore \qquad R_{eq} = \frac{R_m \times R_b}{R_m + R_b} = \frac{200\text{ k} \times 5\text{ k}}{200\text{ k} + 5\text{ k}} = 4.87\text{ k}\Omega$$

The voltmeter reading is

$$VR_b = \frac{R_{eq}}{R_{eq} + R_a} \times V = \frac{4.87\text{ k}}{4.87\text{ k} + 45\text{ k}} \times 50 = 4.88\text{ V}$$

The % error on the 10 V range $= \dfrac{5\text{ V} - 4.88\text{ V}}{5\text{ V}} \times 100 = 2.34\%$

On 30 V range

$$R_m = S \times \text{range} = 20\text{ k}\Omega/\text{V} \times 30\text{ V} = 600\text{ k}$$

$$\therefore \qquad R_{eq} = \frac{R_m \times R_b}{R_m + R_b} = \frac{600\text{ k} \times 5\text{ k}}{600\text{ k} + 5\text{ k}} = \frac{3000\text{ k} \times 1\text{ k}}{605\text{ k}} = 4.95\text{ k}$$

The voltmeter reading on the 30 V range

$$VR_b = \frac{R_{eq}}{R_{eq} + R_a} \times V = \frac{4.95\text{ k}}{45\text{ k} + 4.95\text{ k}} \times 50 = 4.95\text{ V}$$

The % error on the 30 V range

$$= \frac{5\text{ V} - 4.95\text{ V}}{5\text{ V}} \times 100 = \frac{0.05}{5\text{ V}} \times 100 = 1\ \%$$

In the above example, the 30 V range introduces the least error due to loading. However, the voltage being measured causes only a 10% full scale deflection, whereas on the 10 V range the applied voltage causes approximately a one third of the full scale deflection with less than 3% error.

Example 4.14 *A current meter that has an internal resistance of 100 Ω is used to measure the current thro resistor R_3 in Fig 4.8(b) given below. Determine the % of the reading due to ammeter loading.*

Solution

Step 1: The current meter will be connected in to the circuit as shown in Fig 4.8 (a).

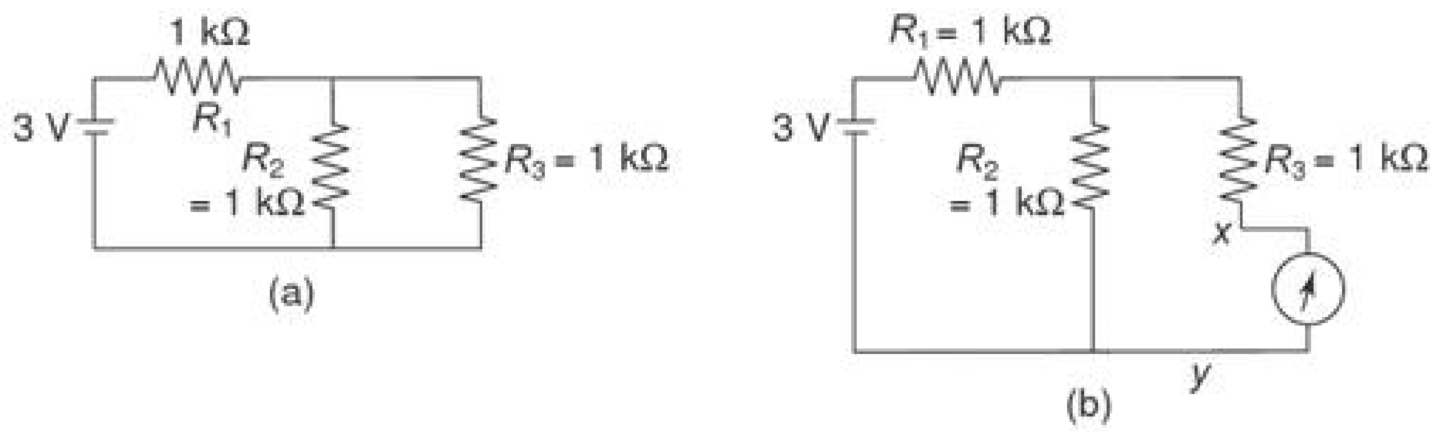


Fig. 4.8

Looking back into terminals x and y and using Thevinin's equivalent resistance,

$$R_t = R_1 + \frac{R_2 \times R_3}{R_2 + R_3} = 1\,\text{k} + \frac{1\,\text{k} \times 1\,\text{k}}{1\,\text{k}} = 1.5\,\text{k}\Omega$$

Step 2: The ratio of the meter current to the expected current is

$$\frac{I_m}{I} = \frac{R_t}{R_t + R_m}$$

Therefore $$I_m = \frac{1.5\,\text{k}\Omega}{1.5\,\text{k}\Omega + 100\,\Omega} = \frac{1.5\,\text{k}}{1.6\,\text{k}} = 0.938$$

Therefore $$I_m = 0.938 \times I$$

The current thro the meter is 93.8% of the expected current, therefore the meter current caused a 6.2% error due to effects of loading .

TRANSISTOR VOLTMETER (TVM) 4.7

Direct coupled amplifiers are economical and hence used widely in general purpose low priced VTVM's. Figure 4.9 gives a simplified schematic diagram of a dc coupled amplifier with an indicating meter. The dc input is applied to a range attenuator to provide input voltage levels which can be accommodated by the dc amplifier. The input stage of the amplifier consists of a FET which provides high input impedance to effectively isolate the meter circuit from the circuit under measurement. The input impedance of a FET is greater than 10 MΩ. The bridge is balanced, so that for zero input the dial indicates zero.

The two transistors, Q_1 and Q_2 forms a dc coupled amplifier driving the meter movement. Within the dynamic range of the amplifier, the meter deflection is proportional to the magnitude of the applied input voltage. The input overload does not burn the meter because the amplifier saturates, limiting the maximum current through the meter. The gain of the dc amplifier allows the instrument to be used for measurement of voltages in the mV range. Instruments in the μV range of measurement require a high gain dc amplifier to supply sufficient current for driving the meter movement. In order to avoid the drift problems of dc amplifiers, chopper type dc amplifiers are commonly used in high sensitivity voltmeters.

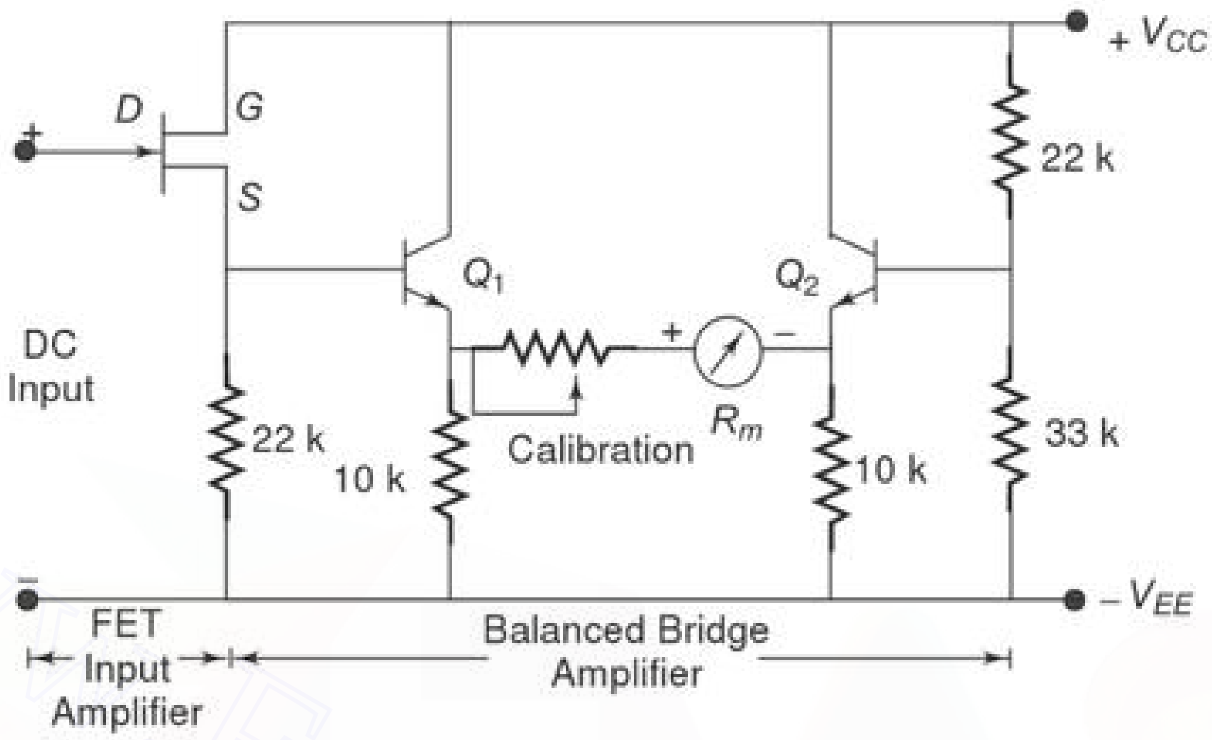


Fig. 4.9 Transistor voltmeter

CHOPPER TYPE DC AMPLIFIER VOLTMETER (MICROVOLTMETER) 4.8

In a chopper type amplifier the dc input voltage is converted into an ac voltage, amplified by an ac amplifier and then converted back into a dc voltage proportional to the original input signal.

The balanced bridge voltmeter has limitations caused by drift problems in dc amplifier. Any fluctuations of voltage supply or variation in the '*Q*' characteristics due to ageing or rise in temperature causes a change in the zero setting or balance. This drift in the steady state conditions of a dc amplifier causes the output indications to change as if the signal input had changed. This drift problem limits the minimum voltage that can be measured. To measure small voltages, a chopper type dc amplifier is used.

A chopper amplifier is normally used for the first stage of amplification in very sensitive instruments of a few μV range. In such an amplifier the dc voltage is chopped to a low frequency of 100 – 300 Hz. It is passed through a blocking capacitor, amplified and then passed through another blocking capacitor, in order to remove the dc drift or offset of the amplified signal.

The principle of operation is as given in Fig. 4.10. An ac amplifier which has a very small drift compared to a dc amplifier is used. The chopper may be mechanical or electronic. Photo diodes are used as nonmechanical choppers for modulation (conversion of dc to ac) and demodulation (conversion of ac to dc). Photo conductors have a low resistance, ranging from a few hundreds to a few thousand ohms, when they are illuminated by a neon or incandescent lamp. The photo conductor resistance increases sharply, usually to several Mega ohms when not illuminated.

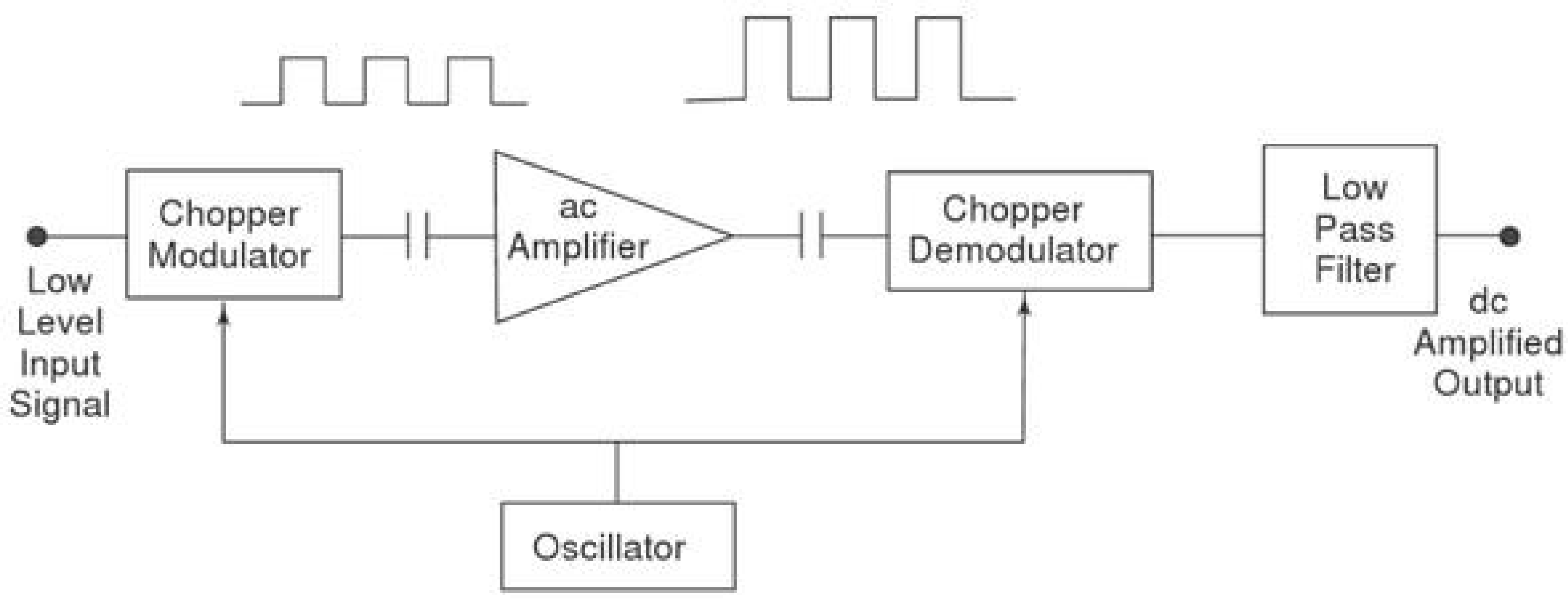


Fig. 4.10 Principle of operation (Chopper type voltmeter)

Figure 4.11 (a) shows a simple circuit for an basic principle of an electronic modulator.

A flashing light source, whose intensity varies from maximum to minimum almost instantaneously, causes the photo diode resistance to change from R_{min} to R_{max} quickly. Therefore the output voltage is an ac, because the photo diode has a high output when its resistance is high and a low output when its resistance is low, as shown in Fig. 4.11 (b).

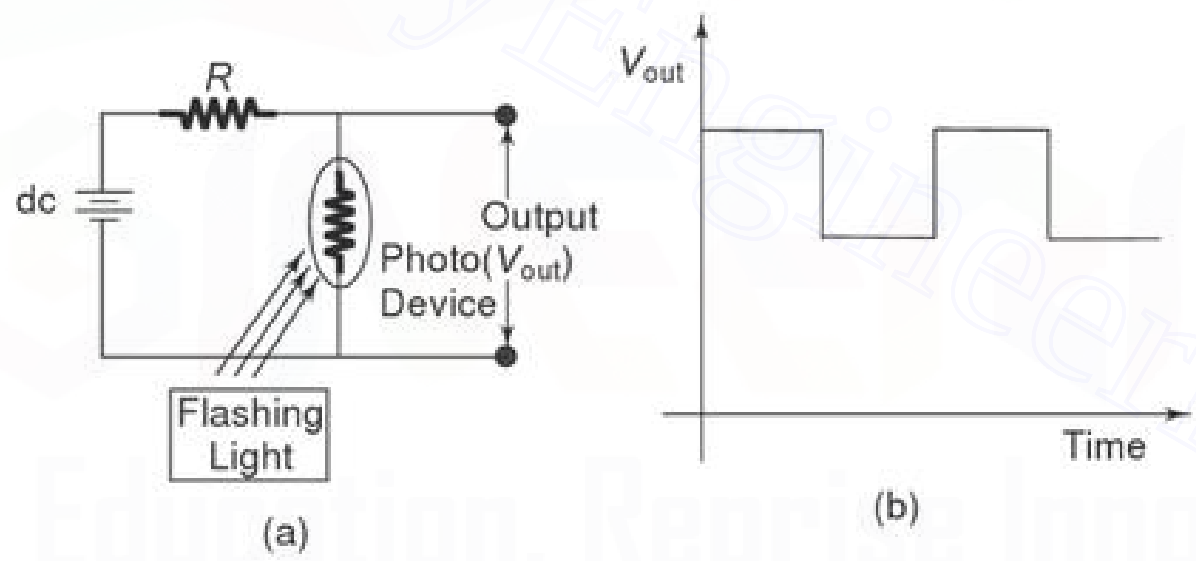


Fig. 4.11 (a) Basic principle of an electronic modulator (b) Output obtained from circuit in Fig. 4.11 (a) (Output voltage waveform)

In the circuit diagram of Fig. 4.12, an oscillator drives two neon lamps into illumination on alternating half cycles of oscillation. The oscillator frequency is limited to a few 100 cycles, because the transition time required for the photo diode to change from high resistance to low resistance limits the chopping range.

Each neon lamp illuminates one photo diode in the input circuit of the amplifier and one in the output circuit. The two photo diodes form a series shunt half wave modulator or chopper. When one photo diode or the input has maximum resistance, the other has minimum resistance. The same conditions exist at the output circuit. Together they act like a switch across the input to the amplifier, alternatively opening and closing at a rate determined by the frequency of the neon oscillator.

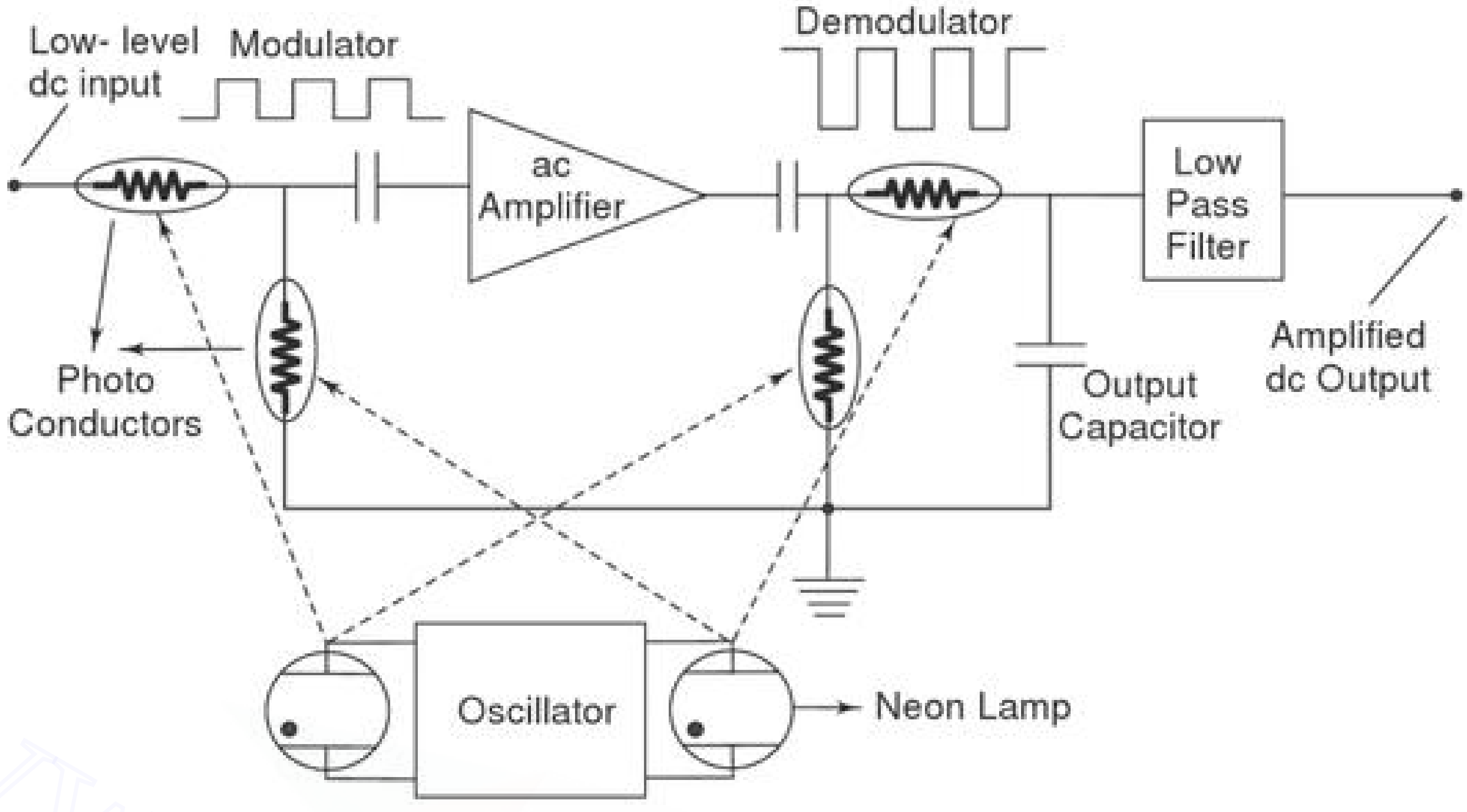


Fig. 4.12 Chopper type voltmeter

The input signal to the amplifier is a square wave whose amplitude is proportional to the input voltage with a frequency equal to the oscillators frequency. The ac amplifier delivers an amplified square wave at its output terminals. The photo diodes (demodulator) in the output circuit operate in antisynchronously with the input chopper, recovering the dc signal by a demodulating action. The dc output signal is then passed to a low pass filter to remove any residual ac component. This amplified drift free dc output is then applied to a PMMC movement for measurement.

The chopper eliminates the need for a high gain dc amplifier with its inherent drift and stability problems.

The input impedance of the chopper amplifier dc voltmeter is usually of the order of 10 MΩ or higher, except in low input ranges. In order to eliminate errors caused by high source impedance, an arrangement for nulling is included in the meter circuit. A control facility provided on the front panel of the instrument permits the input voltage to be nullified with a bucking voltage. When the bucking voltage is equal to the input voltage, a null is indicated, the meter exhibits infinite impedance, and therefore loading effects are totally eliminated. The input voltage is then removed and a bucking voltage equal to the input voltage is indicated by the meter.

A commercially available instrument using a photo chopper amplifier has an input impedance of 100 MΩ, a resolution of 0.1 μV and input ranges from 3 μV full scale to 1 kV full scale with an accuracy of ± 2% of full scale deflection.

Advantages of Chopper Voltmeters

(i) The input impedance of a Chopper Amplifier is usually of the order of 10 MΩ or higher, except on very low input ranges.

(ii) The drift in an ordinary dc amplifier is of the order of mV. The full scale range of an ordinary dc amplifier is limited to measuring input signal of 1 – 100 mV. In a chopper modulator system with the use of ac amplifier, drift can be cut down by a factor of 100, thus allowing an input signal range of about 0.01 mV = 10 μV full scale to be handled.

SOLID STATE VOLTMETER 4.9

Figure 4.13 shows the circuit of an electronic voltmeter using an IC OpAmp 741C. This is a directly coupled very high gain amplifier. The gain of the OpAmp can be adjusted to any suitable lower value by providing appropriate resistance between its output terminal, Pin No. 6, and inverting input, Pin No. 2, to provide a negative feedback. The ratio R_2/R_1 determines the gain, i.e. 101 in this case, provided by the OpAmp. The 0.1 μF capacitor across the 100 k resistance R_2 is for stability under stray pick-ups. Terminals 1 and 5 are called offset null terminals. A 10 kΩ potentiometer is connected between these two offset null terminals with its centre tap connected to a – 5V supply. This potentiometer is called zero set and is used for adjusting zero output for zero input conditions.

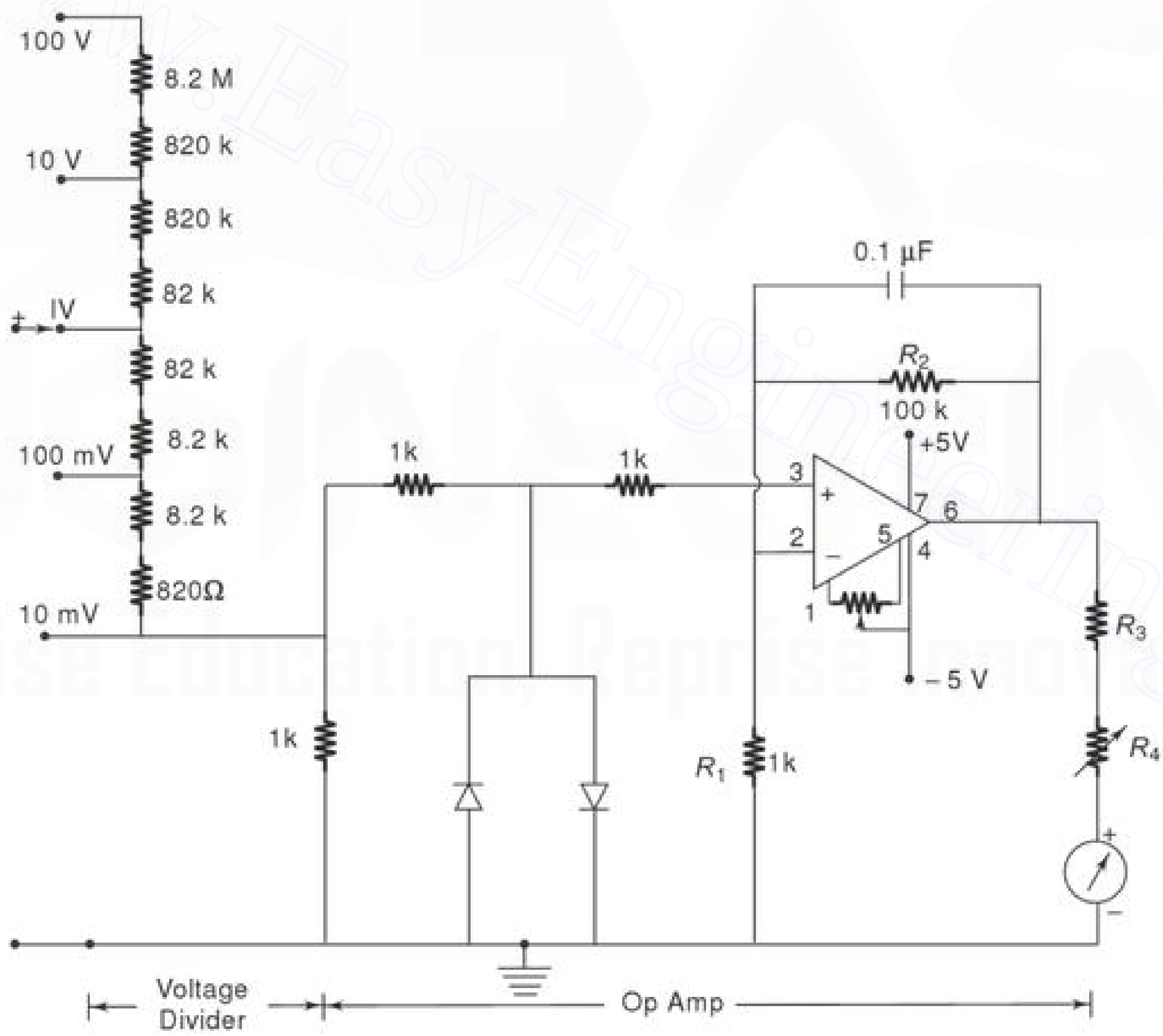


Fig. 4.13 Solid state mV voltmeter using OpAmp

The two diodes used are for IC protection. Under normal conditions, they are non-conducting, as the maximum voltage across them is 10 mV. If an excessive voltage, say more than 100 mV appears across them, then depending upon the polarity of the voltage, one of the diodes conducts and protects the IC. A μA scale of 50 – 1000 μA full scale deflection can be used as an indicator. R_4 is adjusted to get maximum full scale deflection.

DIFFERENTIAL VOLTMETER 4.10

Basic Differential Measurement The differential voltmeter technique, is one of the most common and accurate methods of measuring unknown voltages. In this technique, the voltmeter is used to indicate the difference between known and unknown voltages, i.e., an unknown voltage is compared to a known voltage.

Figure 4.14 (a) shows a basic circuit of a differential voltmeter based on the potentiometric method; hence it is sometimes also called a potentiometric voltmeter.

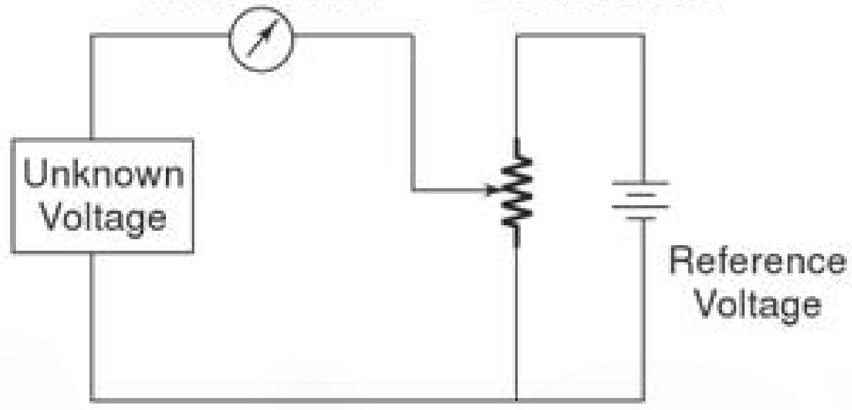


Fig. 4.14 (a) Basic differential voltmeter

In this method, the potentiometer is varied until the voltage across it equals the unknown voltage, which is indicated by the null indicator reading zero. Under null conditions, the meter draws current from neither the reference source nor the unknown voltage source, and hence the differential voltmeter presents an infinite impedance to the unknown source. (The null meter serves as an indicator only.)

To detect small differences the meter movement must be sensitive, but it need not be calibrated, since only zero has to be indicated.

The reference source used is usually a 1 V dc standard source or a zener controlled precision supply. A high voltage reference supply is used for measuring high voltages.

The usual practice, however, is to employ voltage dividers or attenuators across an unknown source to reduce the voltage. The input voltage divider has a relatively low input impedance, especially for unknown voltages much higher than the reference standard. The attenuation will have a loading effect and the input resistance of voltmeter is not infinity when an attenuator is used.

In order to measure ac voltages, the ac voltage must be converted into dc by incorporating a precision rectifier circuit. A block diagram of an ac differential voltmeter is shown in Fig. 4.14 (b).

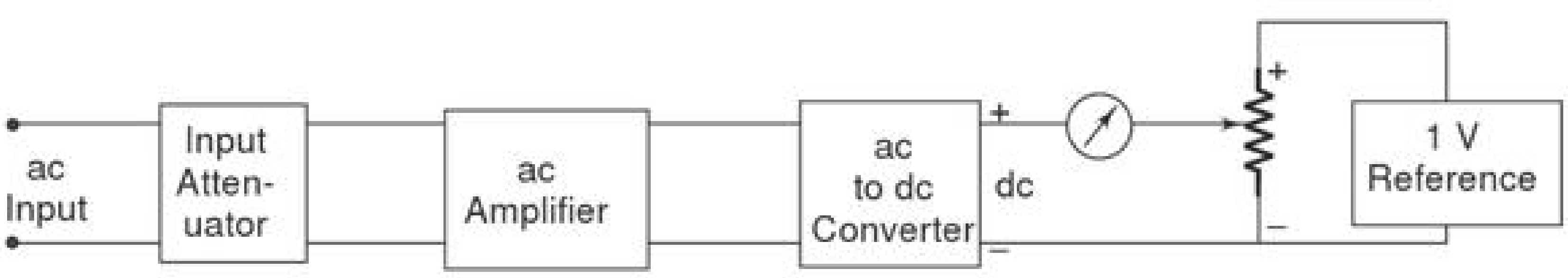


Fig. 4.14 (b) Block diagram of an ac differential voltmeter

DC STANDARD/DIFFERENCE VOLTMETER 4.11

Multifunction Laboratory Instrument

A basic dc standard differential voltmeter can be operated in different modes. The three basic modes of operation are (i) as a dc voltage standard, (ii) as a dc differential voltmeter, and (iii) as a dc voltmeter (conventional).

1. DC Voltage Standard *A + 1 V dc stable supply is obtained from a temperature controlled reference supply, which is applied to a decimal divider network. With the help of switches on the front panel of the voltmeter, the divider ratios can be controlled (varied), allowing the reference supply to be adjusted in steps of 1 μV each, from 0 to 1 V. A low level dc amplifier is used to amplify the low level voltages obtained from the decimal divider to a sufficient level. This reference output voltage is then applied to a high gain dc amplifier with positive feedback to obtain precisely controlled gain characteristics.*

Figure 4.15 (a) illustrates the standard mode of operation. In the standard mode of operation, the differential voltmeter is used to provide a standard reference source in the laboratory, where the instrument generates a precision output voltage from 0 – 1000 V as a reference source.

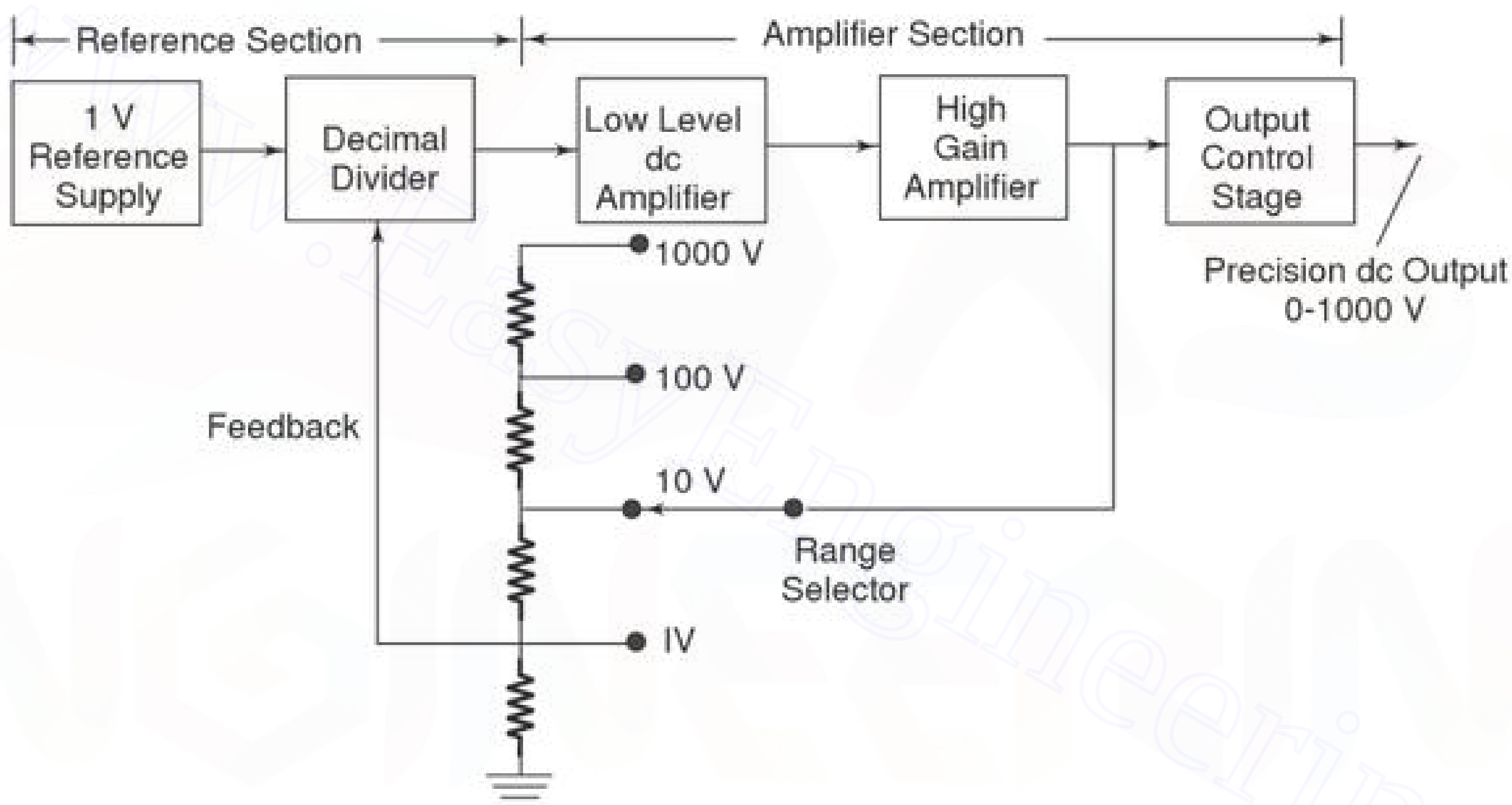


Fig. 4.15 (a) Block diagram of dc standard/differential voltmeter

The dc amplifier consists of several stages in cascade, providing an open loop gain (A) of 10 or higher. (The feedback network monitors the actual output voltage and feeds a controlled fraction of the output back to the amplifier input.)

The closed loop gain of the feedback amplifier is given by

$$G = \frac{A}{1 + A\beta}$$

where G = closed loop gain (voltage gain with feedback)
A = open loop gain (voltage gain without feedback)
β = fraction of the output used as degenerative feedback

If the open loop gain is very high and $A\ \beta$ is much greater than 1, $G = 1/\beta$ implying that the gain of the amplifier depends only on the amount of degenerative feedback.

From the equation ($G = 1/\beta$), it can be seen that as β decreases, the closed loop gain of the amplifier increases. The value of β in turn depends upon the accuracy of the voltage dividers used, i.e. the precision value of the resistors used for the voltage dividers (wire wound precision resistors). The following ranges of standard voltage are available at the output.

0 – 1 V in 1 μV steps (1 V range)
0 – 10 V in 10 μV steps (10 V range)
0 – 100 V in 100 μV steps (100 V range)
0 – 1000 V in 1 mV steps (1000 V range)

2. DC Differential Voltmeter The unknown dc voltage is applied to the input of the amplifier section and a part of the output voltage is fed back to the input stage with the help of one divider network, which controls the closed loop gain of the amplifier. The other section of the voltage divider network applies a fraction of the output voltage to the differential input of the meter amplifier.

The meter circuit measures the difference between the feedback voltage and the reference voltage, indicating a null deflection when the two voltages are equal. The range selector (on the front panel) controls both the feedback voltage and the voltage that is applied in opposition to the reference divider output, such that 1 V capacity of the reference supply is never exceeded.

A differential voltmeter is shown in Fig. 4.15 (b).

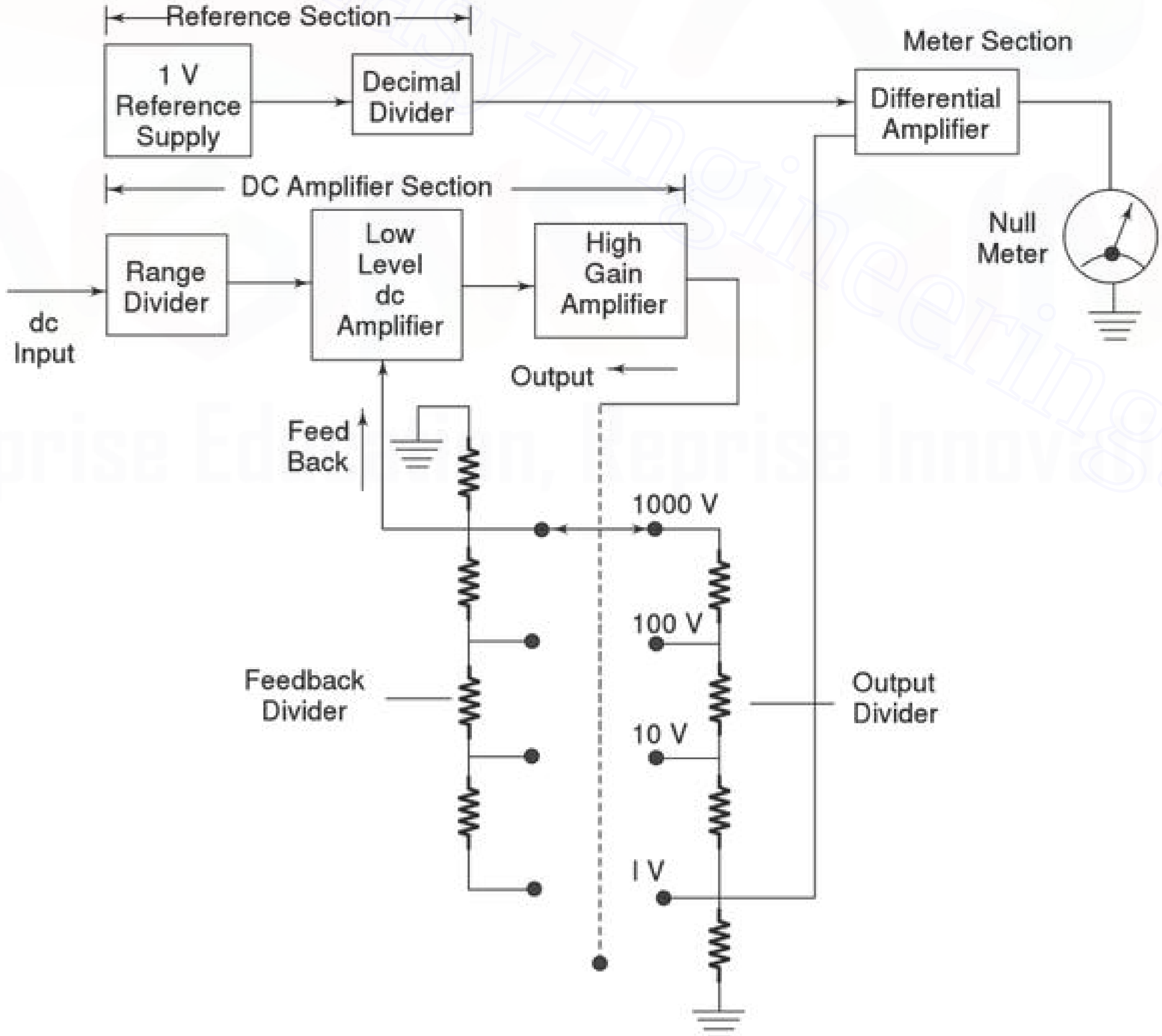


Fig. 4.15 (b) Differential voltmeter

3. DC Voltmeter In this mode of operation the instrument is connected as a dc voltmeter. High input impedance to the unknown voltage source is provided by the dc amplifier, which act as a buffer stage.

The input voltage is amplified and the dc output voltage is applied directly to the meter circuit. The meter circuit involves a feedback controlled amplifier and allows a selection of the sensitivity.

AC VOLTMETER USING RECTIFIERS 4.12

Rectifier type instruments generally use a PMMC movement along with a rectifier arrangement. Silicon diodes are preferred because of their low reverse current and high forward current ratings. Figure 4.16 (a) gives an ac voltmeter circuit consisting of a multiplier, a bridge rectifier and a PMMC movement.

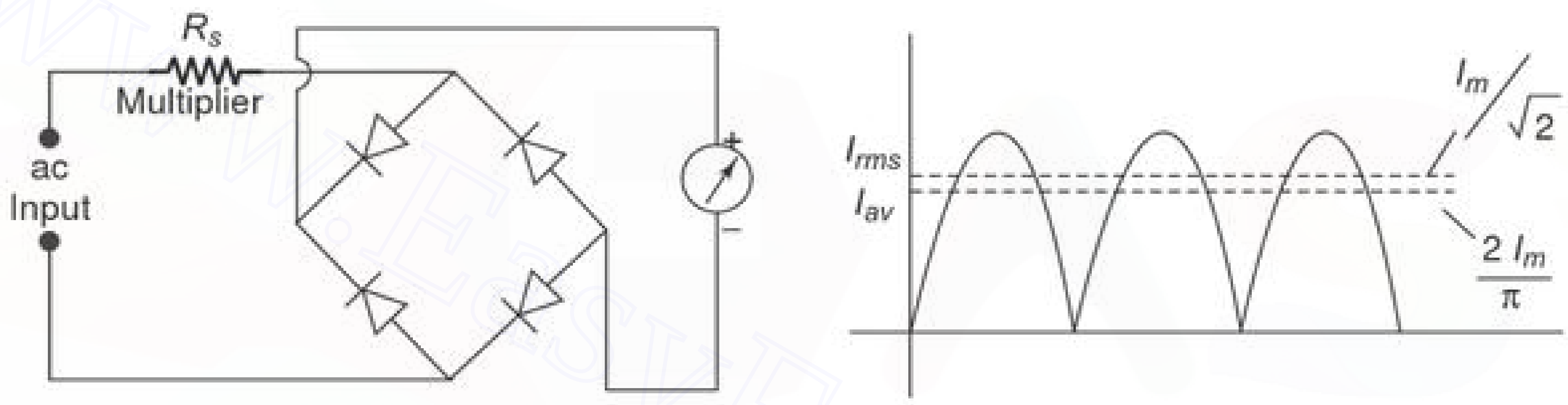


Fig. 4.16 (a) ac voltmeter (b) Average and RMS value of current

The bridge rectifier provides a full wave pulsating dc. Due to the inertia of the movable coil, the meter indicates a steady deflection proportional to the average value of the current (Fig. 4.16 (b)). The meter scale is usually calibrated to give the RMS value of an alternating sine wave input.

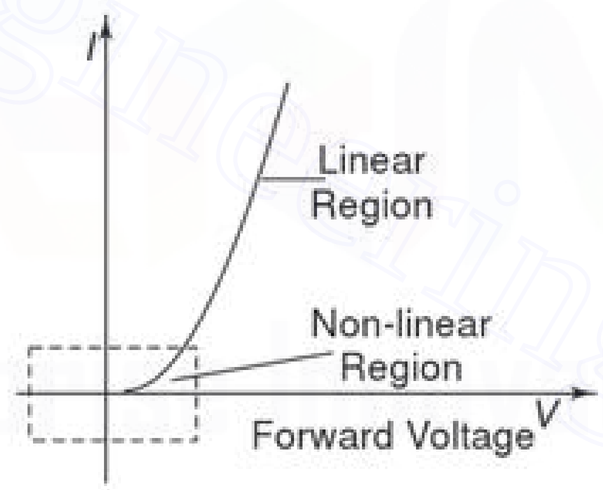


Fig. 4.16 (c) Diode characteristics (Forward)

Practical rectifiers are non-linear devices particularly at low values of forward current (Fig. 4.16 (c)). Hence the meter scale is non-linear and is generally crowded at the lower end of a low range voltmeter. In this part the meter has low sensitivity because of the high forward resistance of the diode. Also, the diode resistance depends on the temperature.

The rectifier exhibits capacitance properties when reverse biased, and tends to bypass higher frequencies. The meter reading may be in error by as much as 0.5% decrease for every 1 kHz rise in frequency.

A general rectifier type ac voltmeter arrangement is given in Fig. 4.17.

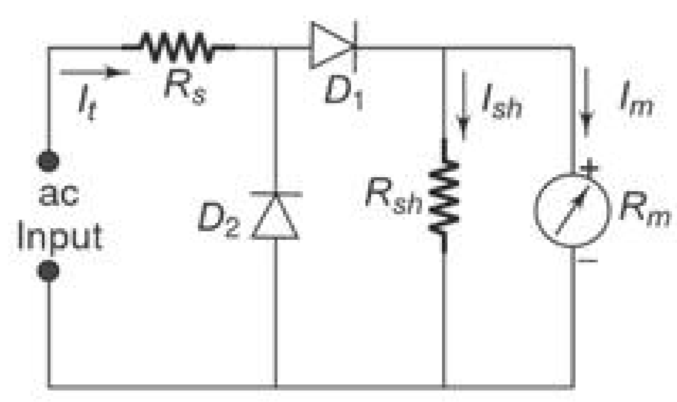


Fig. 4.17 General rectifier type ac voltmeter

Diode D_1 conducts during the positive half of the input cycle and causes the meter to deflect according to the average value of this half cycle. The meter movement is shunted by a resistor, R_{sh}, in order to draw more current through the diode D_1 and move the operating point into the linear portion of the characteristic curve. In the negative half cycle, diode D_2 conducts and the current through the measuring circuit, which is in an opposite direction, bypasses the meter movement.

AC VOLTMETER USING HALF WAVE RECTIFIER 4.13

If a diode D_1 is added to the dc voltmeter, as shown in Fig. 4.18, we have an ac voltmeter using half wave rectifier circuit capable of measuring ac voltages. The sensitivity of the dc voltmeter is given by

$$S_{dc} = 1/I_{fsd} = 1/1 \text{ mA} = 1 \text{ k}\Omega$$

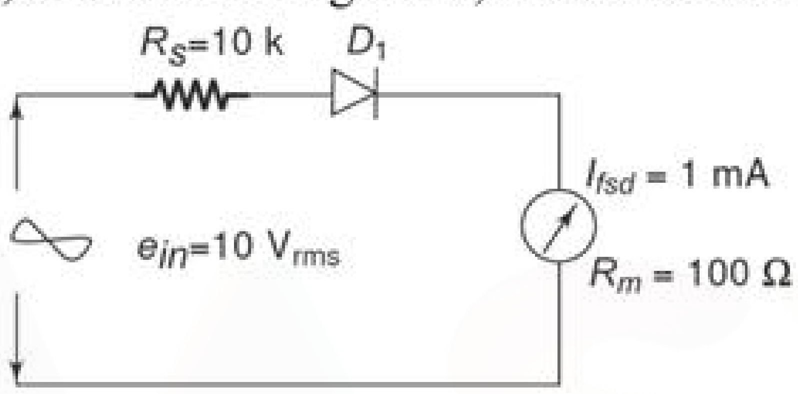


Fig. 4.18 ac voltmeter using half wave rectifier

A multiple of 10 times this value means a 10 V dc input would cause exactly full scale deflection when connected with proper polarity. Assume D_1 to be an ideal diode with negligible forward bias resistance. If this dc input is replaced by a 10 V rms sine wave input. The voltages appearing at the output is due to the +ve half cycle due to rectifying action.

The peak value of 10 V rms sine wave is

$$E_p = 10 \text{ V rms} \times 1.414 = 14.14 \text{ V peak}$$

The dc will respond to the average value of the ac input, therefore

$$E_{av} = E_p \times 0.636 = 14.14 \times 0.636 = 8.99 \text{ V}$$

Since the diode conducts only during the positive half cycle, the average value over the entire cycle is one half the average value of 8.99 V, i.e. about 4.5 V.

Therefore, the pointer will deflect for a full scale if 10 V dc is applied and 4.5 V when a 10 Vrms sinusoidal signal is applied. This means that an ac voltmeter is not as sensitive as a dc voltmeter.

As $$E_{dc} = 0.45 \times E_{rms}$$

∴ The value of the multiplier resistor can be calculated as

$$R_s = \frac{E_{dc}}{I_{dc}} - R_m = \frac{0.45 \times E_{rms}}{I_{dc}} - R_m$$

Example 4.15 *Calculate the value of the multiplier resistor for a 10 V rms range on the voltmeter shown in Fig. 4.19.*

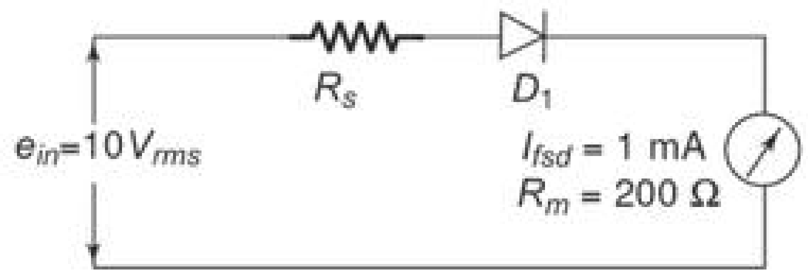


Fig. 4.19

Solution

Method 1 Sensitivity of the meter movement is

$$S_{dc} = 1/I_{fsd} = 1/1 \text{ mA} = 1 \text{ k}\Omega$$
$$R_s = S_{dc} \times \text{range} - R_m = 1 \text{ k}\Omega/\text{V} \times 0.45\, E_{rms} - R_m$$
$$= 1 \text{ k}\Omega/\text{V} \times 0.45 \text{ V} \times 10 \text{ V} - 200\ \Omega$$
$$= 4500 - 200$$
$$= 4.3 \text{ k}\Omega$$

Method 2

$$R_s = \frac{0.45 \times E_{rms}}{1 \text{ mA}} - R_m = \frac{0.45 \times 10}{1 \text{ mA}} - 200$$
$$= 4.5 \text{ k} - 0.2 \text{ k}$$
$$= 4.3 \text{ k}\Omega$$

AC VOLTMETER USING FULL WAVE RECTIFIER 4.14

Consider the circuit shown in Fig. 4.20. The peak value of a 10 V rms signal is

$$E_p = 1.414 \times E_{rms}$$
$$= 1.414 \times 10 = 14.14 \text{ V peak}$$

Average value is

$$E_{av} = 0.636 \times E_{peak}$$
$$= 14.14 \times 0.636 = 8.99 \text{ V}$$
$$\cong 9 \text{ V}$$

Therefore, we can see that a 10 V rms voltage is equal to a 9 V dc for full scale deflection, i.e. the pointer will deflect to 90% of full scale, or

Sensitivity (ac) = 0.9 × Sensitivity (dc)

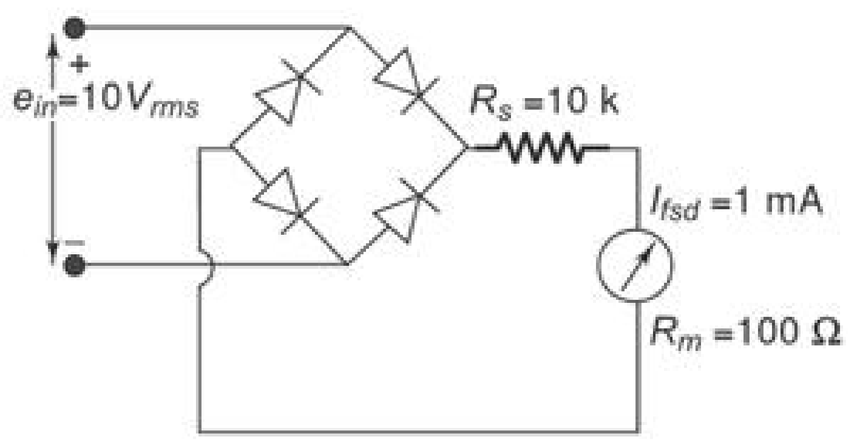


Fig. 4.20 ac voltmeter using full wave rectifier

Example 4.16 *Calculate the value of the multiplier resistor required for a 100 Vrms range on the voltmeter shown in Fig 4.21.*

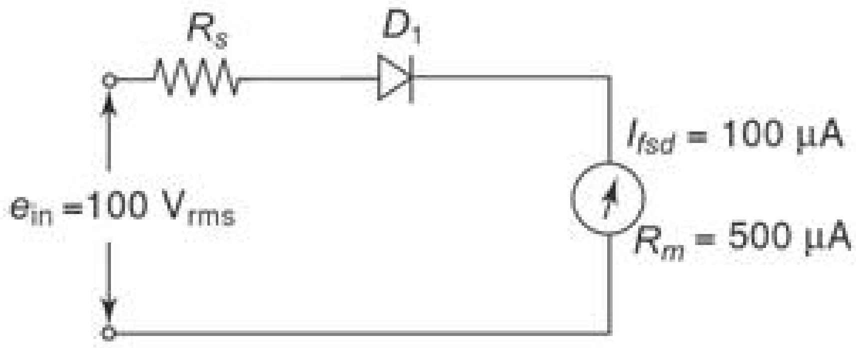


Fig. 4.21

Solution

Method 1 Sensitivity of the voltmeter is given by

$$S_{dc} = 1/I_{fsd} = 1/100\ \mu A = 10^6/100 = 10\ k\Omega/V$$

$$R_s = S_{dc} \times \text{range} - R_m = 10\ k\Omega/V \times 0.45\ V \times 100 - 500\ \Omega$$
$$= 450\ k\Omega - 500\ \Omega = 449.5\ k\Omega$$

Method 2

$$R_s = \frac{0.45 \times E_{rms}}{I_{dc}} - R_m = \frac{0.45 \times 100}{100\ \mu A} - 500\ \Omega$$
$$= 0.45 \times 10^{6} - 500\ \Omega$$
$$= 450\ k\Omega - 500\ \Omega = 449.5\Omega$$

Example 4.17 *Calculate the value of the multiplier resistor for a 50 Vrms ac range on the voltmeter as shown in Fig 4.22.*

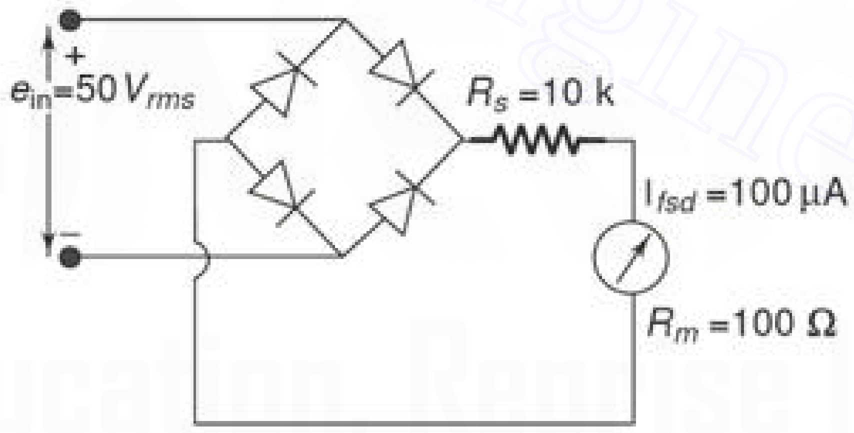


Fig. 4.22

Solution Given $I_{fsd} = 100\ \mu A$, $R_m = 100\ \Omega$

Step 1: The dc sensitivity is given by

$$S_{dc} = 1/I_{fsd} = 1/100\ \mu A = 10^6/100 = 10\ k\Omega/V$$

Step 2: Ac sensitivity = 0.9 × dc sensitivity

$$S_{ac} = 0.9 \times S_{dc} = 0.9 \times 10\ k\Omega/V = 9\ k\Omega/V$$

Step 3: The multiplier resistor is given by

$$R_s = S_{ac} \times \text{range} - R_m$$
$$= 9\ k\Omega/V \times 50\ \text{Vrms} - 100\Omega$$
$$= 450\ K - 100\ \Omega = 449.9\ k\Omega$$

Example 4.18 *Calculate the value of the multiplier resistor for a 10 V rms ac range on the voltmeter in Fig. 4.23.*

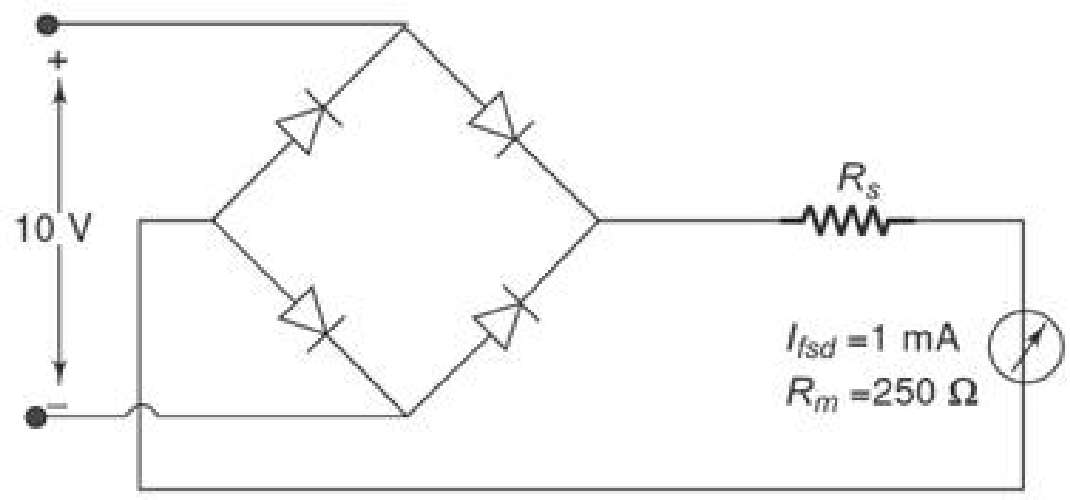


Fig. 4.23

Solution The dc sensitivity is given by

$$S_{dc} = 1/I_{fsd} = 1/1 \text{ mA} = 1 \text{ k}\Omega/\text{V}$$

Therefore

$$\text{AC sensitivity} = 0.9 \times \text{dc sensitivity}$$

$$S_{ac} = 0.9 \times 1 \text{ k}\Omega/\text{V} = 0.9 \text{ k}\Omega/\text{V}$$

The multiplier resistor is given by

$$\begin{aligned} R_s &= S_{\text{ac}} \times \text{range} - R_m = 0.9 \text{ k}\Omega/\text{V} \times 10 \text{ V} - 250 \\ &= 900 \times 10 - 250 \\ &= 9000 - 250 \\ &= 8750 \\ &= 8.75 \text{ k}\Omega \end{aligned}$$

Example 4.19 *Determine the reading obtained with a dc voltmeter in the circuit Fig. Ex4.19, when the switch is set to position A, then set the switch to position B and determine the reading obtained with a half-wave rectifier and fullwave rectifier ac voltmeter.*

All meters use a 100 μA full scale deflection meter movement and are set on 10 V dc or rms ranges.

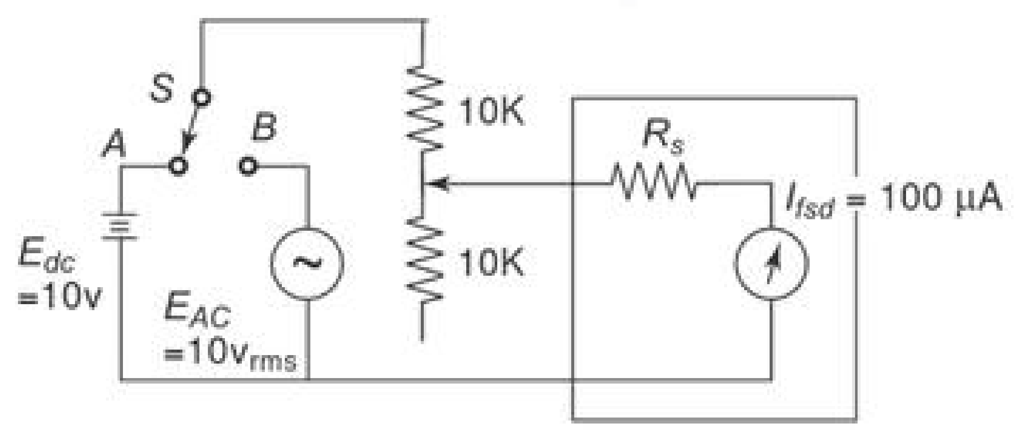


Fig. Ex4.19

Solution

Step 1: The sensitivity with a dc voltmeter is calculated as follows:

$$S_{dc} = 1/I_{fsd} = 1/100 \text{ μA} = 10 \text{ k}\Omega/\text{V}$$

Step 2: The multiplier resistor R_s can be calculated as follows:

$$R_s = S_{dc} \times \text{range} = 10 \text{ k}\Omega/\text{V} \times 10\text{V} = 100 \text{ k}\Omega$$

Step 3: The voltage across resistor R_2 read by the voltmeter can be obtained as follows:

$$ER_2 = \frac{R_2 // R_s}{R_1 + R_2 // R_s} \times e = \frac{10\text{ k} // 100\text{ k}}{10\text{ k} + 10\text{ k} // 100\text{ k}} \times 10\text{ V}$$

$$= \frac{9.09\text{ k}}{10\text{ k} + 9.09\text{ k}} \times 10\text{ V} = \frac{9.09\text{ k}}{19.09\text{ k}} \times 10\text{ V} = 4.76\text{ V}$$

Step 4: The reading obtained with ac voltmeter using a half-wave rectifier is calculated as follows:

$$S_{hw} = 0.45 \times S_{dc} = 0.45 \times 10\text{ k}\Omega/\text{V} = 4.5\text{ k}\Omega/\text{V}$$
$$R_s = S_{dc} \times \text{range} = 4.5\text{ k}\Omega/\text{V} \times 10\text{V} = 45\text{ k}\Omega$$

Step 5: The voltage read by the ac voltmeter is calculated as follows:

$$E = \frac{R_2 // R_s}{R_1 + R_2 // R_s} \times E = \frac{45\text{ k} // 10\text{ k}}{10\text{ k} + 10\text{ k} // 45\text{ k}} \times 10\text{ V}$$

$$= \frac{8.18\text{ k}}{10\text{ k} + 8.18\text{ k}} \times 10\text{ V} = \frac{8.18\text{ k}}{18.18\text{ k}} \times 10\text{ V} = 4.499\text{ V}$$

Step 6: And finally the reading obtained with ac voltmeter using full-wave rectifier is calculated as follows:

$$S_{fw} = \frac{0.90 \times S_{dc}}{V} = 0.90 \times 10\text{ k}\Omega/\text{V} = 9.0\text{ k}\Omega/\text{V}$$
$$R_s = S_{fw} \times \text{range} = 9.0\text{ k}\Omega/\text{V} \times 10\text{V} = 90\text{ k}\Omega$$

Step 7: The voltage read by the ac voltmeter is calculated as follows:

$$E = \frac{R_2 // R_s}{R_1 + R_2 // R_s} \times E = \frac{90\text{ K} // 10\text{ k}}{10\text{ k} + 10\text{ k} // 90\text{ k}} \times 10\text{ V}$$

$$= \frac{9\text{ k}}{10\text{ k} + 9\text{ k}} \times 10\text{ V} = \frac{9\text{ k}}{19\text{ k}} \times 10\text{ V} = 4.73\text{ V}$$

As can be seen an ac voltmeter using half wave or full wave rectifier has more loading effect than dc voltmeter.

MULTIRANGE AC VOLTMETER 4.15

Figure 4.24 is circuit for measuring ac voltages for different ranges. Resistances R_1, R_2, R_3 and R_4 form a chain of multipliers for voltage ranges of 1000 V, 250 V, 50 V, and 10 V respectively.

On the 2.5 V range, resistance R_5 acts as a multiplier and corresponds to the multiplier R_s shown in Fig. 4.17.

R_{sh} is the meter shunt and acts to improve the rectifier operation.

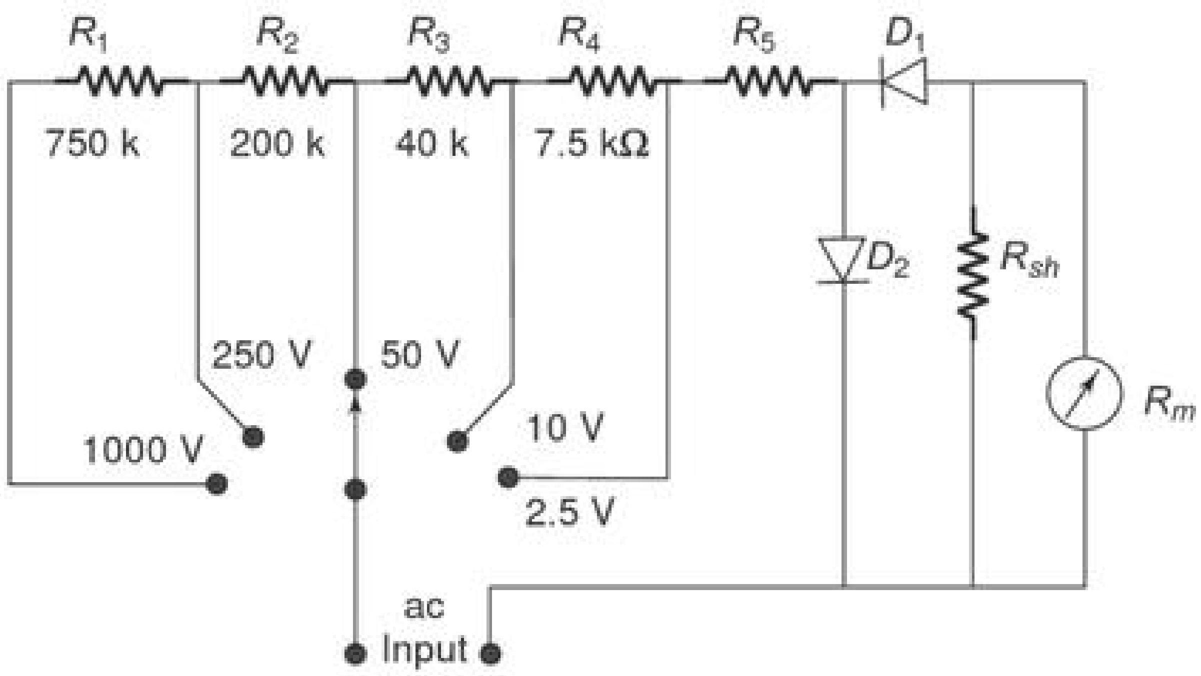


Fig. 4.24 Multirange ac voltmeter

AVERAGE RESPONDING VOLTMETER 4.16

A simplified version of a circuit used in a typical average responding voltmeters is given in Fig. 4.25.

The applied waveform is amplified in a high gain stabilised amplifier to a reasonably high level and then rectified and fed to a dc mA meter calibrated in terms of rms input voltage. In this meter instrument, the rectified current is averaged by a filter to produce a steady deflection of the meter pointer. A dc component in the applied voltage is excluded from the measurement by an input blocking capacitor preceding the high gain amplifier.

The ac amplifier has a large amount of negative feedback, which ensures gain stability for measurement accuracy, and an increased frequency range of the instrument. The inclusion of the meter in the feedback path minimises the effect of diode non-linearity and meter impedance variations on the circuit performance.

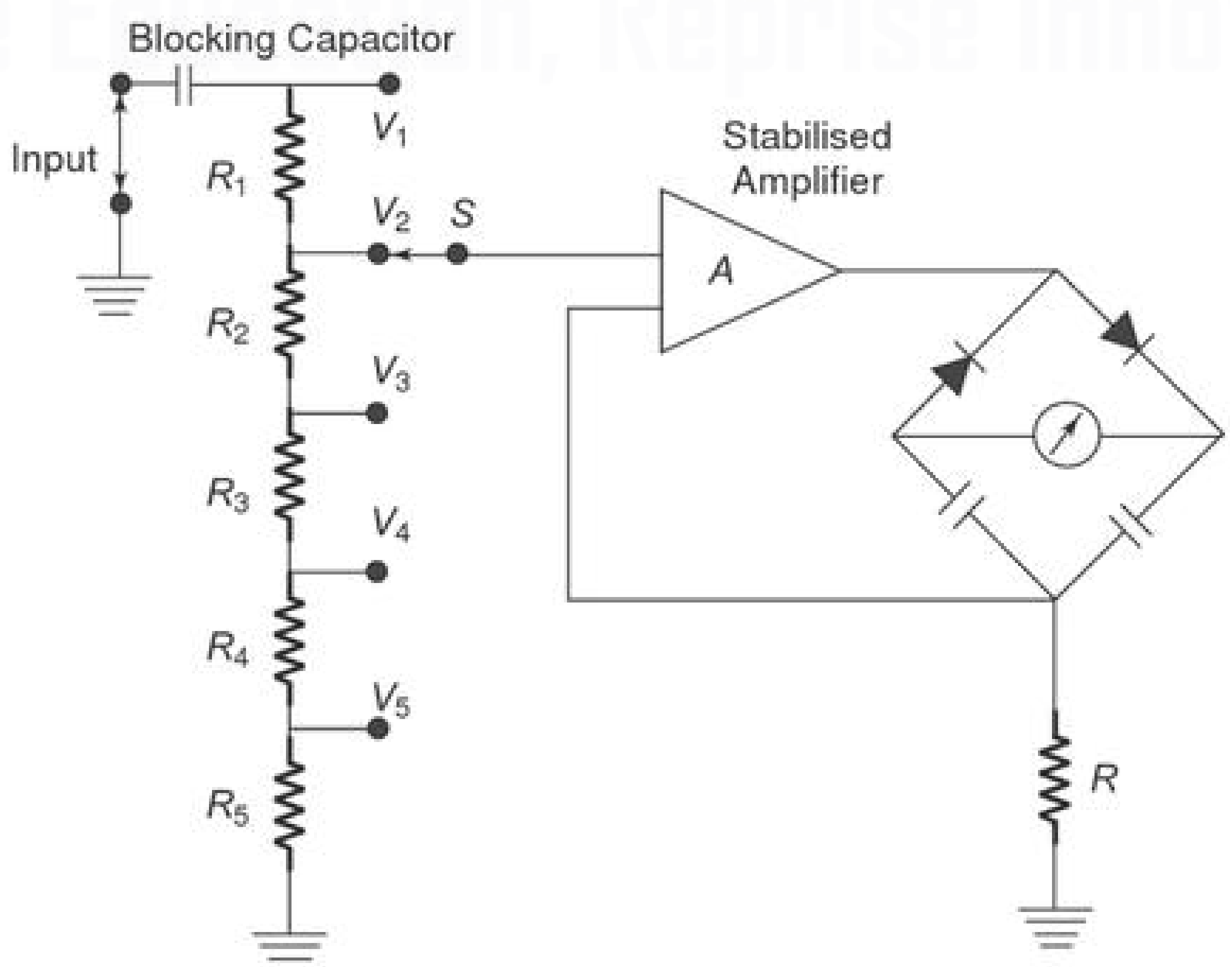


Fig. 4.25 Block diagram of average responding voltmeter

Capacitors in the meter circuit tend to act as storage or filter capacitors for the rectifier diodes as well as coupling capacitors for the feedback signal. The diodes acts as switches to maintain unidirectional meter current despite changes in the instantaneous polarity of the input voltage.

Errors in the reading of an average responding voltmeter may be due to the application of complex waveforms, i.e. a distorted or nonsinusoidal input or the presence of hum or noise.

The accuracy with which an average responding voltmeter indicates the rms value of a wave with harmonic content depends not only on the amplitude of the harmonic but also on the phase.

PEAK RESPONDING VOLTMETER 4.17

The basic difference between peak responding voltmeters and average responding voltmeters is the use of storage capacitors with the rectifying diode in the former case. The capacitor charges through the diode to the peak value of the applied voltage and the meter circuit then responds to the capacitor voltage.

The two most common types of peak responding voltmeters are given in Figs 4.26 (a) and (b).

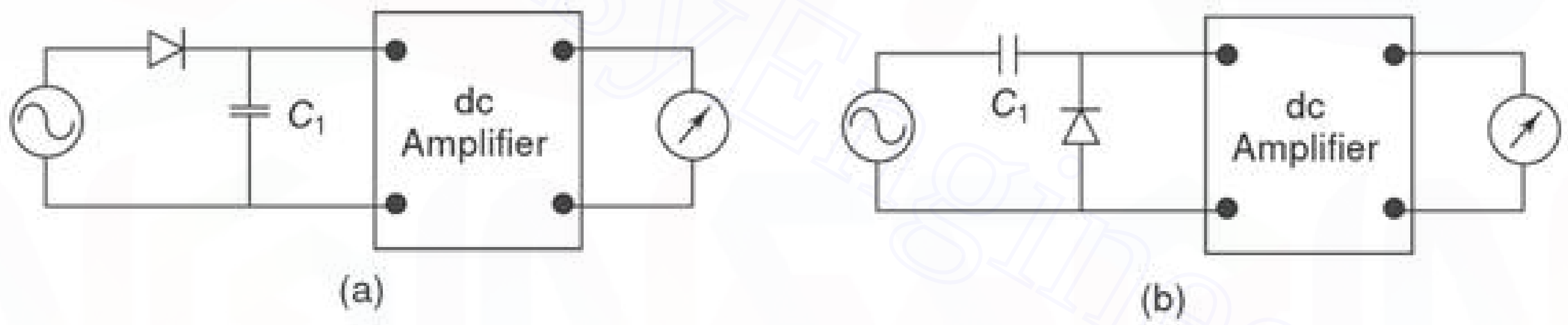


Fig. 4.26 Peak responding voltmeter

Figure 4.26 (a) shows a dc coupled peak voltmeter, in which the capacitor charges to the total peak voltage above ground reference. In this case the meter reading will be affected by the presence of dc with ac voltage.

In Fig. 4.26 (b), an ac coupled peak voltmeter circuit is shown. In both the circuits, the capacitor discharges very slowly through the high impedance input of the dc amplifier, so that a negligible small amount of current supplied by the circuit under test keeps the capacitor charged to the peak ac voltage. The dc amplifier is used in the peak responding meter to develop the necessary meter current.

The primary advantage of a peak responding voltmeter is that the rectifying diode and the storage capacitor may be taken out of the instrument and placed in the probe when no ac pre-amplification is required. The measured ac signal then travels no farther than the diode. The peak responding voltmeter is then able to measure frequencies of up to 100s of MHz with a minimum of circuit loading. The disadvantage of peak responding voltmeters is the error caused due to harmonic distortion in the input waveforms and limited sensitivity of the instrument because of imperfect diode characteristics.

TRUE RMS VOLTMETER 4.18

Complex waveform are most accurately measured with an rms voltmeter. This instrument produces a meter indication by sensing waveform heating power, which is proportional to the square of the rms value of the voltage. This heating power can be measured by amplifying and feeding it to a thermocouple, whose output voltages is then proportional to the E_{rms}.

However, thermocouples are non-linear devices. This difficulty can be overcome in some instruments by placing two thermocouples in the same thermal environment.

Figure 4.27 shows a block diagram of a true rms responding voltmeter.

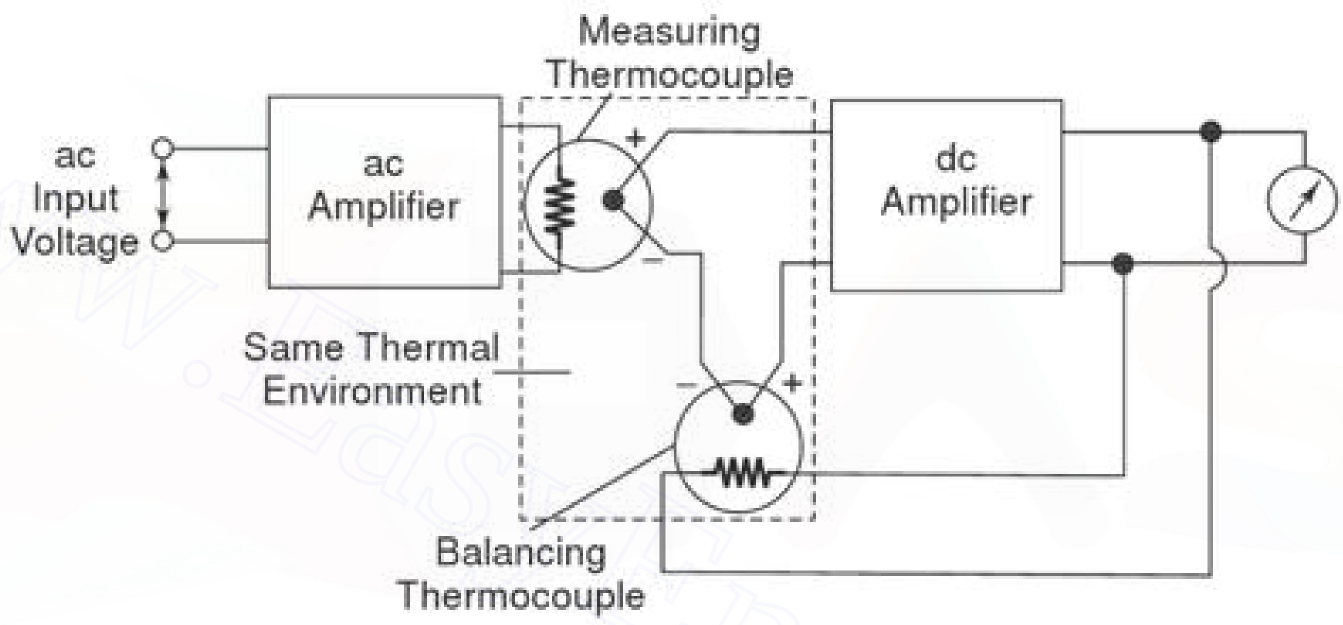


Fig. 4.27 True RMS voltmeter (Block diagram)

The effect of non-linear behaviour of the thermocouple in the input circuit (measuring thermocouple) is cancelled by similar non-linear effects of the thermocouple in the feedback circuit (balancing thermocouple). The two couples form part of a bridge in the input circuit of a dc amplifier.

The unknown ac voltage is amplified and applied to the heating element of the measuring thermocouple. The application of heat produces an output voltage that upsets the balance of the bridge.

The dc amplifier amplifies the unbalanced voltage; this voltage is fed back to the heating element of the balancing thermocouple, which heats the thermocouple, so that the bridge is balanced again, i.e. the outputs of both the thermocouples are the same. At this instant, the ac current in the input thermocouple is equal to the dc current in the heating element of the feedback thermocouple. This dc current is therefore directly proportional to the effective or rms value of the input voltage, and is indicated by the meter in the output circuit of the dc amplifier. If the peak amplitude of the ac signal does not exceed the dynamic range of the ac amplifier, the true rms value of the ac signal can be measured independently.

TRUE RMS METER 4.19

There exists a fundamental difference between the readings on a normal ac meter and on a true rms meter. The first uses a D'Arsonval movement with a full or half wave rectifier, and averages the values of the instantaneous rectified current.

The rms meter, however, averages the squares of the instantaneous current values (proportional, for example, to the instantaneous heating effect). The scale of the true rms meter is calibrated in terms of the square roots of the indicated current values. The resulting reading is therefore the square root of the average of the squared instantaneous input values, which is the rms value of the measured alternating current.

A true rms meter is always a combination of a normal mean value indicating meter and a squaring device whose output at any instant is proportional to the instantaneous squared input.

It can be shown that the ac component of the voltage developed across the common collector resistors of two transistors that are connected in parallel, and between the bases of which a small ac voltage is applied, is proportional to the square of the applied input voltage.

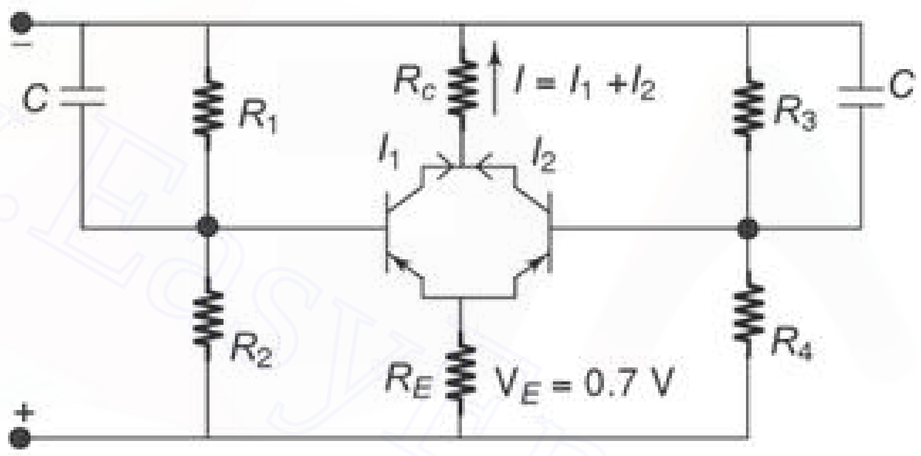


Fig. 4.28 Squaring device

The basic circuit of Fig. 4.28 employing two transistors is completed by a bridge arrangement in which the dc component is cancelled out. This bridge arrangement is given in Fig. 4.29.

One side of the bridge consists of two parallel connected transistors Q_2 and Q_3, and a common collector resistor R_{13}. The side of the bridge, employing P_1 for bias setting, is the basic squaring circuit. The other side of the bridge is made of transistor Q_4 (whose base is biased by means of potentiometer P_2 and collector resistance R_{16}.)

Potentiometer P_1,base bias balance of the squaring circuit, must be adjusted for symmetrical operation of transistors Q_2 and Q_3. To do this, the polarity of a small dc input voltage applied to terminals A and B (bases of Q_2 and Q_3) has to be reversed, and the reading of the output meter must be the same for both input polarities.

Potentiometer P_2 must be set so that for zero input signal (terminals A and B short-circuited), the bridge is balanced and the meter reads zero. The balance condition is reached if the voltage drop across the collector resistance R_{13} of $Q_2 - Q_3$, and collector resistance R_{16} of Q_4, are equal.

Transistor Q_1 is used to improve the temperature stability of the whole circuit, which is basically obtained by the emitter resistance R_{10}. Optimum temperature compensation is obtained if the voltage drop across the emitter resistance for no signal is 0.7 V for silicon transistor.

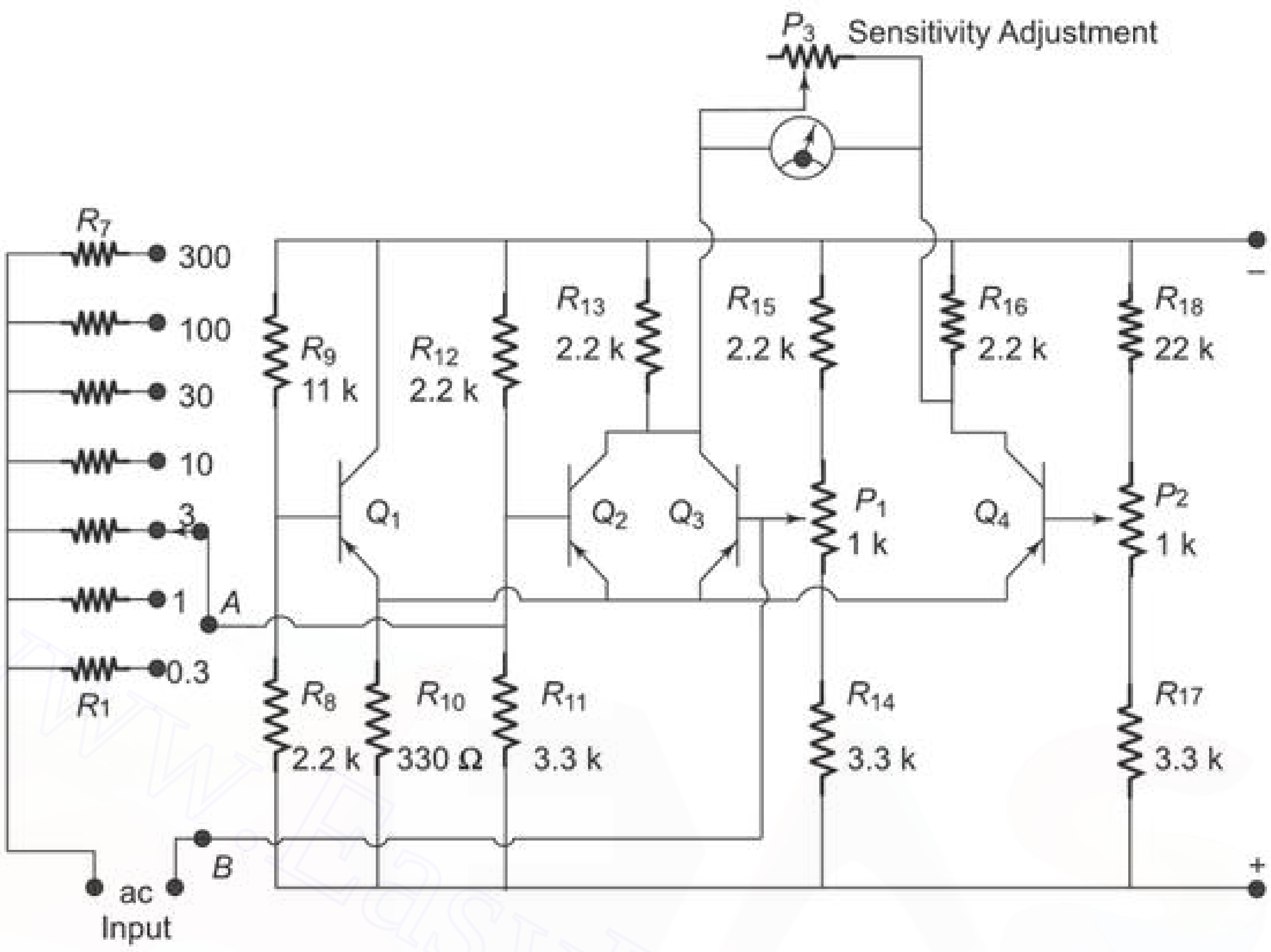


Fig. 4.29 True RMS meter

The low current through Q_2, Q_3, Q_4 requires a large emitter resistance value to fulfil the condition for compensation. Therefore, another transistor, Q_1 has been added to compensate for the temperature changes of Q_2 and Q_3.

The bias on this transistor has to be adjusted by selecting appropriate values of R_8 and R_9 so that the voltage drop across R_{10} in the balanced condition is 0.7 V for silicon transistor.

The input of the squaring devices (*AB*) is connected to a voltage divider that is calibrated in seven ranges, namely 0.3, 1, 3, 10, 30, 100, and 300 volts.

CONSIDERATIONS IN CHOOSING AN ANALOG VOLTMETER 4.20

In choosing an analog voltmeter the following factors are to be considered.

1. Input Impedance The input impedance or resistance of the voltmeter should be as high as possible. It should always be higher than the impedance of the circuit under measurement to avoid the loading effect, discussed in Section 4.6.

The shunt capacitance across the input terminals also determines the input impedance of the voltmeter. At higher frequencies the loading effect of the meter is noticeable, since the shunt capacitance reactance falls and the input shunt reduces the input impedance.

2. Voltage Ranges The voltage ranges on the meter scale may be in a 1–3–10 sequence with 10 db separation or a 1.5–5–15 sequence or in a single scale calibrated in decibels. In any case, the scale division should be compatible with the accuracy of the instrument.

3. Decibels For measurements covering a wide range of voltages, the use of the decibel scale can be very effective, e.g., in the frequency response curve of an amplifier, where the output voltage is measured as a function of the frequency of the applied input voltage.

4. Sensitivity v/s Bandwidth Noise consists of unwanted frequencies. Since noise is a function of the bandwidth, a voltmeter with a narrow bandwidth picks up less noise than a large bandwidth voltmeter.

In general, an instrument with a bandwidth of 10 Hz–10 MHz has a sensitivity of 1 mV. Some voltmeters whose bandwidth extends up to 5 MHz may have a sensitivity of 100 μV.

5. Battery Operation A voltmeter (VTVM) powered by an internal battery is essential for field work.

6. AC Current Measurements Current measurements can be made by a sensitive ac voltmeter and a series resistor.

To summarise, the general guidelines are as follows.

(i) For dc measurement, select the meter with the widest capability meeting the requirements of the circuit.

(ii) For ac measurements involving sine waves with less than 10% distortion, the average responding voltmeter is most sensitive and provides the best accuracy.

(iii) For high frequency measurement (> 10 MHz), the peak responding voltmeter with a diode probe input is best. Peak responding circuits are acceptable if inaccuracies caused by distortion in the input waveform are allowed (tolerated).

(iv) For measurements where it is important to find the effective power of waveforms that depart from the true sinusoidal form, the rms responding voltmeter is the appropriate choice.

OHMMETER (SERIES TYPE OHMMETER) 4.21

A D'Arsonval movement is connected in series with a resistance R_1 and a battery which is connected to a pair of terminals A and B, across which the unknown resistance is connected. This forms the basic type of series ohmmeter, as shown in Fig. 4.30 (a).

The current flowing through the movement then depends on the magnitude of the unknown resistance. Therefore, the meter deflection is directly proportional to the value of the unknown resistance.

Referring to Fig. 4.30 (a)

R_1 = current limiting resistance
R_2 = zero adjust resistance
V = battery
R_m = meter resistance
R_x = unknown resistance

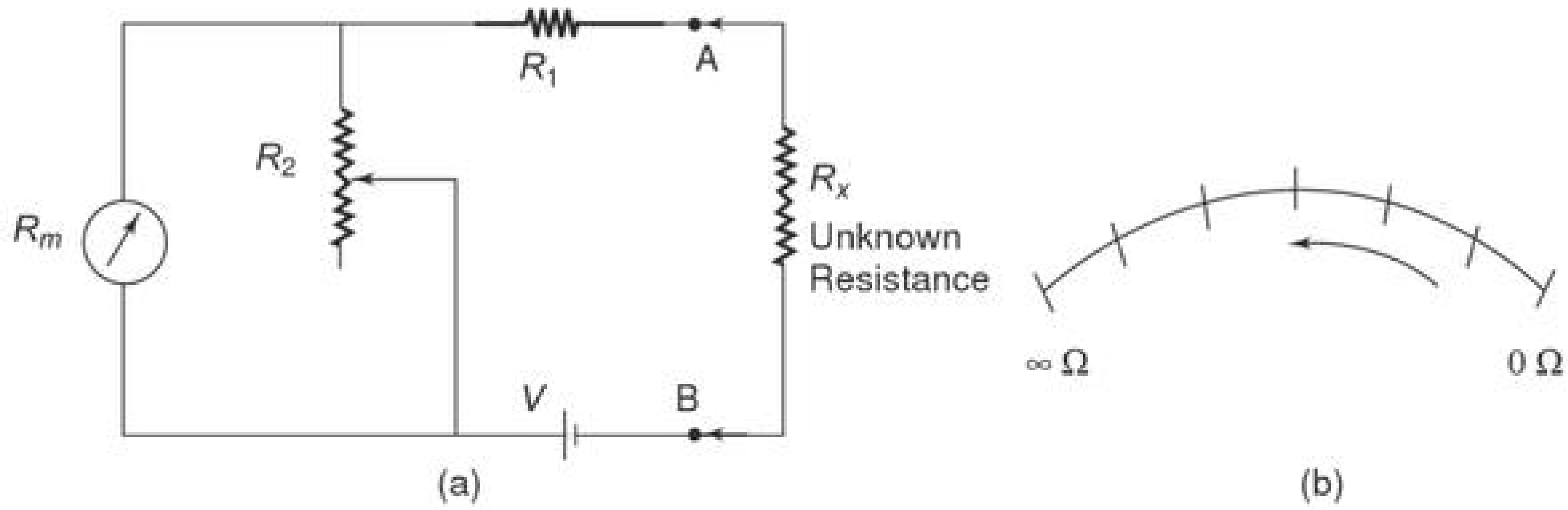


Fig. 4.30 (a) Series type ohmmeter (b) Dial of series ohmmeter

4.21.1 Calibration of the Series Type Ohmmeter

To mark the "0" reading on the scale, the terminals *A* and *B* are shorted, i.e. the unknown resistance $R_x = 0$, maximum current flows in the circuit and the shunt resistance R_2 is adjusted until the movement indicates full scale current (I_{fsd}). The position of the pointer on the scale is then marked "0" ohms.

Similarly, to mark the "∞" reading on the scale, terminals *A* and *B* are open, i.e. the unknown resistance $R_x = \infty$, no current flow in the circuit and there is no deflection of the pointer. The position of the pointer on the scale, is then marked as "∞" ohms.

By connecting different known values of the unknown resistance to terminals *A* and *B*, intermediate markings can be done on the scale. The accuracy of the instrument can be checked by measuring different values of standard resistance, i.e. the tolerance of the calibrated resistance, and noting the readings.

A major drawback in the series ohmmeter is the decrease in voltage of the internal battery with time and age. Due to this, the full scale deflection current drops and the meter does not read "0" when *A* and *B* are shorted. The variable shunt resistor R_2 across the movement is adjusted to counteract the drop in battery voltage, thereby bringing the pointer back to "0" ohms on the scale.

It is also possible to adjust the full scale deflection current without the shunt R_2 in the circuit, by varying the value of R_1 to compensate for the voltage drop. Since this affects the calibration of the scale, varying by R_2 is much better solution. The internal resistance of the coil R_m is very low compared to R_1. When R_2 is varied, the current through the movement is increased and the current through R_2 is reduced, thereby bringing the pointer to the full scale deflection position.

The series ohmmeter is a simple and popular design, and is used extensively for general service work.

Therefore, in a series ohmmeter the scale marking on the dial, has "0" on the right side, corresponding to full scale deflection current, and "∞" on the left side corresponding to no current flow, as given in Fig. 4.30 (b).

Values of R_1 and R_2 can be determined from the value of R_x which gives half the full scale deflection.

$$R_h = R_1 + R_2 \parallel R_m = R_1 + \frac{R_2 R_m}{R_2 + R_m}$$

where R_h = half of full scale deflection resistance.

The total resistance presented to the battery then equals $2R_h$ and the battery current needed to supply half scale deflection is $I_h = V/2\,R_h$.

To produce full scale current, the battery current must be doubled.

Therefore, the total current of the ckt, $I_t = V/R_h$

The shunt current through R_2 is given by $I_2 = I_t - I_{fsd}$

The voltage across shunt, V_{sh}, is equal to the voltage across the meter.

Therefore $\quad V_{sh} = V_m$

$$I_2 R_2 = I_{fsd} R_m$$

Therefore $\quad R_2 = \dfrac{I_{fsd} R_m}{I_2}$

But $\quad I_2 = I_t - I_{fsd}$

$\therefore \quad R_2 = \dfrac{I_{fsd} R_m}{I_t - I_{fsd}}$

But $\quad I_t = \dfrac{V}{R_h}$

Therefore $\quad R_2 = \dfrac{I_{fsd} R_m}{V/R_h - I_{fsd}}$

Therefore $\quad R_2 = \dfrac{I_{fsd} R_m R_h}{V - I_{fsd} R_h} \qquad (4.1)$

As $\quad R_h = R_1 + \dfrac{R_2 R_m}{R_2 + R_m}$

Therefore $\quad R_1 = R_h - \dfrac{R_2 R_m}{R_2 + R_m}$

Hence $\quad R_1 = R_h - \dfrac{\dfrac{I_{fsd} R_m R_h}{V - I_{fsd} R_h} \times R_m}{\dfrac{I_{fsd} R_m R_h}{V - I_{fsd} R_h} + R_m}$

Therefore $\quad R_1 = R_h - \dfrac{I_{fsd} R_m R_h}{V} \qquad (4.2)$

Hence, R_1 and R_2 can be determined.

Example 4.20 *A 100 Ω basic movement is to be used as an ohmmeter requiring full scale deflection of 1 mA and internal battery voltage of 3 V. A half scale deflection marking of 1 kΩ is required. Calculate*

(i) the value of R_1 and R_2 (ii) Maximum value of R_2 to compensate for a 3% drop in battery voltage

Solution Given $I_m = 1$ mA, $R_m = 100\ \Omega$, $R_h = 1\ k\Omega$, $V = 3V$

(i) To find R_1 and R_2

Step 1:

$$R_1 = R_h - \frac{I_{fsd} \times R_m \times R_h}{V} = 1\ k\Omega - \frac{1\ mA \times 100\ \times 1\ k\Omega}{3}$$

$$= 1\ k\Omega - \frac{100}{3} = 1000\ \Omega - 33.3\ \Omega$$

$$= 966.7\ \Omega$$

Step 2:

$$R_2 = \frac{I_{fsd} \times R_m \times R_h}{V - I_{fsd} \times R_h} = -\frac{1\ mA \times 100\ \times 1\ k\Omega}{3 - 1\ mA \times 1\ k\Omega} = \frac{100}{3-1} = \frac{100}{2} = 50\ \Omega$$

Step 3:

(ii) The internal battery voltage is 3 V. 3% of 3 V is .09 V.

Therefore, the battery voltage drop with 3% drop is 3 V – .09 V = 2.91V

$$R_2 = \frac{I_{fsd} \times R_m \times R_h}{V - I_{fsd} \times R_h} = -\frac{1\ mA \times 100\ \times 1\ k\Omega}{2.91 - 1\ mA \times 1\ k\Omega} = \frac{100}{2.91-1} = \frac{100}{1.91} = 52.36\ \Omega$$

$$R_2 = 52.36\ \Omega$$

Example 4.21 *A 100 Ω basic movement is to be used as an ohmmeter requiring a full scale deflection of 1 mA and internal battery voltage of 3 V. A half scale deflection marking of 2 k is desired. Calculate (i) value of R_1 and R_2, and (ii) The maximum value of R_2 to compensate for a 5% drop in battery voltage.*

Solution (i) Using the equations for R_1 and R_2 we have,

$$R_1 = R_h - \frac{I_{fsd} \times R_m \times R_h}{V} \quad \text{and} \quad R_2 = \frac{I_{fsd} \times R_m \times R_h}{V - (I_{fsd} \times R_h)}$$

Hence $$R_1 = 2\ k - \frac{1\ mA \times 100 \times 2\ k}{3} = 2\ k - \frac{200}{3} = 2\ k - 66.6$$

Therefore $$R_1 = 2000 - 66.6 = 1933.3\ \Omega$$

$$R_2 = \frac{1\ mA \times 100 \times 2\ k}{3 - 1\ mA \times 2\ k} = \frac{200}{1} = 200\ \Omega$$

(ii) The internal battery voltage is 3 V, therefore 5% of 3 V is 0.15 V. The battery voltage with 5% drop is 3 V – 0.15 V = 2.85 V.

$$R_2 = \frac{I_{fsd} \times R_h \times R_m}{V - I_{fsd} \times R_h} = \frac{1\text{ mA} \times 100 \times 2\text{ k}}{2.85\text{ V} - 1\text{ mA} \times 2\text{ k}} = \frac{200}{0.85} = 235.29\ \Omega$$

Example 4.22 *A 1 mA full scale deflection (fsd) current meter movement is to be used as an ohmmeter circuit. The meter movement has an internal resistance of 100 Ω and a 3 V battery will be used in the circuit. Mark off the meter face (dial) for reading resistance.*

Solution

Step 1: The value of R_s which will limit current to full scale deflection current can be calculated as

$$R_s = \frac{E}{I_m} - R_m = \frac{3}{1\text{ mA}} - 100\ \Omega = 3\text{ k}\Omega - 100\ \Omega = 2.9\text{ k}\Omega$$

Step 2: The value of R_x with a 20% deflection is

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) \qquad \text{where } P = \frac{I}{I_m} = 20\% = \frac{20}{100} = 0.2$$

Therefore,
$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m)$$
$$= \frac{(2.9\text{ k}\Omega + 0.1\text{ k}\Omega)}{0.2} - (2.9\text{ k}\Omega + 0.1\text{ k}\Omega)$$
$$R_x = \frac{3\text{ k}\Omega}{0.2} - 3\text{ k}\Omega = 15\text{ k}\Omega - 3\text{ k}\Omega = 12\text{ k}\Omega$$

Step 3: The value of R_x with a 40% deflection is

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) \qquad \text{where } P = \frac{I}{I_m} = 40\% = \frac{40}{100} = 0.4$$

Therefore,

$$R_x = \frac{(R_s + R_m)}{4} - (R_s + R_m) = \frac{(2.9\text{ k}\Omega + 0.1\text{ k}\Omega)}{0.4} - (2.9\text{ k}\Omega + 0.1\text{ k}\Omega)$$
$$R_x = \frac{3\text{ k}\Omega}{0.4} - 3\text{ k}\Omega = 7.5\text{ k}\Omega - 3\text{ k}\Omega = 4.5\text{ k}\Omega$$

Step 4: The value of R_x with a 50% deflection is

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) \qquad \text{where } P = \frac{I}{I_m} = 50\% = \frac{50}{100} = 0.5$$

Therefore,

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) = \frac{(2.9\text{ k}\Omega + 0.1\text{ k}\Omega)}{0.5} - (2.9\text{ k}\Omega + 0.1\text{ k}\Omega)$$

$$R_x = \frac{3\text{ k}\Omega}{0.5} - 3\text{ k}\Omega = 6\text{ k}\Omega - 3\text{ k}\Omega = 3\text{ k}\Omega$$

Step 5: The value of R_x with a 75% deflection is

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) \qquad \text{where } P = \frac{I}{I_m} = 75\% = \frac{75}{100} = 0.75$$

Therefore,

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) = \frac{(2.9\text{ k}\Omega + 0.1\text{ k}\Omega)}{0.75} - (2.9\text{ k}\Omega + 0.1\text{ k}\Omega)$$

$$R_x = \frac{3\text{ k}\Omega}{0.75} - 3\text{ k}\Omega = 4\text{ k}\Omega - 3\text{ k}\Omega = 1\text{ k}\Omega$$

Step 6: The value of R_x with a 90% deflection is

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) \qquad \text{where } P = \frac{I}{I_m} = 90\% = \frac{90}{100} = 0.90$$

Therefore,

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) = \frac{(2.9\text{ k}\Omega + 0.1\text{ k}\Omega)}{0.90} - (2.9\text{ k}\Omega + 0.1\text{ k}\Omega)$$

$$R_x = \frac{3\text{ k}\Omega}{0.90} - 3\text{ k}\Omega = 3.333\text{ k}\Omega - 3\text{ k}\Omega = 0.333\text{ k}\Omega$$

Step 7: The value of R_x with a 100% deflection is

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) \qquad \text{where } P = \frac{I}{I_m} = 100\% = \frac{100}{100} = 1$$

Therefore,

$$R_x = \frac{(R_s + R_m)}{P} - (R_s + R_m) = \frac{(2.9\text{ k}\Omega + 0.1\text{ k}\Omega)}{1} - (2.9\text{ k}\Omega + 0.1\text{ k}\Omega)$$

$$R_x = \frac{3\text{ k}\Omega}{1} - 3\text{ k}\Omega = 3\text{ k}\Omega - 3\text{ k}\Omega = 0$$

Example 4.23 *An ohmmeter is designed around a 1mA meter movement and a 3V battery. If the battery voltage decays to 2.8 V because of aging, calculate the resulting error at the midrange on the ohmmeter scale.*

Solution

Step 1: The total internal resistance of the ohmmeter is

$$R_t = E/I = 3/1\ \text{mA} = 3\ \text{k}\Omega$$

Step 2: The Ohmmeter scale should be marked as 3 kΩ at the midrange. An external resistance of 3 kΩ would cause the pointer to deflect to its midscale range.

Step 3: When the battery voltage decreases to 2.8 V, the ohmmeter is adjusted for full scale deflection by reducing R_s, the total internal resistance of the Ohmmeter.

Therefore, $R_t = E/I = 2.8/1\ \text{mA} = 2.8\ \text{k}\Omega$

Step 4: If a 2.8 kΩ resistor is now measured with the ohmmeter, we would expect less than midscale deflection , however the pointer will deflect to midscale which is marked as 3 kΩ. the aging of the battery has caused an incorrect reading.

Step 5: The % error of this reading is given by

$$\%\,\text{Error} = \frac{3\ \text{k}\Omega - 2.8\ \text{k}\Omega}{3\ \text{k}\Omega} \times 100 = \frac{0.2\ \text{k}\Omega}{3\ \text{k}\Omega} \times 100 = \frac{20}{3} \times 100 = 6.66\%$$

Example 4.24 *Design a series type ohmmeter. The movement requires a 1 mA for full scale deflection and has an internal resistance of 100 Ω. The internal battery used has a voltage of 3 V. The desired value for half scale deflection is 2000 Ω. Calculate*

(a) the values of R_1 and R_2. (b) range of R_2 if the battery voltage varies from 2.8 V to 3.1 V (R_1 is the same as in (a).

Solution Value of R_1 and R_2 can be calculated as

Step 1

$$R_2 = \frac{I_m R_m R_h}{E - I_m R_h} = \frac{1\ \text{mA} \times 100 \times 2\ \text{k}\Omega}{3 - 1\ \text{mA} \times 2\ \text{k}\Omega} = \frac{200}{3-2} = 200\ \Omega$$

Step 2: The internal resistance of the ohmmeter is equal to half scale resistance. Therefore,

$$R_h = R_1 + \frac{R_2 R_m}{R_2 + R_m}$$

Therefore,

$$R_1 = R_h - \frac{R_2 R_m}{R_2 + R_m} = 2000\ \Omega - \frac{200 \times 100}{200 + 100}$$

$$R_1 = 2000\ \Omega - \frac{200 \times \cancel{100}}{\cancel{300}} = 2000\ \Omega - \frac{200}{3} = 2000 - 66.6 = 1933.4\ \Omega$$

$R_1 = 1933.4\ \Omega$ that is series resistance

Step 3: The value of resistance R_2 when battery is 2.7 V.

$$R_2 = \frac{I_m R_m R_h}{E - I_m R_h} = \frac{1\text{ mA} \times 100 \times 2\text{ k}\Omega}{2.7 - 1\text{ mA} \times 2\text{ k}\Omega}$$

$$R_2 = \frac{200}{2.7 - 2} = \frac{200}{0.7} = \frac{2000}{7} \approx 285\ \Omega$$

Step 4: The value of resistance R_2 when battery is 3.1 V

$$R_2 = \frac{1\text{ mA} \times 100 \times 2\text{ k}\Omega}{3.1 - 1\text{ mA} \times 2\text{ k}\Omega} = \frac{200}{3.1 - 2} = \frac{200}{1.1} = \frac{2000}{11} \approx 182\ \Omega$$

Multirange Ohmmeter The ohmmeter circuit shown in Fig. 4.30 (a) is only for a single range of resistance measurement. To measure resistance over a wide range of values, we need to extend the ohmmeter ranges. This type of ohmmeter is called a multirange ohmmeter, shown in Fig. 4.31.

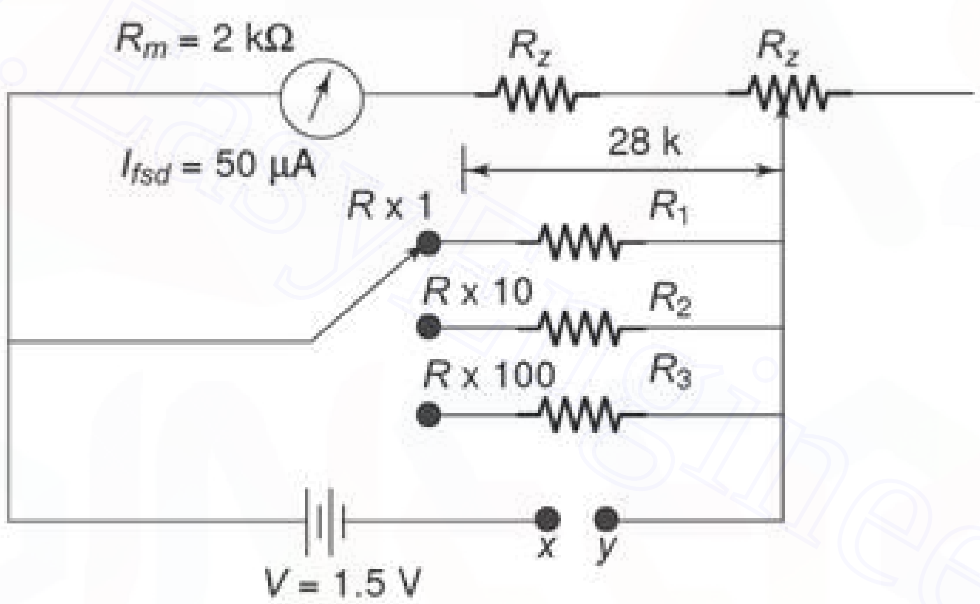


Fig. 4.31 Multirange ohmmeter

SHUNT TYPE OHMMETER 4.22

The shunt type ohmmeter given in Fig. 4.32 consists of a battery in series with an adjustable resistor R_1, and a D'Arsonval movement

The unknown resistance is connected in parallel with the meter, across the terminals A and B, hence the name shunt type ohmmeter.

In this circuit it is necessary to have an ON/OFF switch to disconnect the battery from the circuit when the instrument is not used.

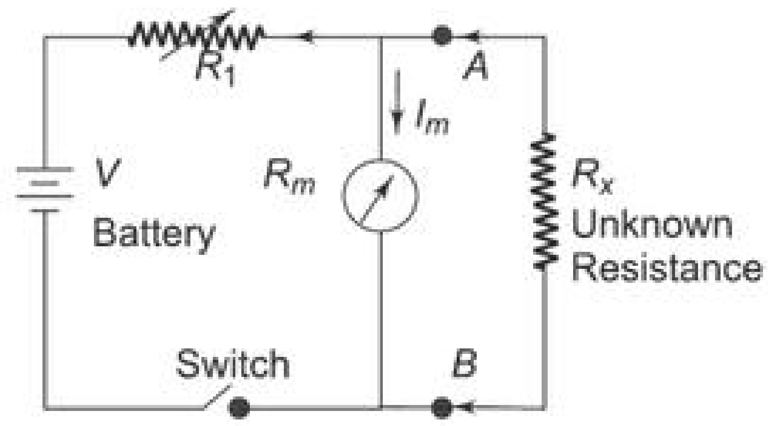


Fig. 4.32 Shunt type ohmmeter

4.22.1 Calibration of the Shunt Type Ohmmeter

To mark the "0" ohms reading on the scale, terminals A and B are shorted, i.e. the unknown resistance $R_x = 0$, and the current through the meter movement is zero, since it is bypassed by the short-circuit. This pointer position is marked as "0" ohms.

Similarly, to mark "∞" on the scale, the terminals A and B are opened, i.e. $R_x = \infty$, and full current flows through the meter movement; by appropriate selection of the value of R_1, the pointer can be made to read full scale deflection current. This position of the pointer is marked "∞" ohms. Intermediate marking can be done by connecting known values of standard resistors to the terminals A and B.

This ohmmeter therefore has a zero mark at the left side of the scale and an ∞ mark at the right side of the scale, corresponding to full scale deflection current as shown in Fig. 4.33.

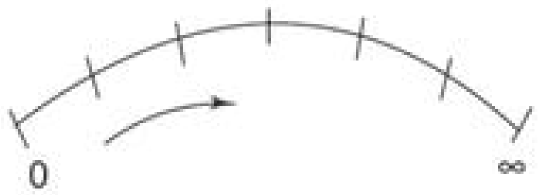


Fig. 4.33 Dial of shunt type ohmmeter

The shunt type ohmmeter is particularly suited to the measurement of low values of resistance. Hence it is used as a test instrument in the laboratory for special low resistance applications.

Example 4.25 *A shunt-type ohmmeter uses a 10 mA basic D'Arsonal movement with an internal resistance of 50 Ω. The battery voltage is 3 V. It is desired to modify the circuit by adding appropriate shunt resistance across the movement so that the instrument indicates 10 Ω at the midpoint scale. Calculate*

(a) the value of shunt resistance (b) value of current limiting resistance R_1.

Solution

Step 1: For half scale definition

$$I_h = 0.5\ \text{mA} \times I_m = 0.5\ \text{mA} \times 10\ \text{mA} = 5\ \text{mA}$$

Step 2: The voltage across the movement

$$V_m = I_m R_m = 5\ \text{mA} \times 50\ \Omega = 250\ \text{mV}$$

Step 3: From the circuit diagram of a shunt-type ohmmeter it is seen that

voltage across unknown resistance = Voltage across meter movement

Step 4: Therefore, current through the unknown resistance

$$I_x = \frac{V_m}{R_h} = \frac{250\ \text{mV}}{10\ \Omega} = 25\ \text{mA}$$

Step 5: Current through the shunt $= I_{sh} = I_x - I_m$

$$I_{sh} = 25\ \text{mA} - 5\ \text{mA} = 20\ \text{mA}$$

Step 6: Therefore, the value of shunt resistance

$$R_{sh} = \frac{250\ \text{mV}}{20\ \text{mA}} = 12.5\ \Omega$$

Step 7:
b) The total battery current

$$I_t = I_x + I_m + I_{sh} = 25 \text{ mA} + 5 \text{ mA} + 20 \text{ mA} = 50 \text{ mA}$$

Step 8: Voltage drop across the limiting resistor

$$= 3 - 250 \text{ mV}$$
$$= 2.75 \text{ V}$$

Step 9: Therefore

$$R_1 = \frac{2.75}{50 \text{ mA}} = \frac{275}{50 \text{ mA}} \times \frac{1}{100} = \frac{275}{5} = 55\ \Omega$$

Example 4.26 *(a) Determine the current through the meter I_m when a 20 Ω resistor is connected across the terminals 'x'and 'y' is measured on R × 1 range.*

(b) Show that this same current flows through the meter movement when a 200 Ω resistor is measured on the R × 100 range.

(c) When a 2 kΩ resistor is measured on the R × 100.

Solution From Fig. 4.31

Step 1:

(a) When the ohmmeter is set on the $R \times 1$ range circuit as shown in Fig Ex4.26 (a).
The voltage across the parallel combination is calculated as

$$V = 3 \times \frac{10\ \Omega}{10\ \Omega + 20\ \Omega} = \frac{30\ \Omega}{30\ \Omega} = 1 \text{ V}$$

Step 2: The current through the meter is calculated as

$$I_m = \frac{1 \text{ V}}{30 \text{ K}} = \frac{1 \text{ mA}}{30} = \frac{100\cancel{0}\ \mu\text{A}}{3\cancel{0}} = 33.3\ \mu\text{A}$$

(b) When the ohmmeter is set on the $R \times 10$ range, circuit as shown in Ex4.26(b).

Step 3: The voltage across the parallel combination is calculated as

$$V = 3 \times \frac{100\ \Omega}{100\ \Omega + 200\ \Omega} = \frac{300\ \Omega}{300\ \Omega} = 1 \text{ V}$$

Step 4: Therefore,

$$I_m = \frac{1 \text{ V}}{30 \text{ k}\Omega} = 33.3\ \mu\text{A}$$

(c) When the ohmmeter is set on $R \times 100$, the circuit is shown in Fig. Ex4.26(c).

Step 5: The voltage across the parallel combination is calculated as

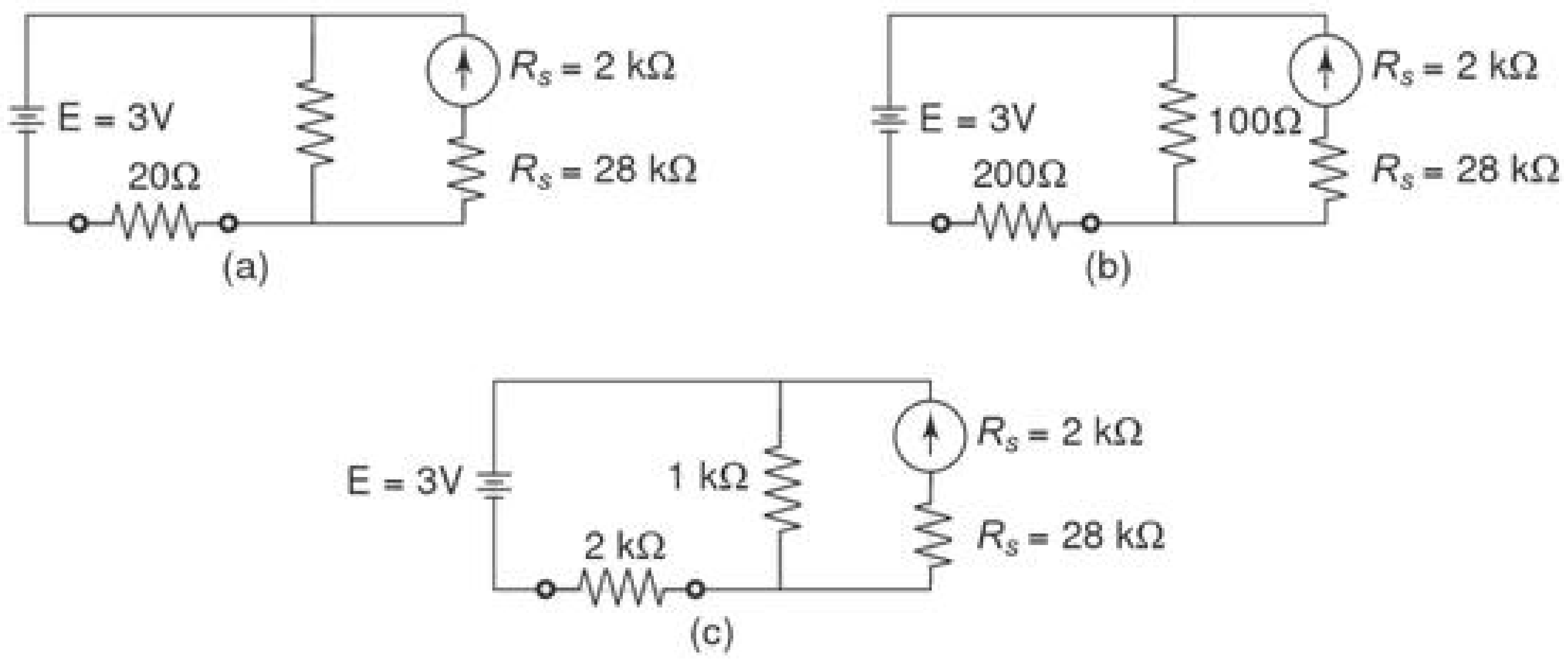


Fig. Ex4.26

$$V = 3 \times \frac{1000\ \Omega}{1000\ \Omega + 2000\ \Omega} = \frac{3000\ \Omega}{3000\ \Omega} = 1\ \text{V}$$

Therefore, $I_m = \dfrac{1\ \text{V}}{30\ \text{k}\Omega} = 33.3\ \mu\text{A}$

CALIBRATION OF DC INSTRUMENT 4.23

The process of calibration involves the comparison of a given instrument with a standard instrument, to determine its accuracy. A dc voltmeter may be calibrated with a standard, or by comparison with a potentiometer. The circuit in Fig. 4.34 is used to calibrate a dc voltmeter; where a test voltmeter reading V is compared to the voltage drop across R. The voltage drop across R is accurately measured with the help of a standard meter. A rheostat, shown in Fig. 4.34, is used to limit the current.

A voltmeter tested with this method can be calibrated with an accuracy of ±0.01%.

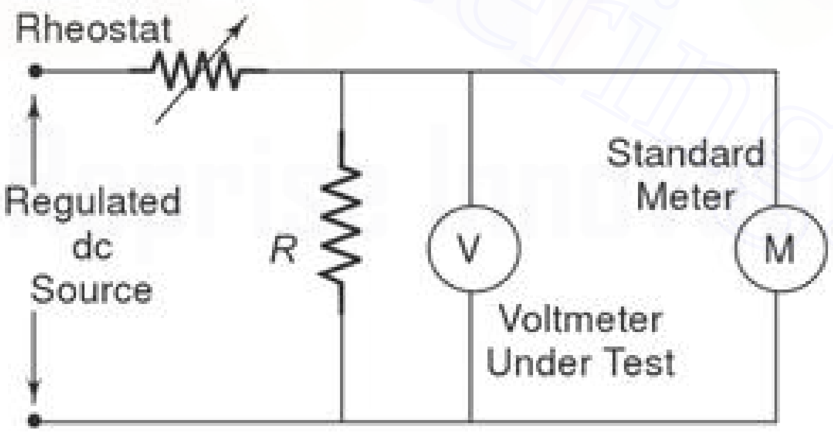


Fig. 4.34 Calibration of voltmeter

CALIBRATION OF OHMMETER 4.24

An ohmmeter is generally considered to be an instrument of moderate accuracy and low precision. A rough calibration may be done by measuring a standard resistance and noting the readings on the ohmmeter. Doing this for several points on the ohmmeter scale and on several ranges allows one to obtain an indication of the accuracy of the instrument.

MULTIMETER 4.25

A multimeter is basically a PMMC meter. To measure dc current the meter acts as an ammeter with a low series resistance.

Range changing is accomplished by shunts in such a way that the current passing through the meter does not exceed the maximum rated value.

A multimeter consists of an ammeter, voltmeter and ohmmeter combined, with a function switch to connect the appropriate circuit to the D'Arsonval movement.

Figure 4.35 shows a meter consisting of a dc milliammeter, a dc voltmeter, an ac voltmeter, a microammeter, and an ohmmeter.

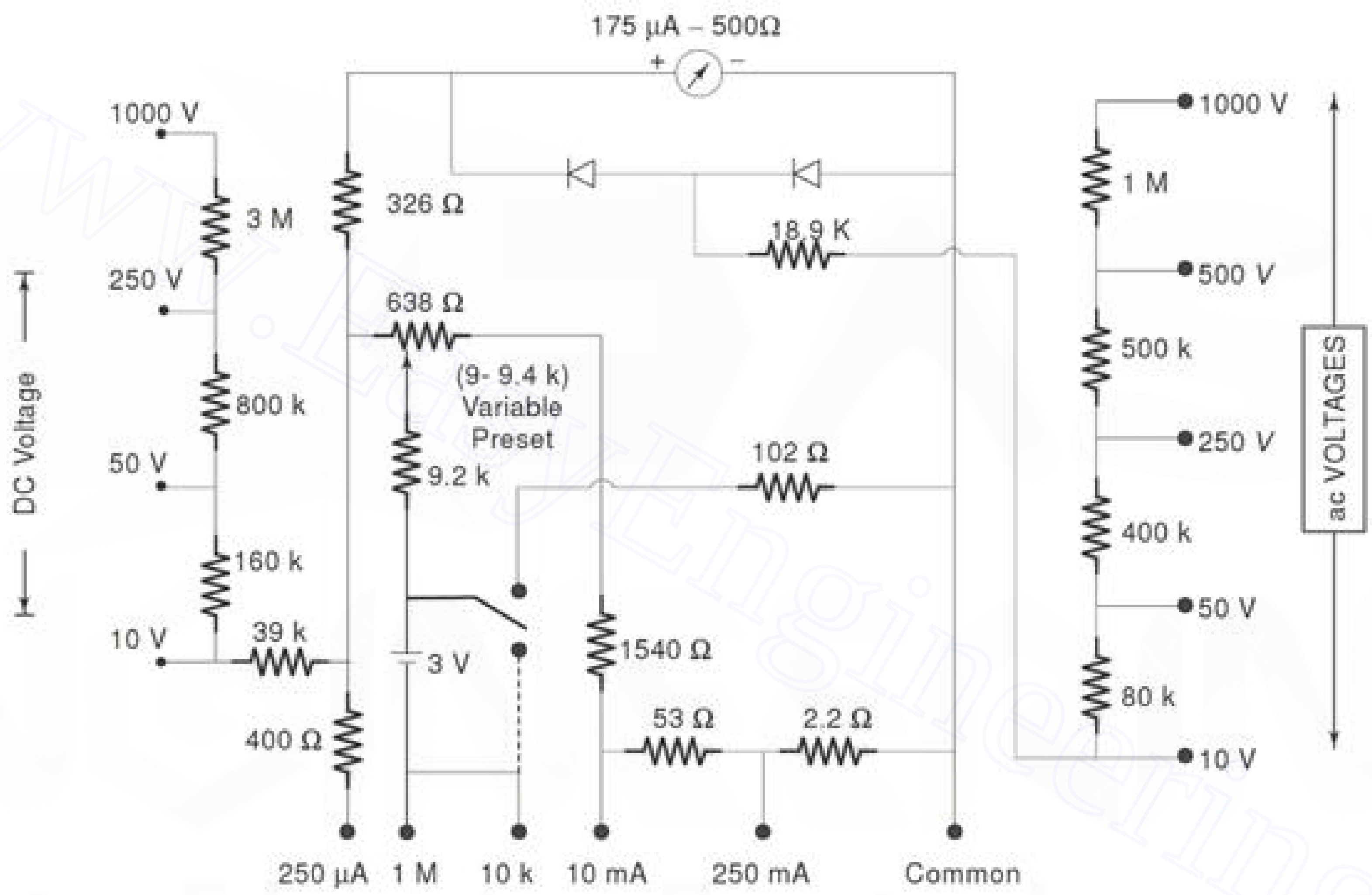


Fig. 4.35 Diagram of a multimeter

Microammeter Figure 4.36 shows a circuit of a multimeter used as a microammeter.

DC Ammeter Figure 4.37 shows a multimeter used as a dc ammeter.

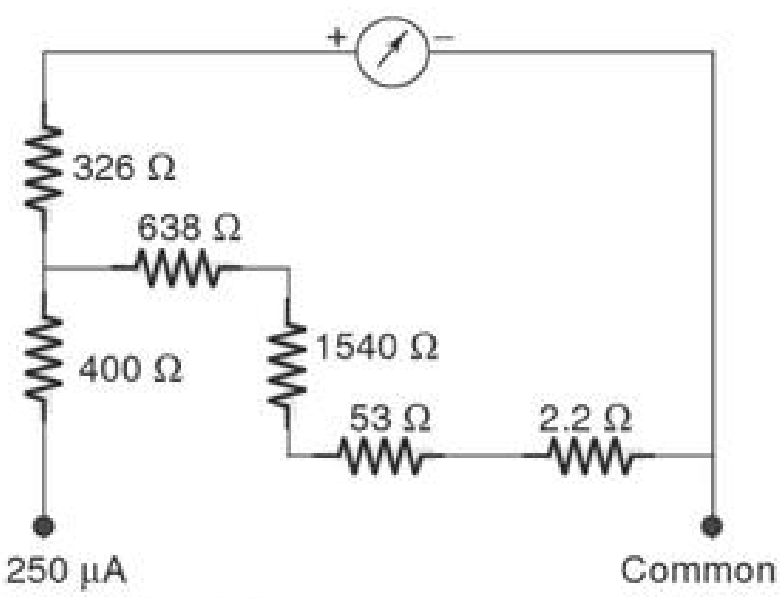


Fig. 4.36 Microammeter section of a multimeter

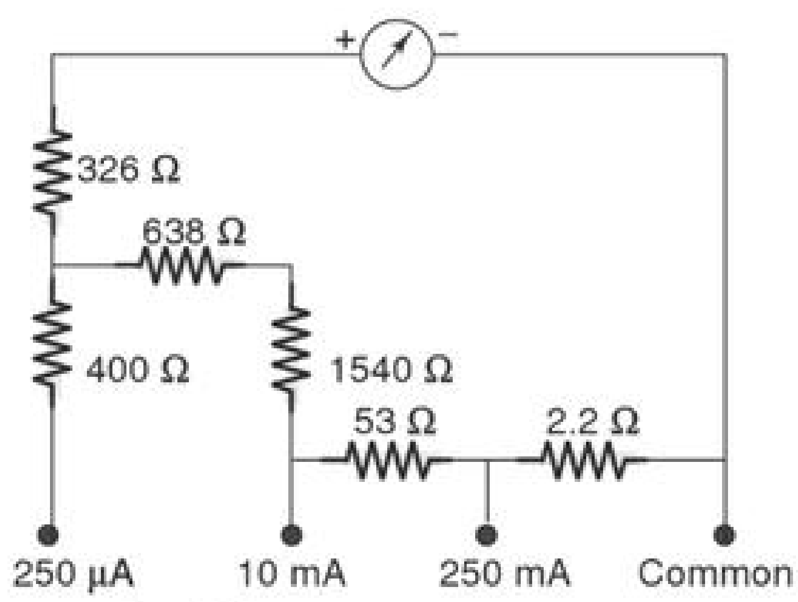


Fig. 4.37 dc ammeter section of a multimeter

DC Voltmeter Figure 4.38 shows the dc voltmeter section of a multimeter.

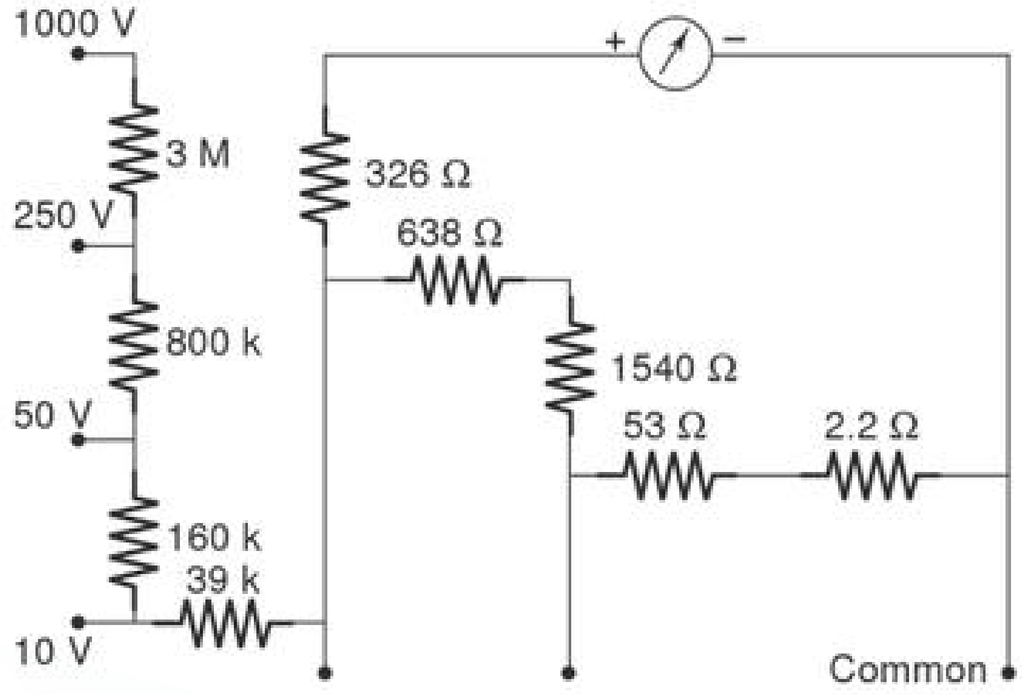


Fig. 4.38 DC voltmeter section of a multimeter

AC Voltmeter Figure 4.39 shows the ac voltmeter section of a multimeter. To measure ac voltage, the output ac voltage is rectified by a half wave rectifier before the current passes through the meter. Across the meter, the other diode serves as protection. The diode conducts when a reverse voltage appears across the diodes, so that current bypasses the meter in the reverse direction.

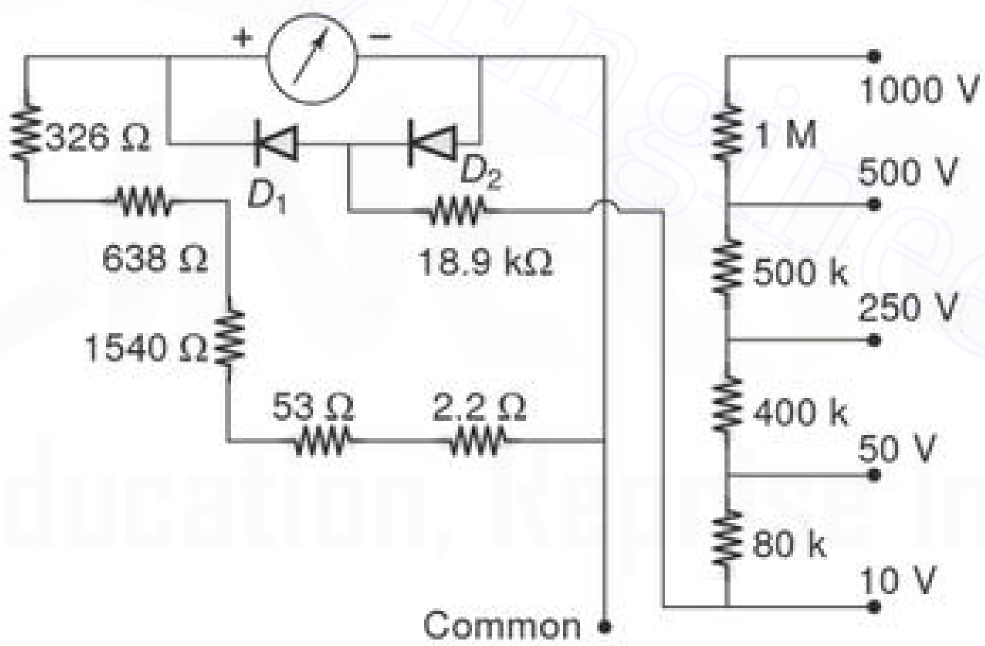


Fig. 4.39 AC voltmeter section of a multimeter

Ohmmeter Referring to Fig. 4.40 which shows the ohmmeter section of a multimeter, in the 10 k range the 102 Ω resistance is connected in parallel with the total circuit resistance and in the 1 MΩ range the 102 Ω resistance is totally disconnected from the circuit.

Therefore, on the 1 M range the half scale deflection is 10 k. Since on the 10 k range, the 102 Ω resistance is connected across the total resistance, therefore, in this range, the half scale deflection is 100 Ω. The measurement of resistance is done by applying a small voltage installed within the meter. For the 1 M range, the internal resistance is 10 kΩ, i.e. value at midscale, as shown in Fig. 4.41. And for the 10 k range, the internal resistance is 100 Ω, i.e. value at mid-scale as shown in Fig. 4.42.

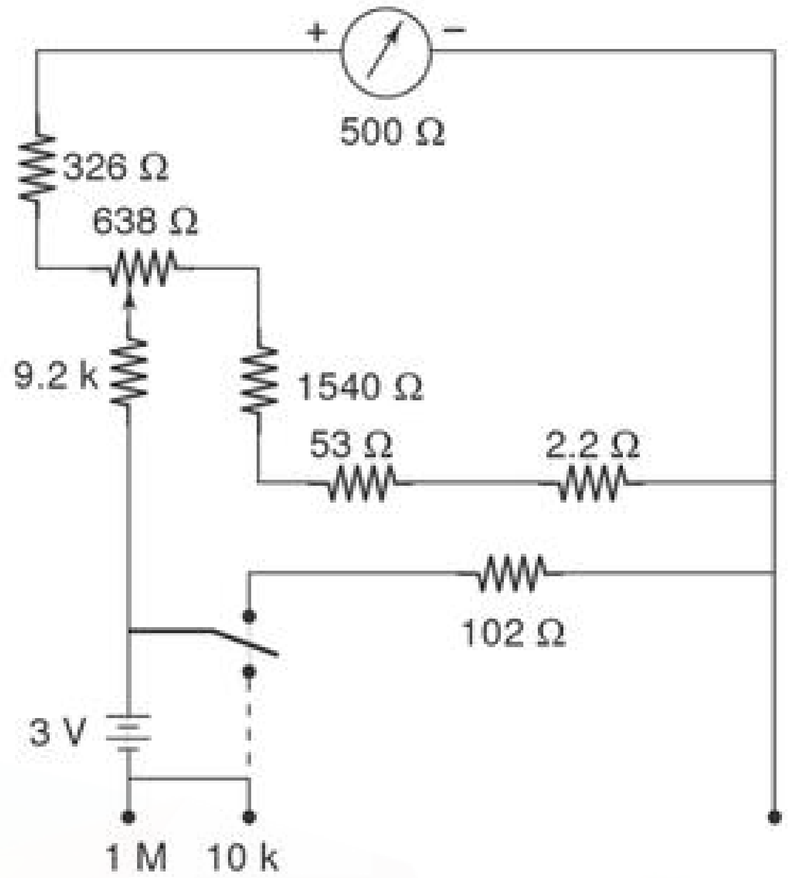


Fig. 4.40 Ohmmeter section of a multimeter

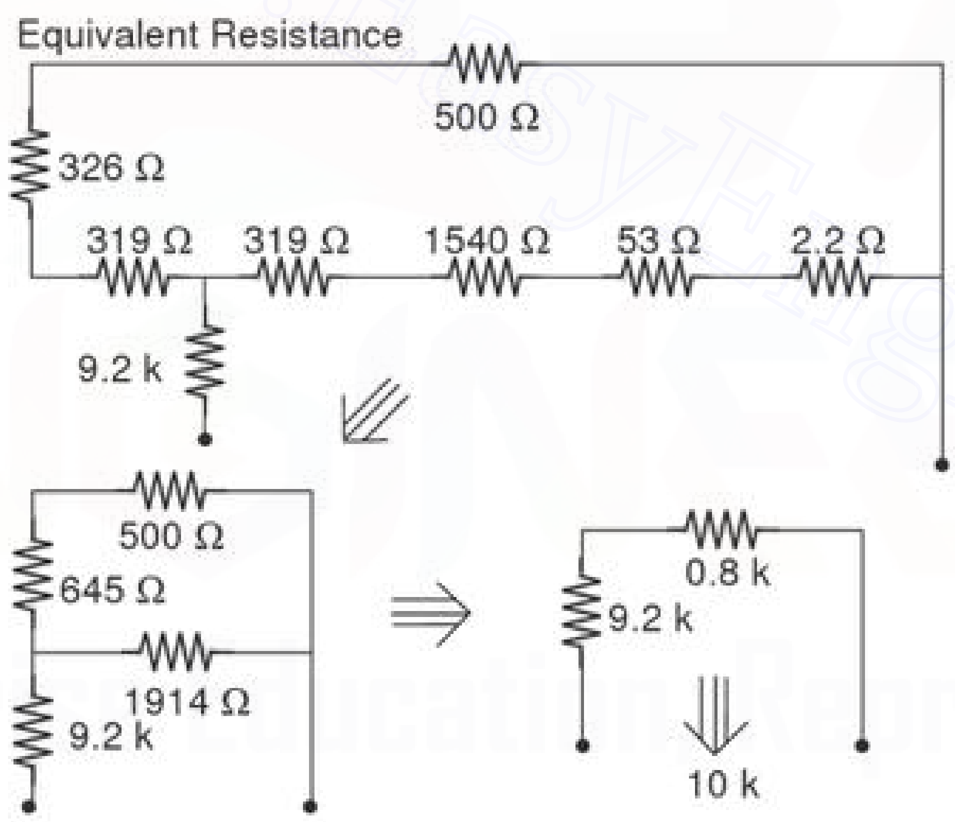


Fig. 4.41 Equivalent resistance on 1 M Ω range

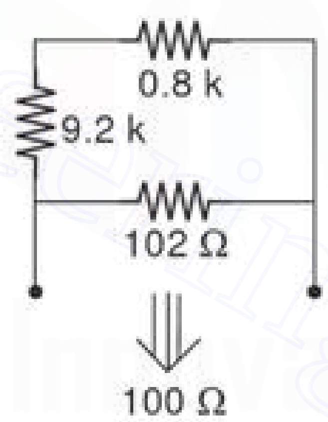


Fig. 4.42 Half scale deflection is 100 Ω on 10k range

The range of an ohmmeter can be changed by connecting the switch to a suitable shunt resistance. By using different values of shunt resistance, different ranges can be obtained.

By increasing the battery voltage and using a suitable shunt, the maximum values which the ohmmeter reads can be changed.

MULTIMETER OPERATING INSTRUCTIONS 4.26

The combination volt-ohm-milliammeter is a basic tool in any electronic laboratory. The proper use of this instrument increases its accuracy and life. The following precautions should be observed.

1. To prevent meter overloading and possible damage when checking voltage or current, start with the highest range of the instrument and move down the range successively.
2. For higher accuracy, the range selected should be such that the deflection falls in the upper half on the meter scale.
3. For maximum accuracy and minimum loading, choose a voltmeter range such that the total voltmeter resistance (ohms per volt × full scale voltage) is at least 100 times the resistance of the circuit under test.
4. Make all resistance readings in the uncrowded portion on the meter scale, whenever possible.
5. Take extra precautions when checking high voltages and checking current in high voltage circuits.
6. Verify the circuit polarity before making a test, particularly when measuring dc current or voltages.
7. When checking resistance in circuits, be sure power to the circuit is switched off, otherwise the voltage across the resistance may damage the meter.
8. Renew ohmmeter batteries frequently to insure accuracy of the resistance scale.
9. Recalibrate the instrument at frequent intervals.
10. Protect the instrument from dust, moisture, fumes and heat.

Review Questions

1. Explain how a PMMC can be used as a basic voltmeter.
2. Explain with a diagram the operation of a multirange voltmeter. State the limitations of a multirange voltmeter.
3. Explain the operation of an Ayrton shunt.
4. Compare a multirange voltmeter with the Ayrton shunt voltmeter.
5. State the drawbacks of using an Ayrton shunt.
6. Why is an Ayrton shunt called a universal shunt.
7. Define sensitivity of voltmeters. What is the significance of sensitivity in voltmeters?
8. State the effects of using a voltmeter of low sensitivity.
9. Explain the above with examples of loading effect.
10. Explain with a diagram the working of a Transistor Voltmeter (TVM). What are the drawbacks of a transistor voltmeter?
11. Explain why an FET is used at the input stage of a transistor voltmeter.
12. Explain why a transistor voltmeter cannot be used for measurement in the μV range.
13. Describe with a diagram how voltage in μV range is measured.
14. Explain the principle of operation of a chopper. Explain the use of a chopper in microvoltmeter.
15. Describe with a diagram the operation of a chopper type microvoltmeter.
16. Describe the operation of an electronic voltmeter using an IC OPAMP.
17. Explain the functions of a diode used in an electronic voltmeter. Explain the function of offset used in an electronic voltmeter.
18. Explain with diagram the operation of a dc differential voltmeter.

19. Explain how a PMMC can be used as an ac voltmeter.
20. State why silicon diodes are preferred as rectifiers in ac voltmeter.
21. Explain the operation of a full wave rectifier type ac voltmeter.
22. Explain with a diagram the operation of a half wave rectifier type ac voltmeter.
23. Why is a PMMC movement shunted by a resistor when used as an ac voltmeter?
24. Compare sensitivity of an ac voltmeter with that of the dc voltmeter.
25. Compare sensitivity of an ac voltmeter using FWR with that of a HWR.
26. Explain with a diagram how a multirange ac voltmeter can be constructed using a PMMC.
27. Explain with a diagram the operations of an average responding voltmeter. Where is it used?
28. Explain with a diagram the operations of a peak responding voltmeter. Where is it used?
29. Compare average responding voltmeters with peak responding voltmeters.
30. Explain the operating principle of a true RMS voltmeter.
31. Explain with diagram the operation of true RMS voltmeter.
32. Compare a true RMS voltmeter with an ac voltmeter.
33. What is the need of using a squaring device in a true RMS meter? Explain with a diagram the operation of a squaring device.
34. Compare a true RMS meter with an average responding meter.
35. Explain with a diagram the operation of a series type ohmmeter. Explain with a diagram how an ohmmeter is calibrated.
36. Why is there a '0' mark on the right-hand side for a series type ohmmeter? How can you estimate the internal resistance of a series type ohmmeter from its dial?
37. Explain with a diagram the operation of a shunt type ohmmeter.
38. Compare series type and shunt type ohmmeters.
39. How can you distinguish between a series type ohmmeter and a shunt type ohmmeter from dial calibration?
40. Define sensitivity of a multimeter.
41. Explain with the help of a diagram, the working of a simple multimeter.
42. Explain with the help of a diagram the various sections of a multimeter.
43. Draw a practical multimeter.
44. Explain with a diagram how a multimeter can be used as a voltmeter and ammeter.
45. Explain with a diagram how a multimeter can be used for measuring resistance.

Multiple Choice Questions

1. The instrument required to measure voltage is
   (a) ohmmeter (b) ammeter
   (c) voltmeter (d) wattmeter
2. A D'Arsonval movement is
   (a) taut band
   (b) PMMC
   (c) electrodynamometer
   (d) moving iron type
3. To select the range, a multirange voltmeter uses
   (a) double pole double throw switch
   (b) make before break type switch
   (c) single pole double throw switch
   d) simple switch
4. The sensitivity of a voltmeter is defined as
   (a) Ω / V (b) V / Ω
   (c) I / Ω (d) Ω / I

5. Loading effect in a voltmeter can be avoided by
   (a) using an accurate and precise instrument
   (b) using a low sensitivity voltmeter
   (c) using a high sensitivity voltmeter
   (d) using high voltage range
6. The input stage of TVM consists of
   (a) UJT stage (b) FET stage
   (c) BJT stage (d) SCR stage
7. TVM is used to measure
   (a) dc mV (b) dc μV
   (c) ac μV (d) ac mV
8. Chopper type voltmeter is used to measure
   (a) dc μV, (b) dc mV,
   (c) ac μV, (d) ac mV.
9. A diode used as rectifier in ac voltmeter should have
   (a) high forward current and low reverse currents
   (b) high forward current and high reverse current
   (c) low forward current and high reverse current
   (d) low forward current and low reverse current
10. The ac voltmeter using PMMC measures
    (a) true RMS voltage
    (b) peak voltage
    (c) average voltage
    (d) instantaneous voltage
11. To move the operating point of rectifier used in an ac voltmeter in the linear region, the meter is shunted by
    (a) capacitor (b) diode
    (c) inductor (d) resistor
12. A true RMS voltmeter measures
    (a) average value
    (b) instantaneous value
    (c) RMS value
    (d) peak value
13. The ohms per volt rating on ac ranges as compared to the same rating on dc ranges is
    (a) less
    (b) more
    (c) equal
    (d) none of the above
14. In a 20 kΩ / V sensitivity multimeter, the input resistance for measuring ac voltage in 10 V fsd is
    (a) 200 kΩ (b) 20 kΩ
    (c) 10 kΩ (d) 2 kΩ
15. Ac measurement is achieved by connecting a/an in series with a PMMC.
    (a) resistor (b) diode
    (c) inductor (d) capacitor
16. The internal resistance of an ohmmeter can be estimated from
    (a) 0 deflection
    (b) full scale deflection
    (c) half scale deflection
    (d) quarter deflection

Practice Problems

1. What series resistance must be used to extend the 0–200 V range of a 20000 Ω/V meter to a 2000 V? What must be the power of this resistor?
2. Calculate the value of a series resistor used to extend the 0–100 V range of a 20 kΩ / V Voltmeter to a 500 V range. Calculate the power of the resistor.
3. A basic D'Arsonval movement with a full scale deflection of 50 μA and having an internal resistance of 500 Ω is available. It is to be converted into a 0–1 V, 0–5 V, 0–20 V, 0–100 V multirange voltmeter using individual multipliers for each range. Calculate the values of the individual resistor.
4. A basic D'Arsonval movement with a full scale deflection of 50 μA and an internal resistance of 1800 Ω is available. It is to be converted into a 0–1 V, 0–5 V, 0–25 V and 0–225 V multirange voltmeter using individual

multipliers for each range. Calculate the values of the individual resistors.

5. Convert a basic D'Arsonval movement with an internal resistance of 100 Ω and a full scale deflection of 1 mA into a multirange dc voltmeter with voltage ranges of 0–1 V, 0–10 V, 0–50 V .

6. A meter movement has an internal resistance of 100 Ω and requires 1 mA dc full scale deflection. Shunting resistor R_{sh} placed across the movement has a value of 100 Ω. Diodes $D1$ and D_2 have an average forward resistance of 400 Ω and are assumed to have infinite reverse resistance in the reverse direction. For 10 V ac range, calculate (i) the value of the multiplier, (ii) the voltmeter sensitivity on ac range. (Rs = 1800, S = 225 Ω/V). Refer to Fig. 4.43.

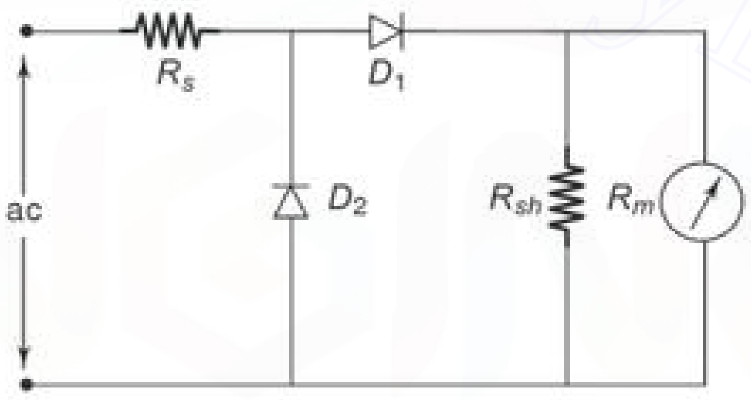


Fig. 4.43

7. The circuit diagram of Fig. 4.44 shows a full wave rectifier ac voltmeter. The meter movement has an internal resistance of 250 Ω and required 1 mA for full scale deflection. The diodes each have a forward resistance of 50 Ω and infinite reverse resistance.

Calculate:
(i) the series resistance required for full scale meter deflection when 25 V rms is applied to the meter terminals.
(ii) the ohms per volt rating of this ac voltmeter.

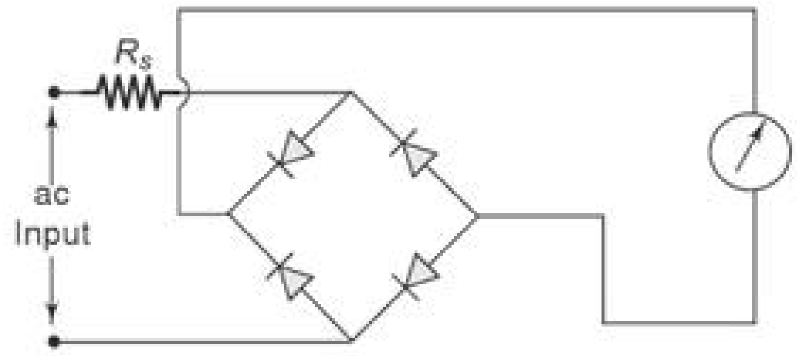


Fig. 4.44

7. A series ohmmeter uses a 50 Ω basic movement requiring a full scale deflection of 1 mA. The internal battery voltage is 3 V. The desired scale marking for half scale deflection is 2000 Ω.
Calculate
(i) values of R_1 and R_2
(ii) maximum value of R_2 to compensate for a 10% drop in battery.

8. A series type ohmmeter is designed to operate with a 6 V battery. The meter movement has an internal resistance of 2 kΩ and requires a current of 100 μA for full scale deflection. The value of R_1 is 49 k.
(i) Assuming the battery voltage has fallen to 5.9 V, calculate the value of R_2 required to "0" the meter.
(ii) Under the condition mentioned in (i), an unknown resistance is connected to the meter, causing a 60% deflection. Calculate the value of the unknown resistance.

Further Reading

1. John. H. Fasal, *Simplified Electronics Measurements*, Hayden Book Co., 1971.
2. *Handbook of Electronic Measurements*, vols. I & II, Polytechnic Institute of Brooklyn, 1956.
3. Larry D. Jones and A. Foster Chin, *Electronic Instruments and Measurements*, John Wiley and Sons, 1987.
4. W.D. Copper and A.D. Helfrick, *Electronic Instrumentation and Measurement Techniques*, 3rd Edition, 1985. Prentice-Hall of India.

Chapter 5

Digital Voltmeters

INTRODUCTION 5.1

Digital voltmeters (DVMs) are measuring instruments that convert analog voltage signals into a digital or numeric readout. This digital readout can be displayed on the front panel and also used as an electrical digital output signal.

Any DVM is capable of measuring analog dc voltages. However, with appropriate signal conditioners preceding the input of the DVM, quantities such as ac voltages, ohms, dc and ac current, temperature, and pressure can be measured. The common element in all these signal conditioners is the dc voltage, which is proportional to the level of the unknown quantity being measured. This dc output is then measured by the DVM.

DVMs have various features such as speed, automation operation and programability. There are several varieties of DVM which differ in the following ways:

1. Number of digits
2. Number of measurements
3. Accuracy
4. Speed of reading
5. Digital output of several types.

The DVM displays ac and dc voltages as discrete numbers, rather than as a pointer on a continuous scale as in an analog voltmeter. A numerical readout is advantageous because it reduces human error, eliminates parallax error, increases reading speed and often provides output in digital form suitable for further processing and recording. With the development of IC modules, the size, power requirements and cost of DVMs have been reduced, so that DVMs compete with analog voltmeters in portability and size. Their outstanding qualities are their operating and performance characteristics, as detailed below.

1. Input range from + 1.000 V to + 1000 V with automatic range selection and overload indication
2. Absolute accuracy as high as ±0.005% of the reading
3. Resolution 1 part in million (1 μV reading can be read or measured on 1 V range)
4. Input resistance typically 10 MΩ, input capacitance 40 pF
5. Calibration internally from stabilised reference sources, independent of measuring circuit

6. Output in BCD form, for print output and further digital processing. Optional features may include additional circuitry to measure current, ohms and voltage ratio.

RAMP TECHNIQUE 5.2

The operating principle is to measure the time that a linear ramp takes to change the input level to the ground level, or vice-versa. This time period is measured with an electronic time-interval counter and the count is displayed as a number of digits on an indicating tube or display. The operating principle and block diagram of a ramp type DVM are shown in Figs 5.1 and 5.2.

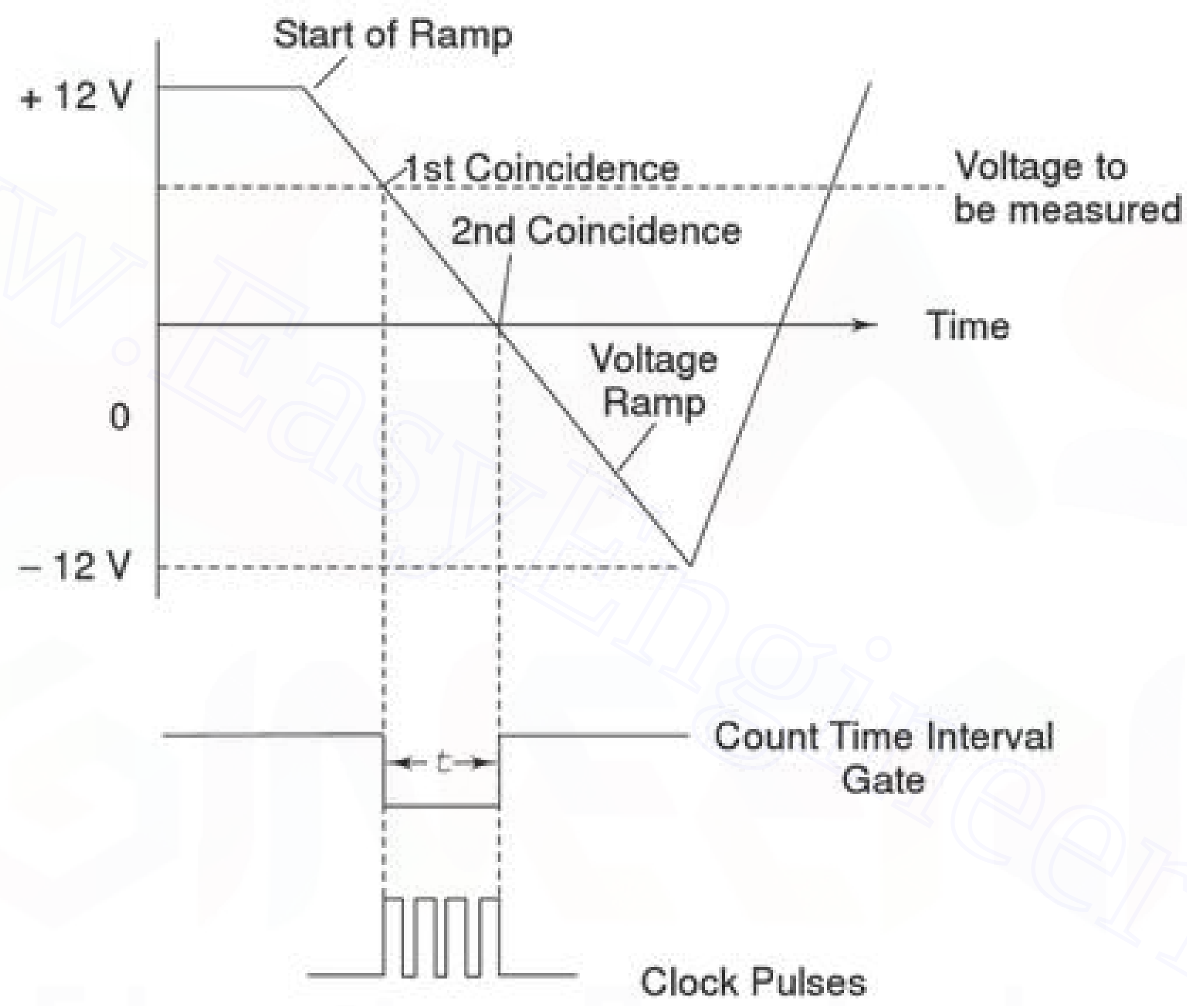


Fig. 5.1 Voltage to time conversion

The ramp may be positive or negative; in this case a negative ramp has been selected.

At the start of the measurement a ramp voltage is initiated (counter is reset to 0 and sampled rate multivibrator gives a pulse which initiates the ramp generator). The ramp voltage is continuously compared with the voltage that is being measured. At the instant these two voltage become equal, a coincidence circuit generates a pulse which opens a gate, i.e. the input comparator generates a start pulse. The ramp continues until the second comparator circuit senses that the ramp has reached zero value. The ground comparator compares the ramp with ground. When the ramp voltage equals zero or reaches ground potential, the ground comparator generates a stop pulse. The output pulse from this comparator closes the gate. The time duration of the gate opening is proportional to the input voltage value.

In the time interval between the start and stop pulses, the gate opens and the oscillator circuit drives the counter. The magnitude of the count indicates the magnitude of the input voltage, which is displayed by the readout. Therefore, the voltage is converted into time and the time count represents the magnitude of the voltage. The sample rate multivibrator determines the rate of cycle of measurement. A typical value is 5 measuring cycles per second, with an accuracy of ± 0.005% of the reading. The sample rate circuit provides an initiating pulse for the ramp generator to start its next ramp voltage. At the same time a reset pulse is generated, which resets the counter to the zero state.

Any DVM has a fundamental cycle sequence which involves sampling, displaying and reset sequences.

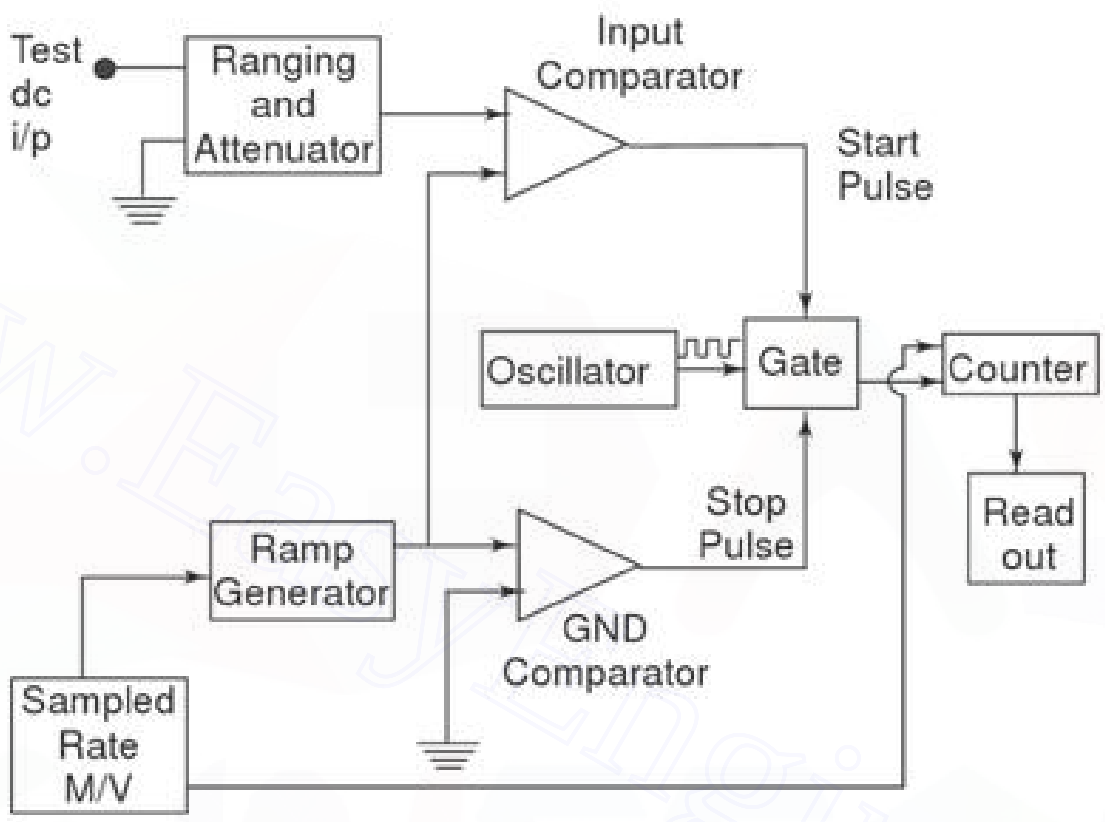


Fig. 5.2 Block diagram of ramp type DVM

Advantages and Disadvantages The ramp technique circuit is easy to design and its cost is low. Also, the output pulse can be transmitted over long feeder lines. However, the single ramp requires excellent characteristics regarding linearity of the ramp and time measurement. Large errors are possible when noise is superimposed on the input signal. Input filters are usually required with this type of converter.

DUAL SLOPE INTEGRATING TYPE DVM (VOLTAGE TO TIME CONVERSION) 5.3

In ramp techniques, superimposed noise can cause large errors. In the dual ramp technique, noise is averaged out by the positive and negative ramps using the process of integration.

Principle of Dual Slope Type DVM As illustrated in Fig. 5.3, the input voltage 'e_i' is integrated, with the slope of the integrator output proportional to the test input voltage. After a fixed time, equal to t_1, the input voltage is disconnected and the integrator input is connected to a negative voltage $-e_r$. The integrator output will have a negative slope which is constant and proportional to the magnitude of the input voltage. The block diagram is given in Fig. 5.4.

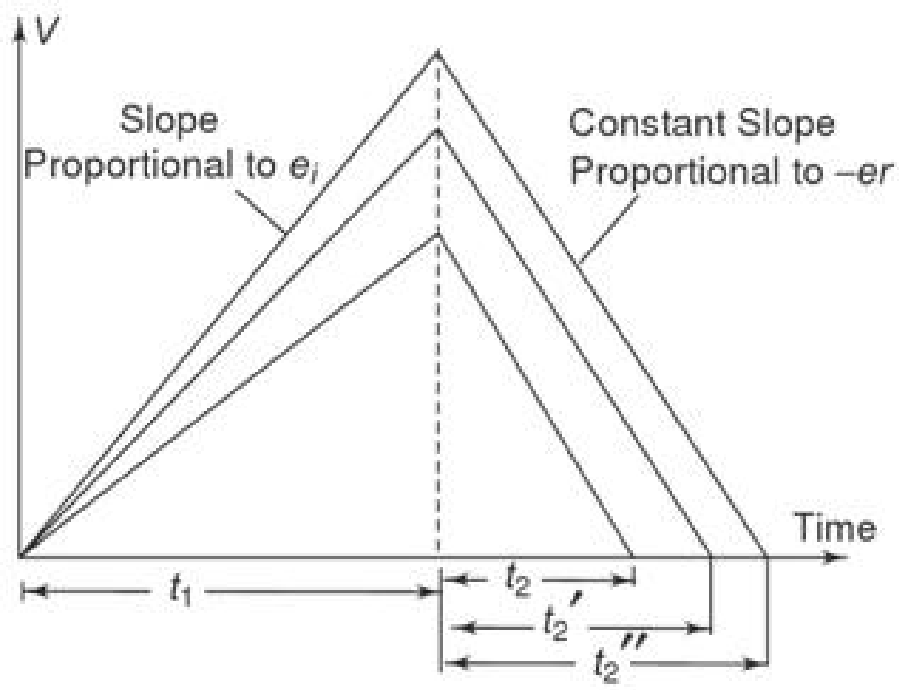


Fig. 5.3 Basic principle of dual slope type DVM

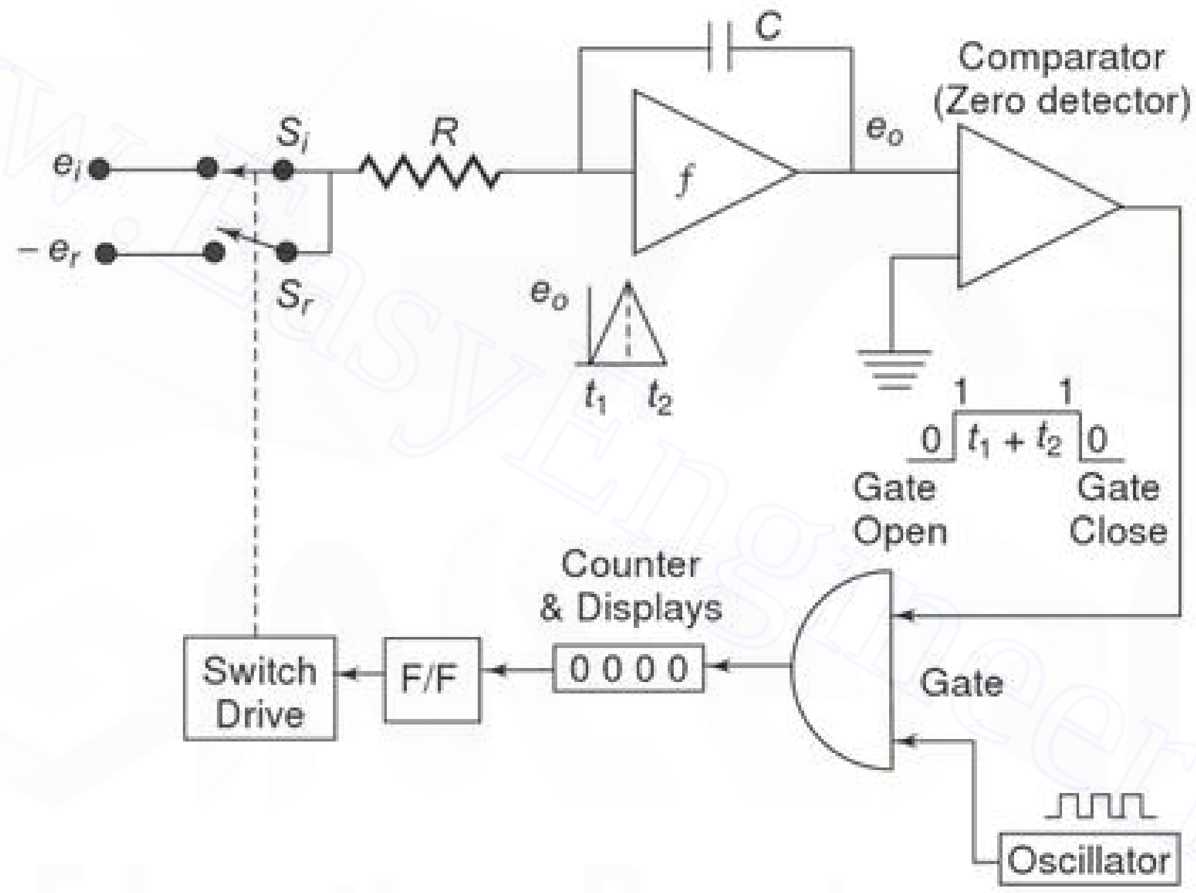


Fig. 5.4 Block diagram of a dual slope type DVM

At the start a pulse resets the counter and the F/F output to logic level '0'. S_i is closed and S_r is open. The capacitor begins to charge. As soon as the integrator output exceeds zero, the comparator output voltage changes state, which opens the gate so that the oscillator clock pulses are fed to the counter. (When the ramp voltage starts, the comparator goes to state 1, the gate opens and clock pulse drives the counter.) When the counter reaches maximum count, i.e. the counter is made to run for a time 't_1' in this case 9999, on the next clock pulse all digits go to 0000 and the counter activates the F/F to logic level '1'. This activates the switch drive, e_i is disconnected and $-e_r$ is connected to the integrator. The integrator output will have a negative slope which is constant, i.e. integrator output now decreases linearly to 0 volts. Comparator output state changes again and locks the gate. The discharge time t_2 is now proportional to the input voltage. The counter indicates the count during time t_2. When the negative slope of the integrator reaches zero, the comparator switches to state 0 and the gate closes, i.e. the capacitor C is now discharged with a constant slope. As soon as the comparator input (zero detector) finds that e_o is zero, the counter is stopped. The pulses counted by the counter thus have a direct relation with the input voltage.

During charging

$$e_o = -\frac{1}{RC}\int_0^t e_i\,dt = -\frac{e_i\,t_1}{RC} \tag{5.1}$$

During discharging

$$e_o = \frac{1}{RC}\int_0^{t_2} -e_r dt = -\frac{e_r\,t_2}{RC} \tag{5.2}$$

Subtracting Eqs 5.2 from 5.1 we have

$$e_o - e_o = \frac{-e_r\,t_2}{RC} - \left(\frac{-e_i\,t_1}{RC}\right)$$

$$0 = \frac{-e_r\,t_2}{RC} - \left(\frac{-e_i\,t_1}{RC}\right)$$

$$\Rightarrow \qquad \frac{e_r\,t_2}{RC} = \frac{e_i\,t_1}{RC}$$

$$\therefore \qquad e_i = e_r\frac{t_2}{t_1} \tag{5.3}$$

If the oscillator period equals T and the digital counter indicates n_1 and n_2 counts respectively,

$$\therefore \qquad e_i = \frac{n_2\,T}{n_1\,T}e_r \quad \text{i.e.} \quad e_i = \frac{n_2}{n_1}e_r$$

Now, n_1 and e_r are constants. Let $K_1 = \frac{e_r}{n_1}$. Then $e_i = K_1\,n_2$ (5.4)

From Eq. 5.3 it is evident that the accuracy of the measured voltage is independent of the integrator time constant. The times t_1 and t_2 are measured by the count of the clock given by the numbers n_1 and n_2 respectively. The clock oscillator period equals T and if n_1 and e_r are constants, then Eq. 5.4 indicates that the accuracy of the method is also independent of the oscillator frequency.

The dual slope technique has excellent noise rejection because noise and superimposed ac are averaged out in the process of integration. The speed and accuracy are readily varied according to specific requirements; also an accuracy of ± 0.05% in 100 ms is available.

INTEGRATING TYPE DVM (VOLTAGE TO FREQUENCY CONVERSION) 5.4

The principle of operation of an integrating type DVM is illustrated in Fig. 5.5.

A constant input voltage is integrated and the slope of the output ramp is proportional to the input voltage. When the output reaches a certain value, it is discharged to 0 and another cycle begins. The frequency of the output waveform is propor-tional to the input voltage. The block diagram is illustrated in Fig. 5.6.

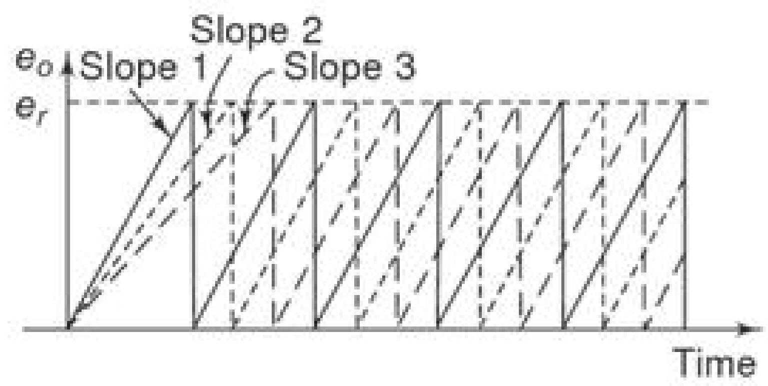


Fig. 5.5 Voltage to frequency conversion

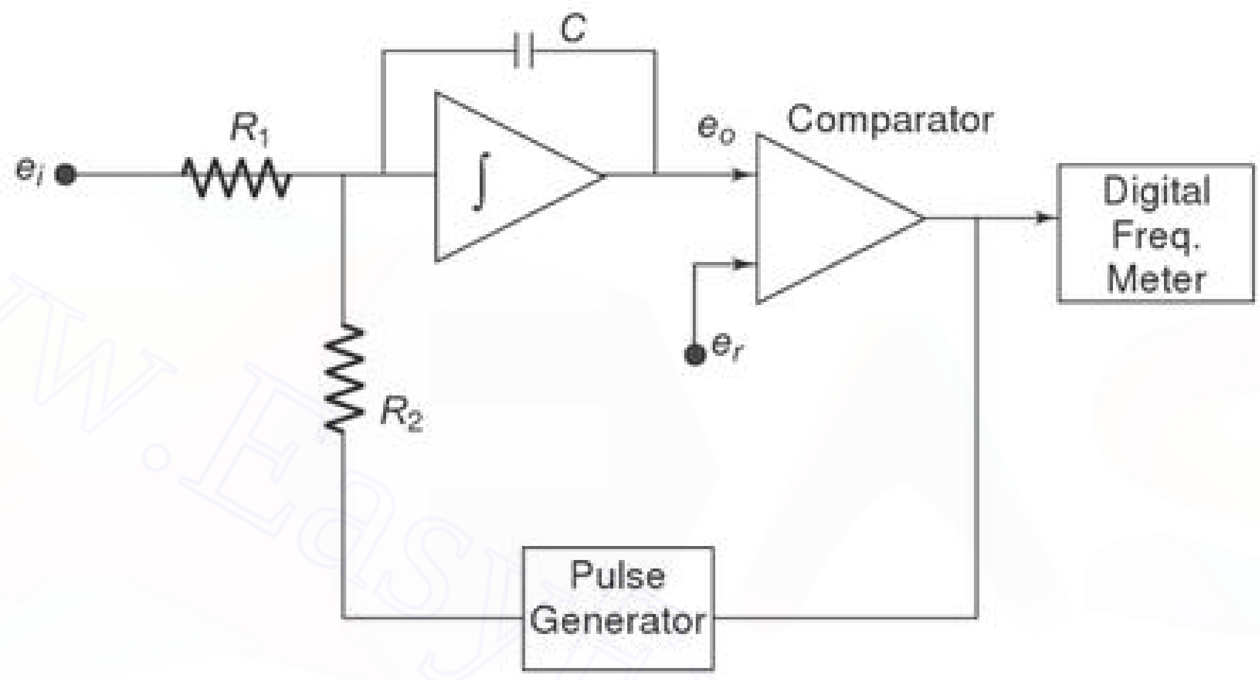


Fig. 5.6 Block diagram of an integrating type DVM

The input voltage produces a charging current, e_i/R_1, that charges the capacitor 'C' to the reference voltage e_r. When e_r is reached, the comparator changes state, so as to trigger the precision pulse generator. The pulse generator produces a pulse of precision charge content that rapidly discharges the capacitor. The rate of charging and discharging produces a signal frequency that is directly proportional to e_i.

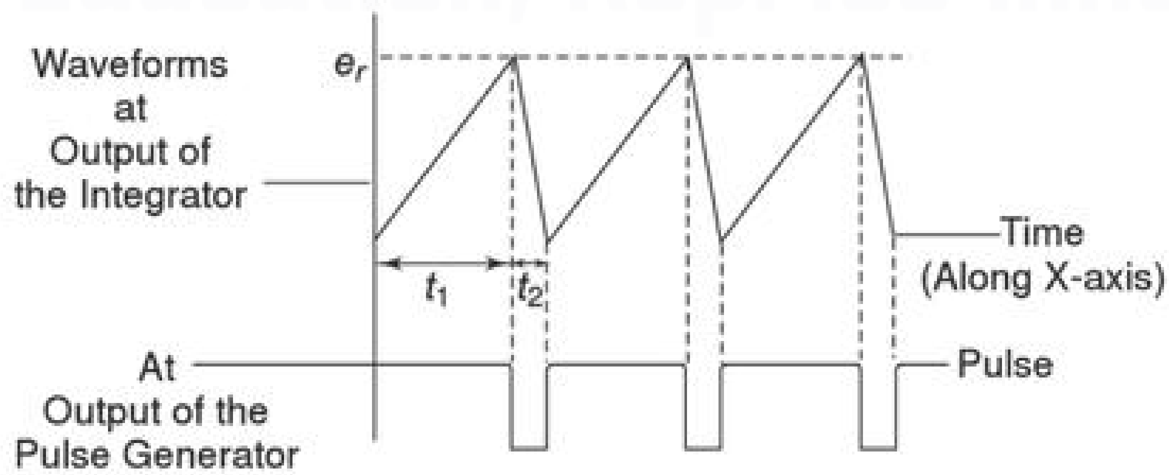


Fig. 5.7

The voltage-frequency conversion can be considered to be a dual slope method, as shown in Fig. 5.7.

Referring to Eq. 5.3 we have

$$e_i = \frac{e_r\, t_2}{t_1}$$

But in this case e_r and t_2 are constants.

Let $$K_2 = e_r\, t_2$$

$$\therefore \quad e_i = K_2\left(\frac{1}{t_1}\right) = K_2(f_0)$$

The output frequency is proportional to the input voltage e_i. This DVM has the disadvantage that it requires excellent characteristics in linearity of the ramp. The ac noise and supply noise are averaged out.

Example 5.1 *An integrator contains a 100 kΩ and 1 μF capacitor. If the voltage applied to the integrator input is 1 V, what voltage will be present at the output of the integrator after 1 s.*

Solution Using the equation

$$e_o = \frac{e_i \times t_1}{RC} = \frac{1\times 1\,\text{s}}{100\,\text{k}\times 1\,\mu\text{F}} = \frac{1}{0.1} = 10\text{ V}$$

Example 5.2 *Now if a reference voltage is applied to the integrator of the above example at time t_1 is 5 V in amplitude, what is the time interval of t_2?*

Solution Using the equation

$$\frac{e_i \times t_1}{RC} = \frac{e_r \times t_2}{RC}$$

Therefore, $t_2 = \dfrac{e_i}{e_r}\times t_1$; $\qquad t_2 = \dfrac{1\times 1}{5} = 0.2\text{ s}$

Example 5.3 *An integrator consists of a 100 kΩ and 2 μF capacitor. If the applied voltage is 2V, what will be the output of the integrator after 2 seconds?*

Solution Given, $R = 100\text{ k}\Omega$, $C = 2\ \mu\text{F}$, $e_1 = 2$ V and $t_1 = 2$ s

Using the equation,

$$e_0 = \frac{e_1 \times t_1}{R\times C} = \frac{2\text{ V}\times 2\text{ s}}{100\text{ k}\times 2\ \mu\text{F}} = \frac{4}{200\times 10^3\times 10^{-6}} = \frac{4\times 10^3}{200} = \frac{4000}{200} = 20\text{ V}$$

Example 5.4 *Now if a reference voltage of 10 V is applied to the integrator of the above example (Ex 5.3) at time t_1, what is the time interval of t_2?*

Solution Given reference voltage 10 V.

$$\frac{e_1\times t_1}{R\times C} = \frac{e_2 \times t_2}{R\times C}$$

therefore, $$t_2 = \frac{e_1 \times t_1}{e_2} = \frac{2 \times 2\text{ s}}{10} = 0.4\text{ s}$$

MOST COMMONLY USED PRINCIPLES OF ADC (ANALOG TO DIGITAL CONVERSION) 5.5

5.5.1 Direct Compensation

The input signal is compared with an internally generated voltage which is increased in steps starting from zero. The number of steps needed to reach the full compensation is counted. A simple compensation type is the staircase ramp.

The Staircase Ramp The basic principle is that the input signal V_i is compared with an internal staircase voltage, V_c, generated by a series circuit consisting of a pulse generator (clock), a counter counting the pulses and a digital to analog converter, converting the counter output into a dc signal. As soon as V_c is equal to V_i, the input comparator closes a gate between the clock and the counter, the counter stops and its output is shown on the display. The basic block diagram is shown in Fig. 5.8.

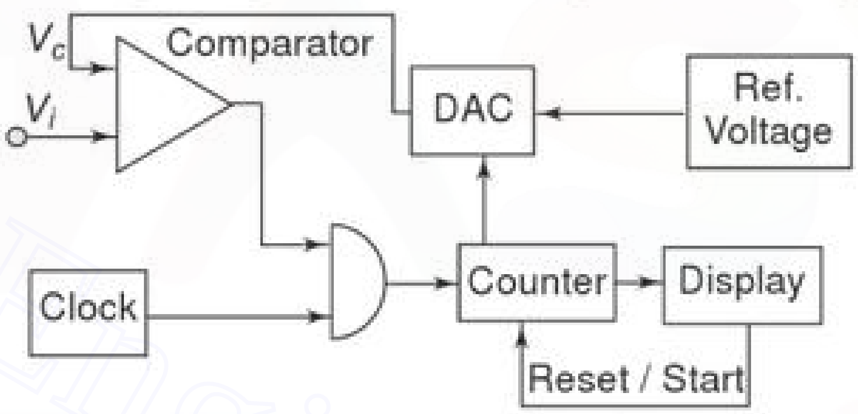


Fig. 5.8 Block diagram of a staircase ramp type

Operation of the Circuit The clock generates pulses continuously. At the start of a measurement, the counter is reset to 0 at time t_1 so that the output of the digital to analog converter (DAC) is also 0. If V_i is not equal to zero, the input comparator applies an output voltage that opens the gate so that clock pulses are passed on to the counter through the gate. The counter starts counting and the DAC starts to produce an output voltage increasing by one small step at each count of the counter. The result is a staircase voltage applied to the second input of the comparator, as shown in Fig. 5.9.

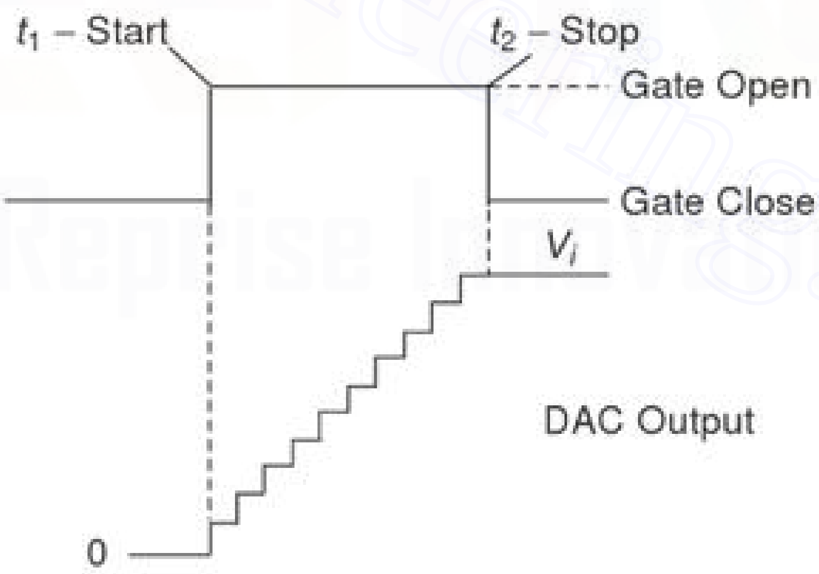


Fig. 5.9 Staircase waveform

This process continues until the staircase voltage is equal to or slightly greater than the input voltage V_i. At that instant t_2, the output voltage of the input comparator changes state or polarity, so that the gate closes and the counter is stopped.

The display unit shows the result of the count. As each count corresponds to a constant dc step in the DAC output voltage, the number of counts is directly proportional to V_c and hence to V_i. By appropriate choice of reference voltage, the step height of the staircase voltage can be determined. For example, each count can represent 1 mV and direct reading of the input voltage in volts can be realised by placing a decimal point in front of the 10 decade.

The advantages of a staircase type DVM are as follows:

1. Input impedance of the DAC is high when the compensation is reached.
2. The accuracy depends only on the stability and accuracy of the voltage and DAC. The clock has no effect on the accuracy.

The disadvantages are the following:

1. The system measures the instantaneous value of the input signal at the moment compensation is reached. This means the reading is rather unstable, i.e. the input signal is not a pure dc voltage.
2. Until the full compensation is reached, the input impedance is low, which can influence the accuracy.

SUCCESSIVE APPROXIMATIONS 5.6

The successive approximation principle can be easily understood using a simple example; the determination of the weight of an object. By using a balance and placing the object on one side and an approximate weight on the other side, the weight of the object is determined.

If the weight placed is more than the unknown weight, the weight is removed and another weight of smaller value is placed and again the measurement is performed. Now if it is found that the weight placed is less than that of the object, another weight of smaller value is added to the weight already present, and the measurement is performed. If it is found to be greater than the unknown weight the added weight is removed and another weight of smaller value is added. In this manner by adding and removing the appropriate weight, the weight of the unknown object is determined. The successive approximation DVM works on the same principle. Its basic block diagram is shown in Fig. 5.10. When the start pulse signal activates the control circuit, the successive approximation register (SAR) is cleared. The output of the SAR is 00000000. V_{out} of the D/A converter is 0. Now, if $V_{in} > V_{out}$ the comparator output is positive. During the first clock pulse, the control circuit sets the D_7 to 1, and V_{out} jumps to the half reference voltage. The SAR output is 10000000. If V_{out} is greater than V_{in}, the comparator output is negative and the control circuit resets D_7. However, if V_{in} is greater than V_{out}, the comparator output is positive and the control circuits keeps D_7 set. Similarly the rest of the bits beginning from D_7 to D_0 are set and tested. Therefore, the measurement is completed in 8 clock pulses.

Table 5.1

$V_{in} = 1\ V$	Operation	D_7	D_6	D_5	D_4	D_3	D_2	D_1	D_0	Compare	Output	Voltage
00110011	D_7 Set	1	0	0	0	0	0	0	0	$V_{in} < V_{out}$	D_7 Reset	2.5
”	D_6 Set	0	1	0	0	0	0	0	0	$V_{in} < V_{out}$	D_6 Reset	1.25
”	D_5 Set	0	0	1	0	0	0	0	0	$V_{in} > V_{out}$	D_5 Set	0.625
”	D_4 Set	0	0	1	1	0	0	0	0	$V_{in} > V_{out}$	D_4 Set	0.9375
”	D_3 Set	0	0	1	1	1	0	0	0	$V_{in} < V_{out}$	D_3 Reset	0.9375
”	D_2 Set	0	0	1	1	0	1	0	0	$V_{in} < V_{out}$	D_2 Reset	0.9375
”	D_1 Set	0	0	1	1	0	0	1	0	$V_{in} > V_{out}$	D_1 Set	0.97725
”	D_0 Set	0	0	1	1	0	0	1	1	$V_{in} > V_{out}$	D_0 Set	0.99785

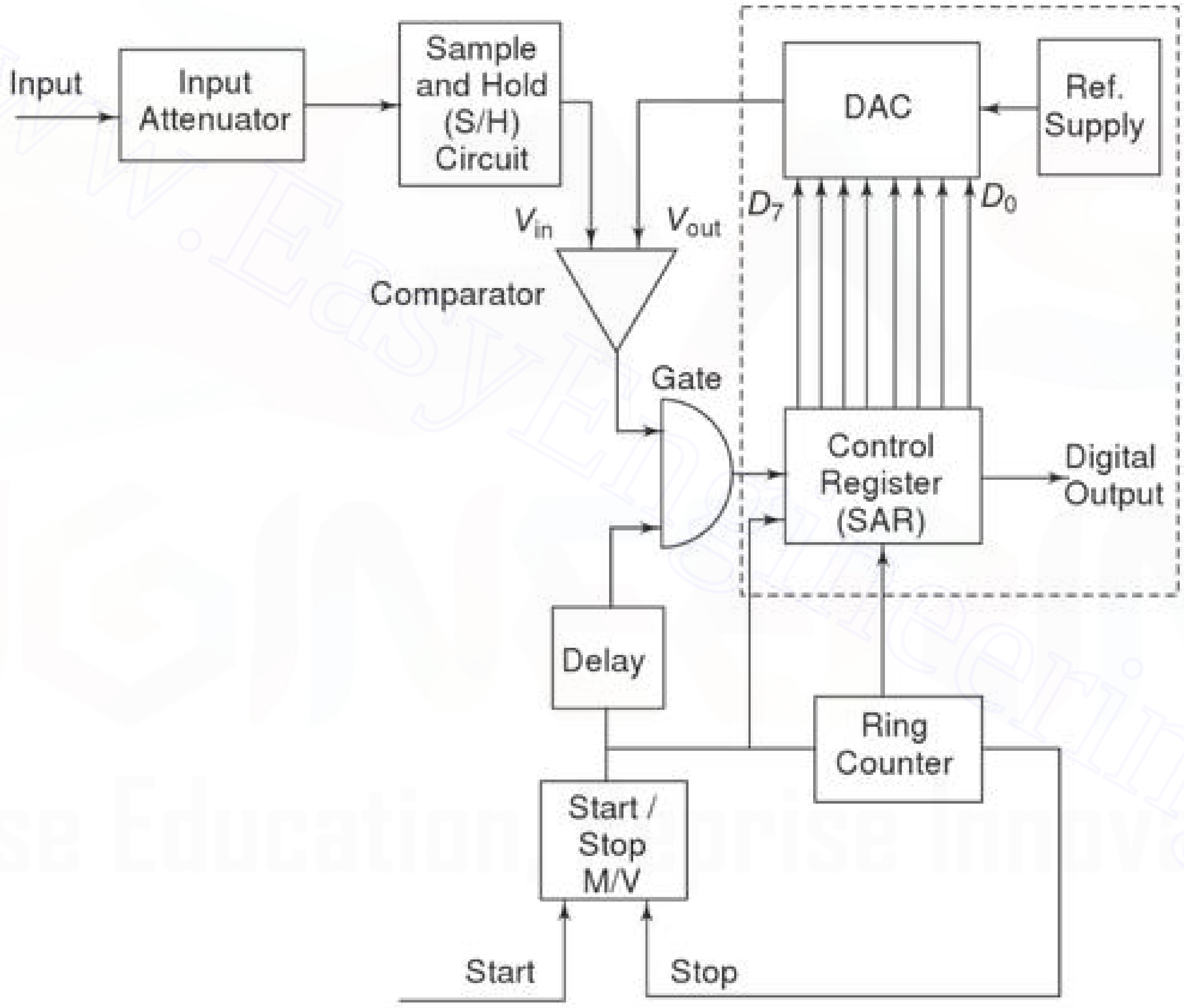


Fig. 5.10 Successive approximation DVM

At the beginning of the measurement cycle, a start pulse is applied to the start-stop multivibrator. This sets a 1 in the MSB of the control register and a 0 in all bits (assuming an 8-bit control) its reading would be 10000000. This initial setting of the register causes the output of the D/A converter to be half the reference voltage, i.e. 1/2 V. This converter output is compared to the unknown input by the comparator. If the input voltage is greater than the converter reference voltage, the comparator output produces an output that causes the control register to retain the 1 setting in its MSB and the converter continues to supply its reference output voltage of 1/2 V_{ref}.

The ring counter then advances one count, shifting a 1 in the second MSB of the control register and its reading becomes 11000000. This causes the D/A converter to increase its reference output by 1 increment to 1/4 V, i.e. 1/2 V + 1/4 V, and again it is compared with the unknown input. If in this case the total reference voltage exceeds the unknown voltage, the comparator produces an output that causes the control register to reset its second MSB to 0. The converter output then returns to its previous value of 1/2 V and awaits another input from the SAR. When the ring counter advances by 1, the third MSB is set to 1 and the converter output rises by the next increment of 1/2 V + 1/8 V. The measurement cycle thus proceeds through a series of successive approximations. Finally, when the ring counter reaches its final count, the measurement cycle stops and the digital output of the control register represents the final approximation of the unknown input voltage.

Example *Suppose the converter can measure a maximum of 5 V, i.e. 5 V corresponds to the maximum count of 11111111. If the test voltage V_{in} = 1 V the following steps will take place in the measurement. (Refer to Table 5.1 and Fig. 5.11.)*

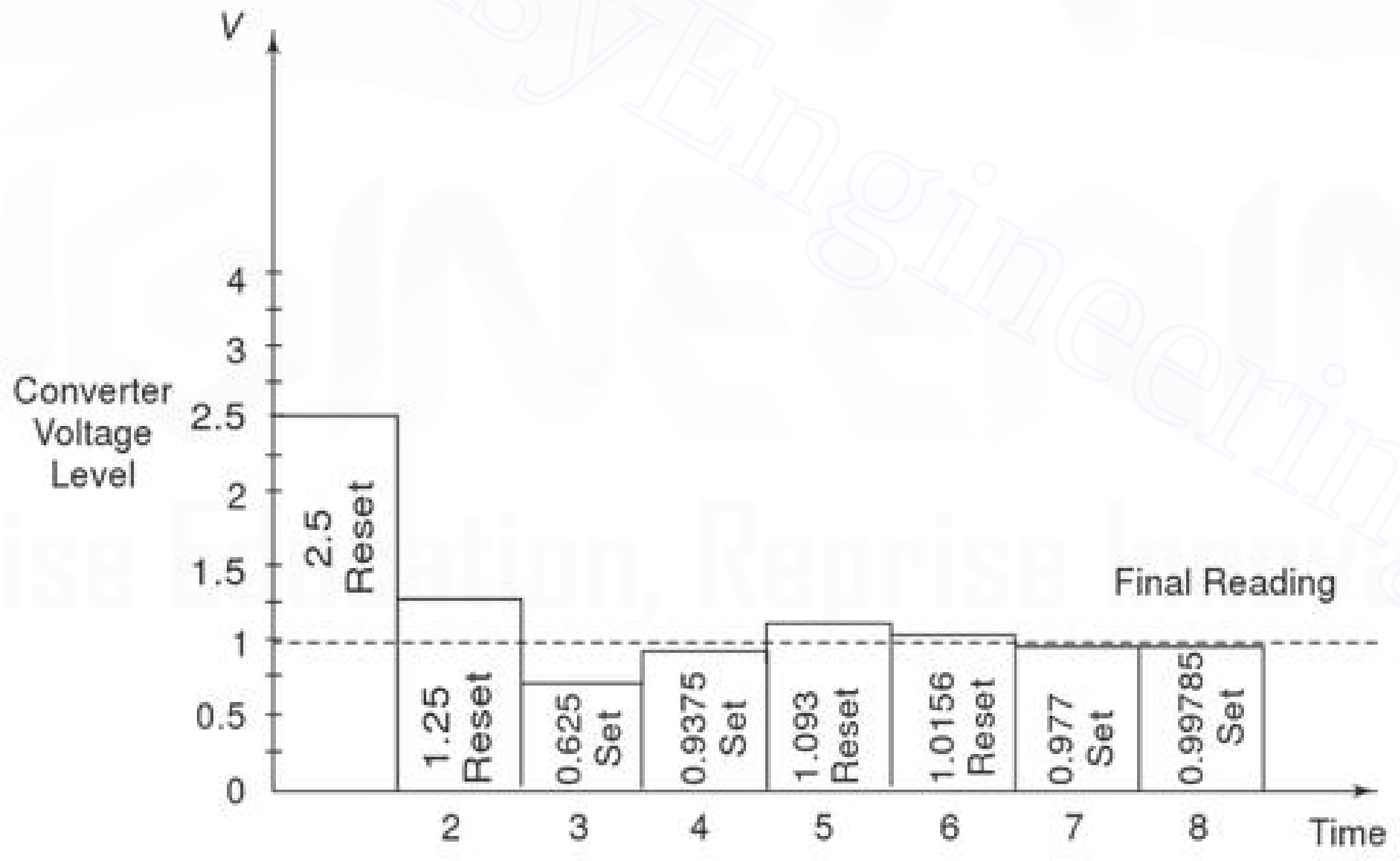


Fig. 5.11 Various output levels for each bit (8-Bit shows the voltage level very nearly equal to 1 V)

Therefore, V_{in} nearly equals V_{out}, i.e. V_{in} = 1 V and V_{out} = 0.99785. The main advantage of this method is speed. At best it takes n clock pulses to produce an n bit result. Even if the set, test, set or reset operation takes more than 1 clock pulse, the SAR method is still considerably faster than the counter method. However the control circuit is more complex in design and cost is enhanced. This digital voltmeter is capable of 1000 readings per second.

With input voltages greater than dc, the input level changes during digitisation and decisions made during conversion are not consistent. To avoid this error, a sample and hold circuit is used and placed in the input directly following the input attenuator and amplifier.

In its simplest form, the sample and hold (S/H) circuit can be represented by a switch and a capacitor, as shown in Fig. 5.12.

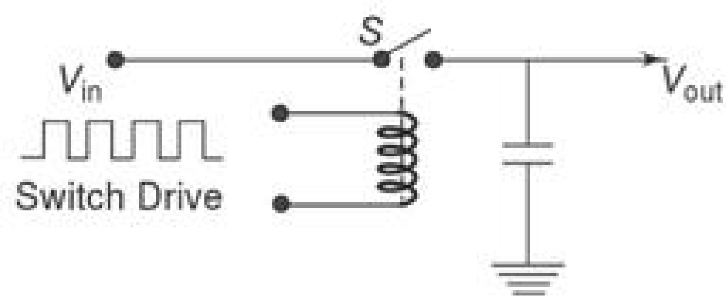


Fig. 5.12 Simple sample hold circuit

In the Sample mode, the switch is closed and the capacitor charges to the instantaneous value of the input voltage.

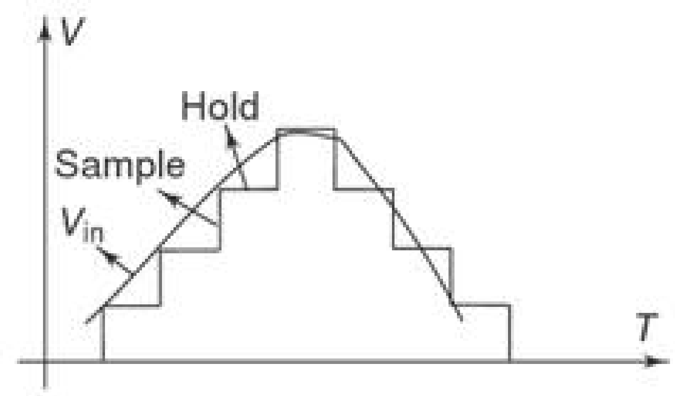


Fig. 5.13 Output waveform of a sample and hold circuit

In the Hold mode, the switch is opened and the capacitor holds the voltage that it had at the instant the switch was opened. If the switch drive is synchronized with the ring counter pulse, the actual measurement and conversion takes place when the S/H circuit is in the Hold mode. The output waveform of a sample and hold circuit is shown in Fig. 5.13.

An actual sample and hold circuit is shown in Fig. 5.14. The sample pulse operates switches 1 and 3. The hold pulse operates switches 2 and 4. The sample-hold pulses are complementary.

In the sample mode the hold capacitor is charged up by the Opamp. In the hold mode, the capacitor is switched into the feedback loop, while input resistors R_1 and R_f are switched to ground. Opamps are used to increase the available driving current into the capacitor or to isolate the capacitor from an external load on the output.

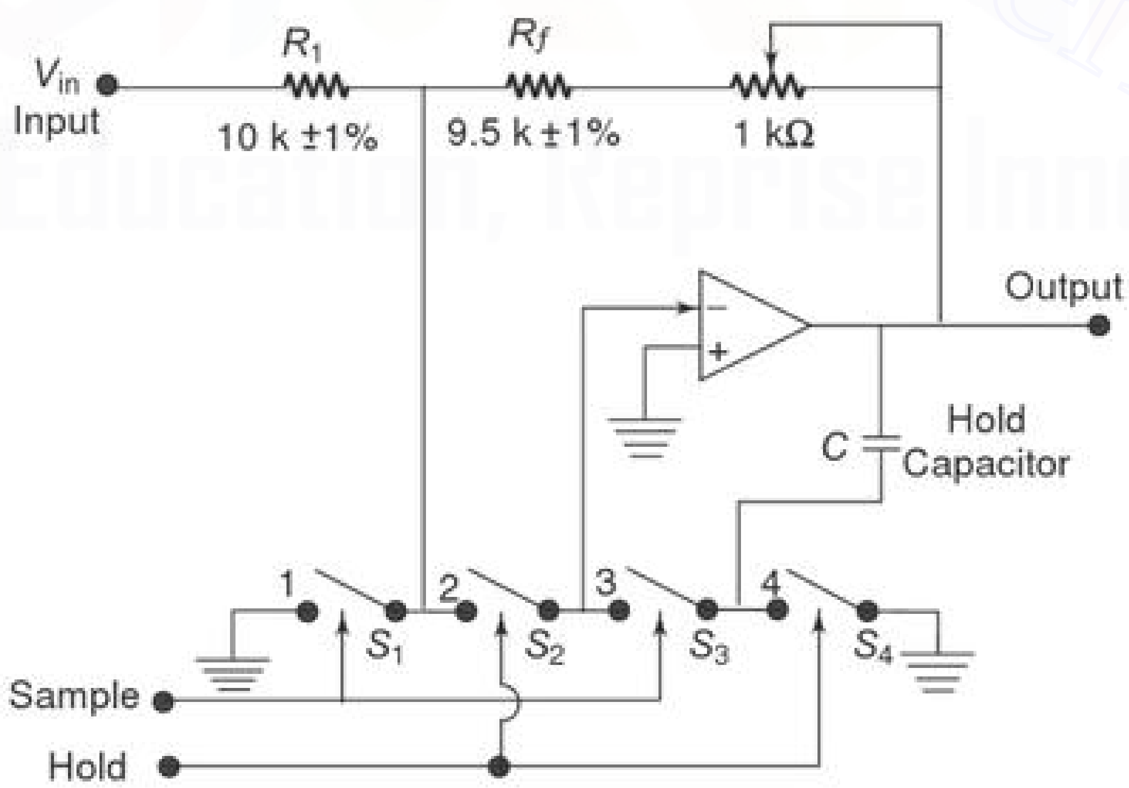


Fig. 5.14 Practical sample and hold circuit

The S/H circuit is basically an Opamp that charges the capacitor during the Sample mode and retains the charge during the Hold mode.

CONTINUOUS BALANCE DVM OR SERVO BALANCING POTENTIOMETER TYPE DVM 5.7

The basic block diagram of a servo balancing potentiometer type DVM is shown in Fig. 5.15.

The input voltage is applied to one side of a mechanical chopper comparator, the other side being connected to the variable arm of a precision potentiometer. The output of the chopper comparator, which is driven by the line voltage at the line frequency rate, is a square wave signal whose amplitude is a function of the difference in voltages connected to the opposite side of the chopper. The square wave signal is amplified and fed to a power amplifier, and the amplified square wave difference signal drives the arm of the potentiometer in the direction needed to make the difference voltage zero. The servo-motor also drives a mechanical readout, which is an indication of the magnitude of the input voltage.

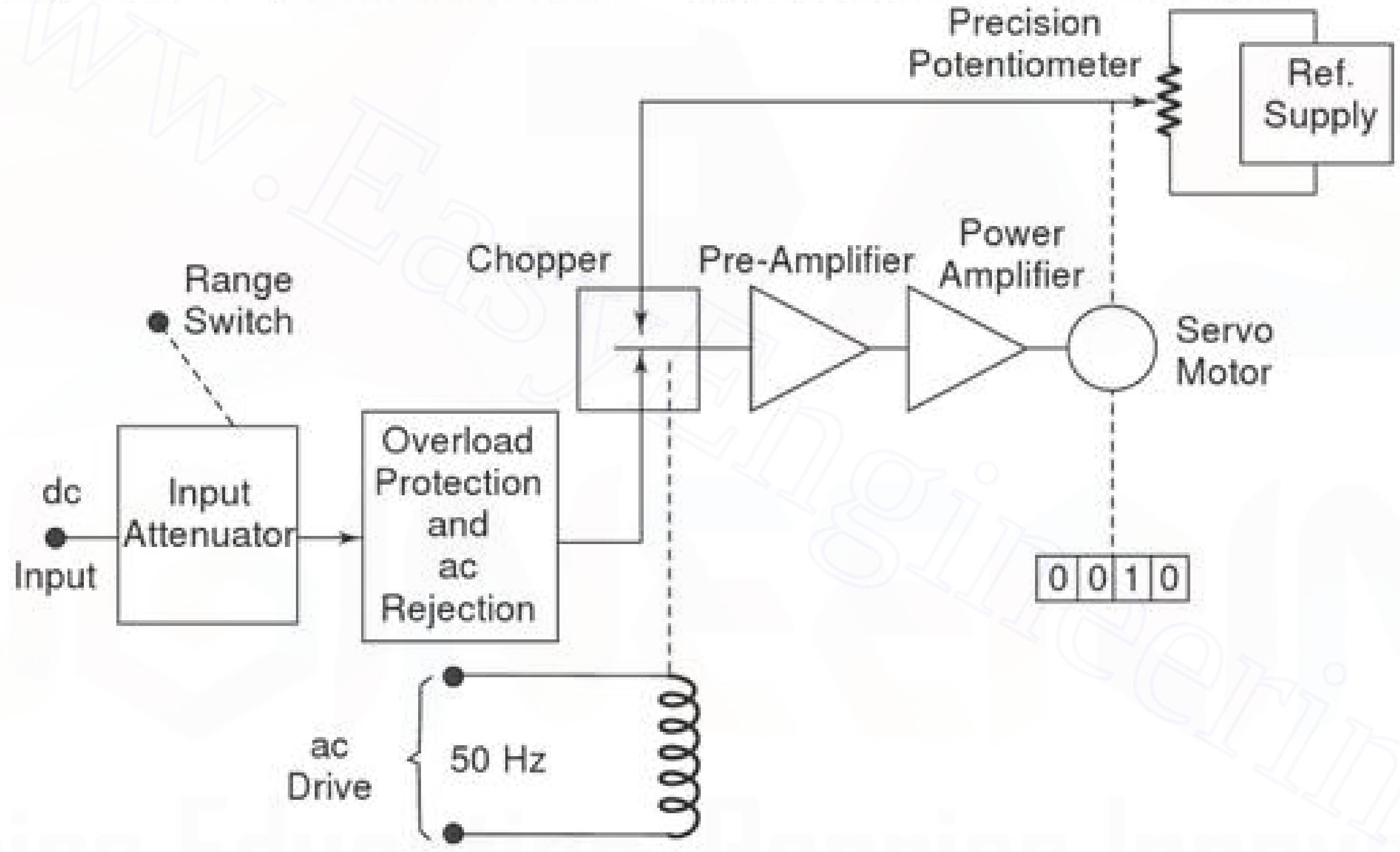


Fig. 5.15 Block diagram of a servo balancing potentiometer type DVM

This DVM uses the principle of balancing, instead of sampling, because of mechanical movement. The average reading time is 2 s.

3½-DIGIT 5.8

The number of digit positions used in a digital meter determines the resolution. Hence a 3 digit display on a DVM for a 0 –1 V range will indicate values from 0 – 999 mV with a smallest increment of 1 mV.

Normally, a fourth digit capable of indicating 0 or 1 (hence called a Half Digit) is placed to the left. This permits the digital meter to read values above 999 up to 1999, to give overlap between ranges for convenience, a process called over-ranging. This type of display is called a 3½ digit display, shown in Fig. 5.16.

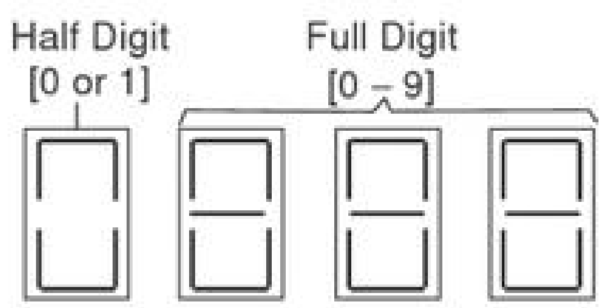


Fig. 5.16 3½-Digit display

RESOLUTION AND SENSITIVITY OF DIGITAL METERS 5.9

Resolution If n = number of full digits, then resolution (R) is $1/10^n$.

The resolution of a DVM is determined by the number of full or active digits used,

If $n = 3$, $$R = \frac{1}{10^n} = \frac{1}{10^3} = 0.001 \text{ or } 0.1\,\%$$

Sensitivity of Digital Meters Sensitivity is the smallest change in input which a digital meter is able to detect. Hence, it is the full scale value of the lowest voltage range multiplied by the meter's resolution.

$$\text{Sensitivity } S = (fs)_{\min} \times R$$

where $(f_S)_{\min}$ = lowest full scale of the meter
R = resolution expressed as decimal

Example 5.5 *What is the resolution of a 3½ digit display on 1 V and 10 V ranges?*

Solution Number of full digits is 3. Therefore, resolution is $1/10^n$ where $n = 3$.
Resolution $R = 1/10^3 = 1/1000 = 0.001$

Hence the meter cannot distinguish between values that differ from each other by less than 0.001 of full scale.

For full scale range reading of 1 V, the resolution is $1 \times 0.001 = 0.001$ V.

For full scale reading of 10 V range, the resolution is $10 \text{ V} \times 0.001 = 0.01$ V.

Hence on 10 V scale, the meter cannot distinguish between readings that differ by less than 0.01 V.

Example 5.6 *A 4½ digit voltmeter is used for voltage measurements.*

(i) Find its resolution

(ii) How would 12.98 V be displayed on a 10 V range?

(iii) How would 0.6973 be displayed on 1 V and 10 V ranges.

Solution

(i) Resolution $= 1/10^n = 1/10^4 = 0.0001$
where the number of full digits is $n = 4$

(ii) There are 5 digit places in 4½ digits, therefore 12.98 would be displayed as 12.980.
Resolution on 1 V range is $1 \text{ V} \times 0.0001 = 0.0001$
Any reading up to the 4th decimal can be displayed.
Hence 0.6973 will be displayed as 0.6973.

(iii) Resolution on 10 V range $= 10 \text{ V} \times 0.0001 = 0.001$ V
Hence decimals up to the 3rd decimal place can be displayed.
Therefore on a 10 V range, the reading will be 0.697 instead of 0.6973.

GENERAL SPECIFICATIONS OF A DVM 5.10

Display	:	3-1/2 digits, LCD
Unit Annunciation	:	mV, V, mA, Ω, kΩ, MΩ, buzzer, B(low battery)
	:	MANU (Manual), ac and ⊣▷⊢ (diode test)
Max. Indication	:	1999 or – 1999
Over-range indication	:	only (1) or (– 1) displayed at the MSB position.
Polarity	:	AUTO negative polarity indication.
Zero adjustment	:	Automatic
Functions	:	DC volts, AC volts, DC amps, AC amps, Ohms, continuity test, diode test.
Ranging	:	Selectable automatic or manual
Automatic	:	Instrument automatically selects maximum range for measurement and display. Auto ranging operates on all functions except for dc or ac current.
Manual	:	Switch selection as desired
Sampling Rate	:	2 sample/s, nominal
Low Battery	:	B mark on LCD readout
Temperature	:	Operating 0°C – 40°C, < 80% RH (Relative humidity)
	:	Storage – 20°C – 60°C, < 70% RH
Power	:	Two AA size 1.5 V batteries. Life 2000 hours typically with zinc-carbon.
Standard accessories	:	Probe red-black, safety fuse 250 – 0.2 A
Size	:	160 (L) × 80 (B) × 30 (H)
Weight	:	250 g without batteries.
Input impedance	:	11 MΩ – 1000 MΩ
Accuracy	:	± 0.5% – 0.7% or ± 5 digit for dc
	:	1.0% reading or ± 5 digit for ac at 40 – 500 kHz

MICROPROCESSOR-BASED RAMP TYPE DVM 5.11

A basic block diagram of a microprocessor-based Ramp type DVM and its operating waveform is shown in Fig. 5.17 (a) and (b) respectively. Depending on the command fed to the control input of the multiplexer by the microprocessor, input 1 of the comparator can be consecutively connected to the input 1, 2 or 3 of the multiplexer.

The multiplexer has three inputs -- input 1 is connected to ground potential, input 2 is the unknown input, and input 3 is the reference voltage input. The comparator has two inputs -- input 1 accepts the output signal from the multiplexer, and input 2 accepts the ramp voltage from the ramp generator.

The microprocessor remains suspended in the resting state until it receives a command to start conversion. During the resting period, it regularly sends reset signals to the ramp generator. Each time the ramp generator is reset, its capacitor discharges. It produces a ramp, i.e. a sawtooth voltage whose duration, T_r and amplitude, V_m remain constant. The time duration between the consecutive pulses is sufficiently large enough for the capacitor to get discharged.

Whenever a conversion command arrives at the microprocessor at a time t_1, the multiplexer first connects input 1 of the comparator to its input 1 (i.e. ground potential) and brings the former to ground potential.

The microprocessor pauses until another sawtooth pulse begins. When input 2 voltage, arriving from the ramp generator becomes equal to input 1 of the comparator, the comparator sends a signal to the microprocessor, that ramp voltage is zero. The microprocessor measures this time interval Δt_1 (shown in Fig. 5.17 (b)), by counting the number of clock pulses supplied by the clock generator during this time interval. Let the count during this time be N_1, which is then stored by the microprocessor. A command from the microprocessor now causes the comparator input 1 to be connected to input 2 of the multiplexer. This connects the unknown voltage, V_x to the input 1 of the comparator. At an instant, when the ramp voltage equals the unknown voltage, the comparator sends a signal to the microprocessor that measure the time interval Δt_2 (Fig. 5.17 (b)). The count N_2, during this time interval is also stored.

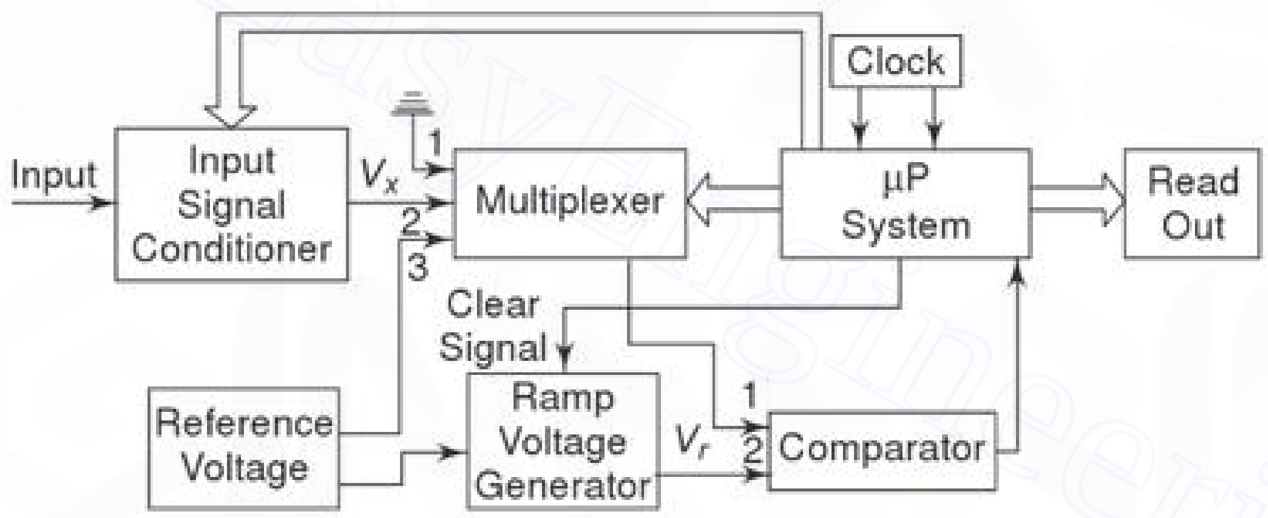


Fig. 5.17 (a) Basic block diagram of a microprocessor-based ramp type DVM

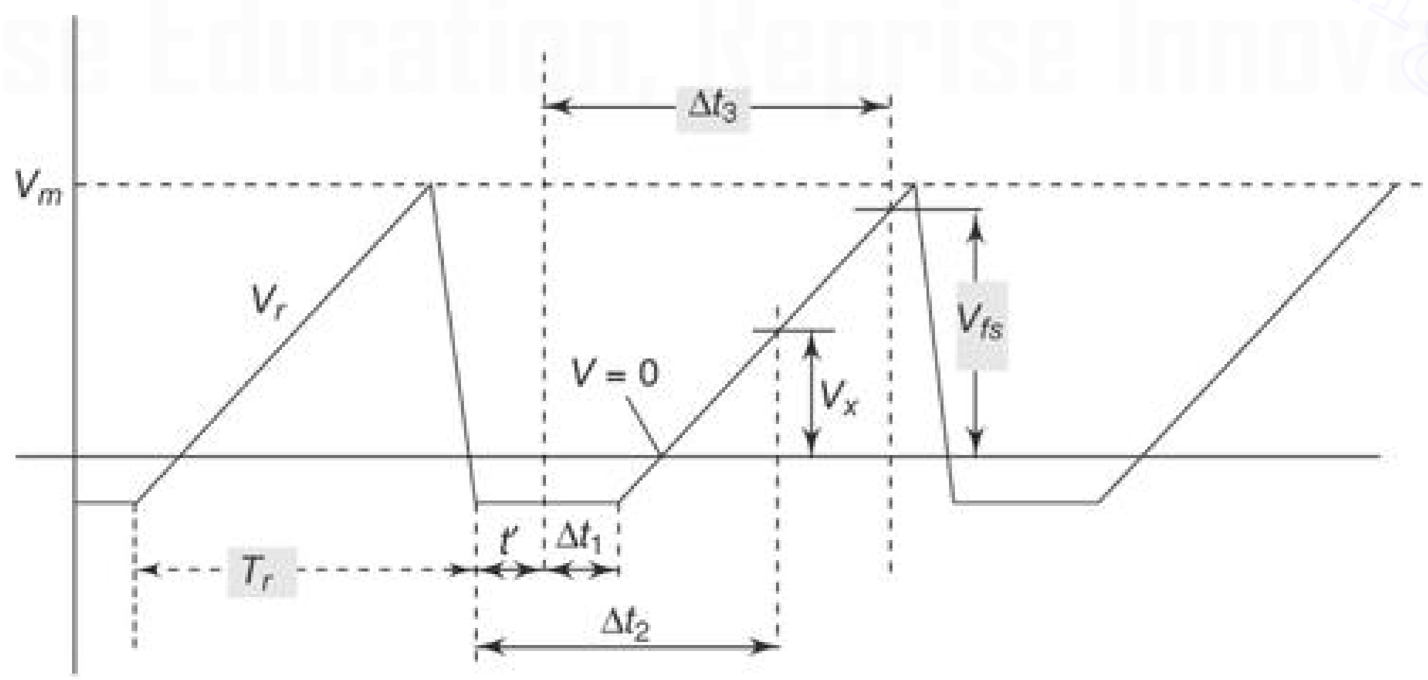


Fig. 5.17 (b) Operating waveform of a rp-based ramp type DVM

Now, the next command from the microprocessor causes the comparator input 1 to be connected to the input 3 of the multiplexer, which is the reference voltage (full scale voltage). The value of the reference voltage sets the upper limit of measurement, that is, full scale value. At the instant, when the ramp voltage equals the reference voltage, a pulse is sent to the microprocessor from the comparator output to measure this time interval, Δt_3 (Fig. 5.17 (b)). The count, N_3 during this time interval is also stored.

The microprocessor then computes the unknown voltage V_x by the equation

$$V_x = C \cdot \frac{(N_2 - N_1)}{(N_3 - N_1)}$$

where C is the coefficient dependent on the characteristics of the instrument and the units selected to express the result.

In this method of measurement, the zero drift has practically no effect on the result, because of the variation of slope of the ramp.

Hence from the Fig. 5.17 (b),

$$\frac{(\Delta t_2 - \Delta t_1)}{(\Delta t_3 - \Delta t_1)} = \frac{V_x}{V_{fs}}$$

$$\therefore \qquad V_x = V_{fs} \cdot \frac{(\Delta t_2 - \Delta t_1)}{(\Delta t_3 - \Delta t_1)}$$

Since the clock pulse repetition frequency f_c and full scale voltage V_{fs} are maintained at a very high level of stability and clock pulses allowed to fall within all the time intervals come from a common source, the above equation may be rewritten as

$$V_x = C \cdot \frac{(N_2 - N_1)}{(N_3 - N_1)}$$

where N_1, N_2, N_3 are the counts representing respectively, the zero drift, the unknown voltage, and the full scale voltage.

Advantages

1. Its scale size remains constant due to zero drift correction and maximum count.
2. The accuracy of the instrument is not affected by the time and temperature instabilities of the circuit element values.
3. There is a good repeatability in switching instants in the presence of noise and interference. This is because the ramp approaches the point at which the comparator operates always the same side and always the same rate.

Disadvantages

Noise and interference cannot be suppressed.

Review Questions

1. State the advantages of a DVM over an analog meter.
2. How are DVMs classified?
3. State the operating and performance characteristics of a digital voltmeter.
4. State distinguished features of digital instruments as compared to analog instruments.
5. Explain the operating principle of a ramp type DVM.
6. Describe with a diagram the operation of ramp type DVM. State limitations of a ramp type DVM and how it is overcome.
7. Explain with the help of diagram the working principle of dual slope type DVM.
8. Describe with a diagram the operation of a dual slope type DVM.
9. State the advantages of a dual slope DVM over a ramp type DVM.
10. Explain the operating principle of Voltage to frequency type DVM.
11. Describe with the help of a block diagram the operation of integrating type digital voltmeter.
12. State the principle of a staircase ramp type DVM.
13. Describe with a diagram the operation of a staircase ramp type DVM. State the advantages of a staircase ramp type DVM.
14. Explain with a diagram, the basic principle of a successive approximation type DVM.
15. Describe with a diagram the operation of a SAR type DVM.
16. State features of a SAR type DVM over other DVMs. What are the advantages of a SAR type DVM over other DVMs?
17. State the principle of operation of a continuous balance DVM.
18. Describe with a diagram the operation of a servo balancing potentiometer type DVM.
19. Define sensitivity of a digital meter. State significance of a half digit.
20. Define the term overrange and half digit. Define resolution of digital meter.
21. What is a sample hold circuit? State its significance. What is the advantage of using a sample hold circuit?
22. State some of the general features of a DVM.
23. State the basic principle of a microprocessor based DVM.
24. Describe with a block diagram the operation of a microprocessor based DVM. State the advantages of a microprocessor based DVM.

Multiple Choice Questions

1. Measurement in a ramp type DVM is performed during the
   (a) negative slope
   (b) positive slope
   (c) both of the slope
   (d) none of the above
2. Measurement by dual slope DVM is performed during
   (a) rising slope
   (b) falling slope
   (c) rising and falling slope
   (d) none of the slope
3. The principle of voltage to time conversion is used in
   (a) dual slope type DVM
   (b) successive approximation type DVM
   (c) integrating type DVM
   (d) none of the above
4. SAR type DVM uses the principle of
   (a) voltage to time conversion
   (b) voltage to frequency conversion
   (c) voltage to binary conversion
   (d) voltage to current conversion

5. Dual slope operates on the principle of
   (a) voltage to time conversion
   (b) voltage to frequency conversion
   (c) frequency to voltage conversion
   (d) voltage to current conversion

Practice Problems

1. The lowest range on a 4-1/2 digit multimeter is 10 mV full scale. Determine the sensitivity of the meter.
2. The lowest range on a 3-1/2 digit multimeter is 10 mV full scale. Determine the sensitivity of the meter.
3. A 3-1/2 digit DVM is used for measuring voltage .Determine the resolution. How would a voltage of 14.42 be displayed on 10 V range and 100 V range.
4. A 3-1/2 digit DVM has an accuracy of ±0.5% of reading ±1 digit. Determine the possible error in V, when the instrument is reading 5 V in 10 V range
5. A 3-1/2 digit voltmeter is used for voltage measurement.
   (i) Find its resolution.
   (ii) How would 11.52 V be displayed on the 10 V range?
   (iii) How would .5234 V be displayed on 1 V and 10 V ranges?
6. Determine the binary equivalent of 2.567 V for a SAR type DVM having 10 bits output and a reference voltage of +5 V.
7. Determine the binary equivalent of 8.735 V for a SAR type DVM having 10 bits output and a reference voltage of +12 V.

Further Reading

1. A.J. Bouwens, *Digital Instrumentation*, McGraw-Hill, 1986.
2. K.J. Dean, *Digital Instruments*, Chapman and Hall, 1965.
3. E.O. Doebelin, *Measurements Systems: Applications and Design*, 4th Edition, McGraw-Hill, 1990.

Chapter 6

Digital Instruments

INTRODUCTION 6.1

Digital instruments are rapidly replacing their analog counterparts. The parameters of interest in a laboratory environment are (i) voltage (ii) current (iii) power (iv) frequency, and (v) logic.

We shall consider digital systems which measure the above parameters. To enable digital systems to recognise information, inputs which are analog in nature must be converted to digital form. Hence any digital instrument would invariably consist of an analog to digital converter in its input stage. The basic building block of a digital instrument is shown in Fig. 6.1.

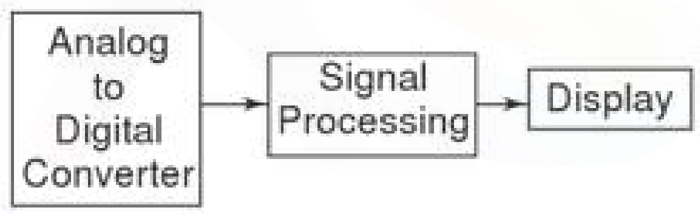


Fig. 6.1 Building block of a digital instrument

The display block may be analog or digital in nature. If an analog readout is desired, it becomes necessary to include a stage involving digital to analog conversion.

Digital systems may consist of the following components.

1. Resistors
2. Capacitors
3. Transistors
4. Linear ICs
5. Digital ICs
6. Display devices
7. Analog to digital converters
8. Digital to analog converters

The digital form of measurement can be used to display the measured quantity numerically instead of a deflection, as in conventional analog meters. Data in digital form facilitates various operations that are normally required in signal processing. An increase in the availability and type of computer facilities and a decrease in the cost of various modules required for digital systems is accelerating the development of digital instrumentation for measurement and signal processing.

DIGITAL MULTIMETERS 6.2

Analog meters require no power supply, they give a better visual indication of changes and suffer less from electric noise and isolation problems. These meters are simple and inexpensive.

Digital meters, on the other hand, offer high accuracy, have a high input impedance and are smaller in size. They gives an unambigious reading at greater viewing distances. The output available is electrical (for interfacing with external equipment), in addition to a visual readout.

The three major classes of digital meters are panel meters, bench type meters and system meters.

All digital meters employ some kind of analog to digital (A/D) converters (often dual slope integrating type) and have a visible readout display at the converter output.

Panel meters are usually placed at one location (and perhaps even a fixed range), while bench meters and system meters are often multimeters, i.e. they can read ac and dc voltage currents and resistances over several ranges.

The basic circuit shown in Fig. 6.2 (a) is always a dc voltmeter. Current is converted to voltage by passing it through a precision low shunt resistance while alternating current is converted into dc by employing rectifiers and filters. For resistance measurement, the meter includes a precision low current source that is applied across the unknown resistance; again this gives a dc voltage which is digitised and readout as ohms.

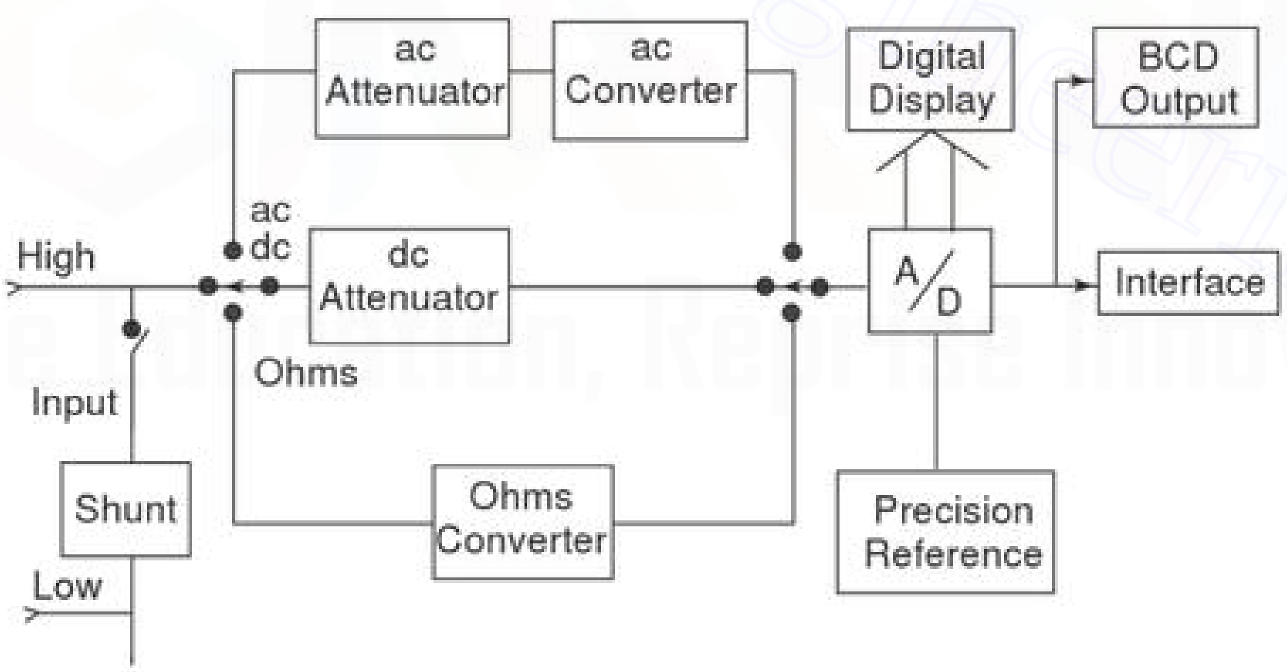


Fig. 6.2 (a) Digital multimeter

Bench meters are intended mainly for stand alone operation and visual operation reading, while system meters provide at least an electrical binary coded decimal output (in parallel with the usual display), and perhaps sophisticated interconnection and control capabilities, or even microprocessor based computing power.

A basic digital multimeter (DMM) is made up of several A/D converters, circuitry for counting and an attenuation circuit. A basic block diagram of a DMM is shown in Fig. 6.2 (b). The current to voltage converter shown in the block diagram of Fig. 6.2 (b) can be implemented with the circuit shown in Fig. 6.2 (c).

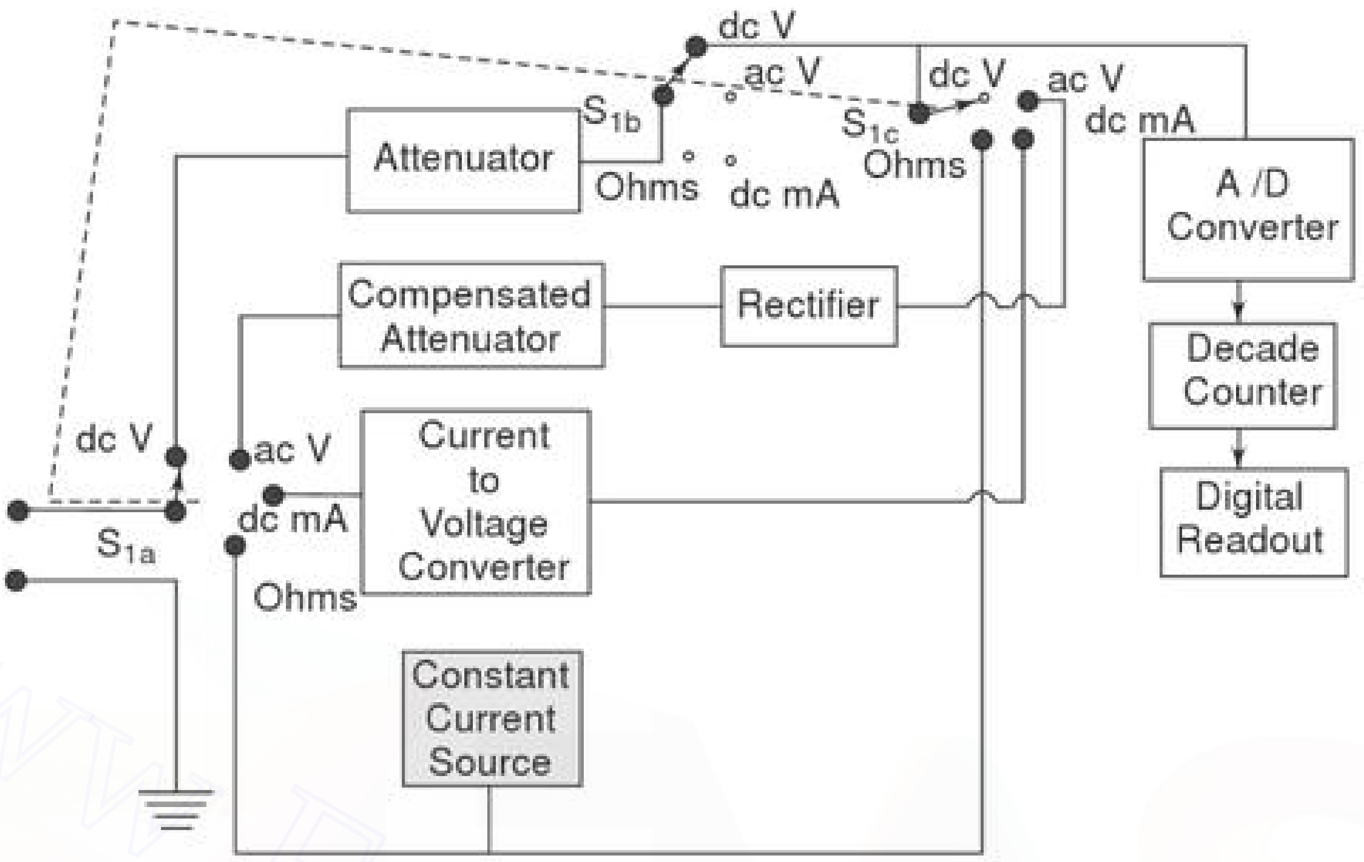


Fig. 6.2 (b) Block diagram of a basic digital multimeter

The current to be measured is applied to the summing junction ($\Sigma\ i$) at the input of the opamp. Since the current at the input of the amplifier is close to zero because of the very high input impedance of the amplifier, the current I_R is very nearly equal to I_i, the current I_R causes a voltage drop which is proportional to the current, to be developed across the resistors. This voltage drop is the input to the A/D converter, thereby providing a reading that is proportional to the unknown current.

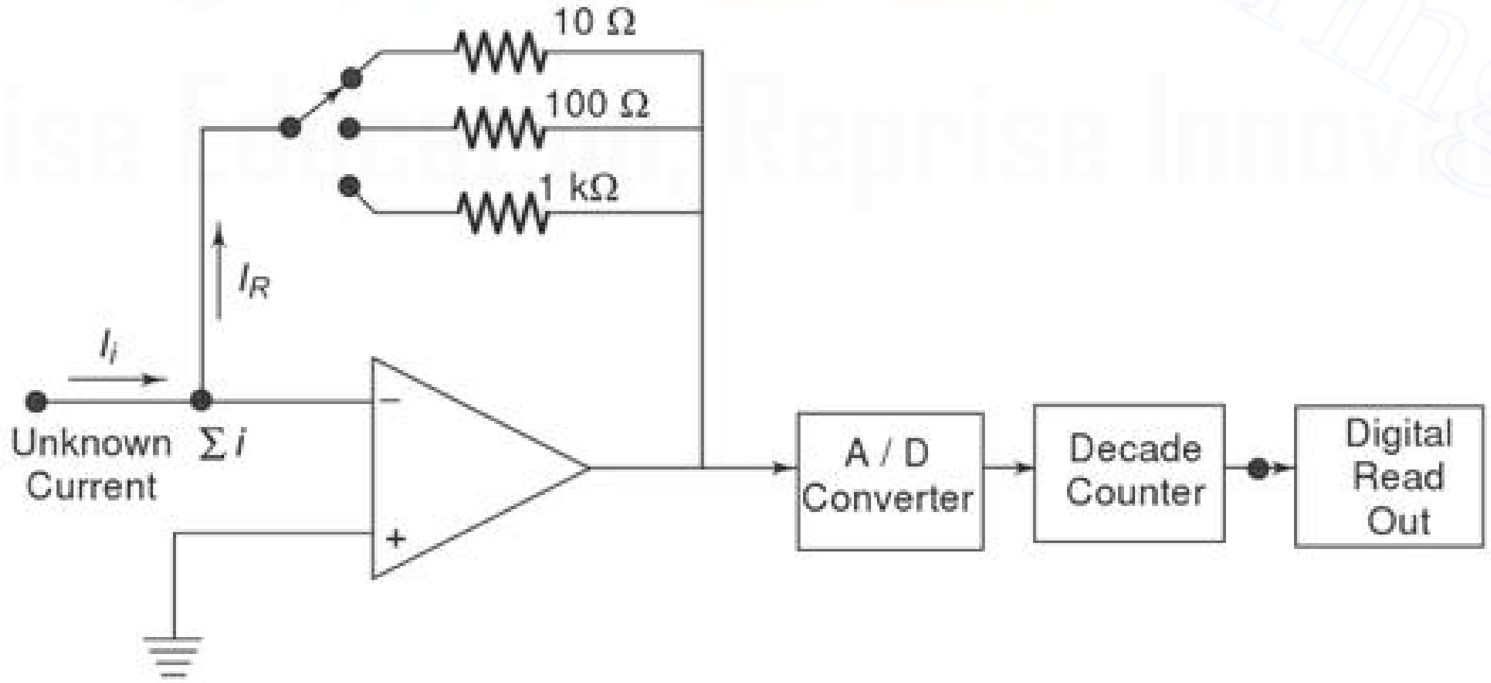


Fig. 6.2 (c) Current to voltage converter

Resistance is measured by passing a known current, from a constant current source, through an unknown resistance. The voltage drop across the resistor is applied to the A/D converter, thereby producing an indication of the value of the unknown resistance.

6.2.1 Digital Panel Meters (DPM)

Digital panel meters are available in a very wide variety of special purpose functions. They have a readout range from the basic 3 digit (999 counts, accuracy of ± 0.1% of reading, ± 1 count) to high precision 4¾ digit ones (± 39,999 counts, accuracy ± 0.005% of reading ± 1 count). Units are available to accept inputs such as dc voltage (from microvolts range to ± 20 volts) ac voltage (for true rms measurement), line voltage, strain gauge bridges (meter provides bridge excitation), RTDs (meter provides sensor excitation), thermocouples of many types (meter provides cold junction compensation and linearisation) and frequency inputs, such as pulse tachometers.

Figure 6.3 shows some details of a high precision unit with an input resistance of $10^9\ \Omega$, ± 0.00250% resolution (10 μV), and ± 0.005% of reading ± 1 count accuracy, which uses a dual slope A/D conversion with automatic zero. The sampling rate is 2.5 per second when it is free running and a maximum of 10 per second when it is externally triggered.

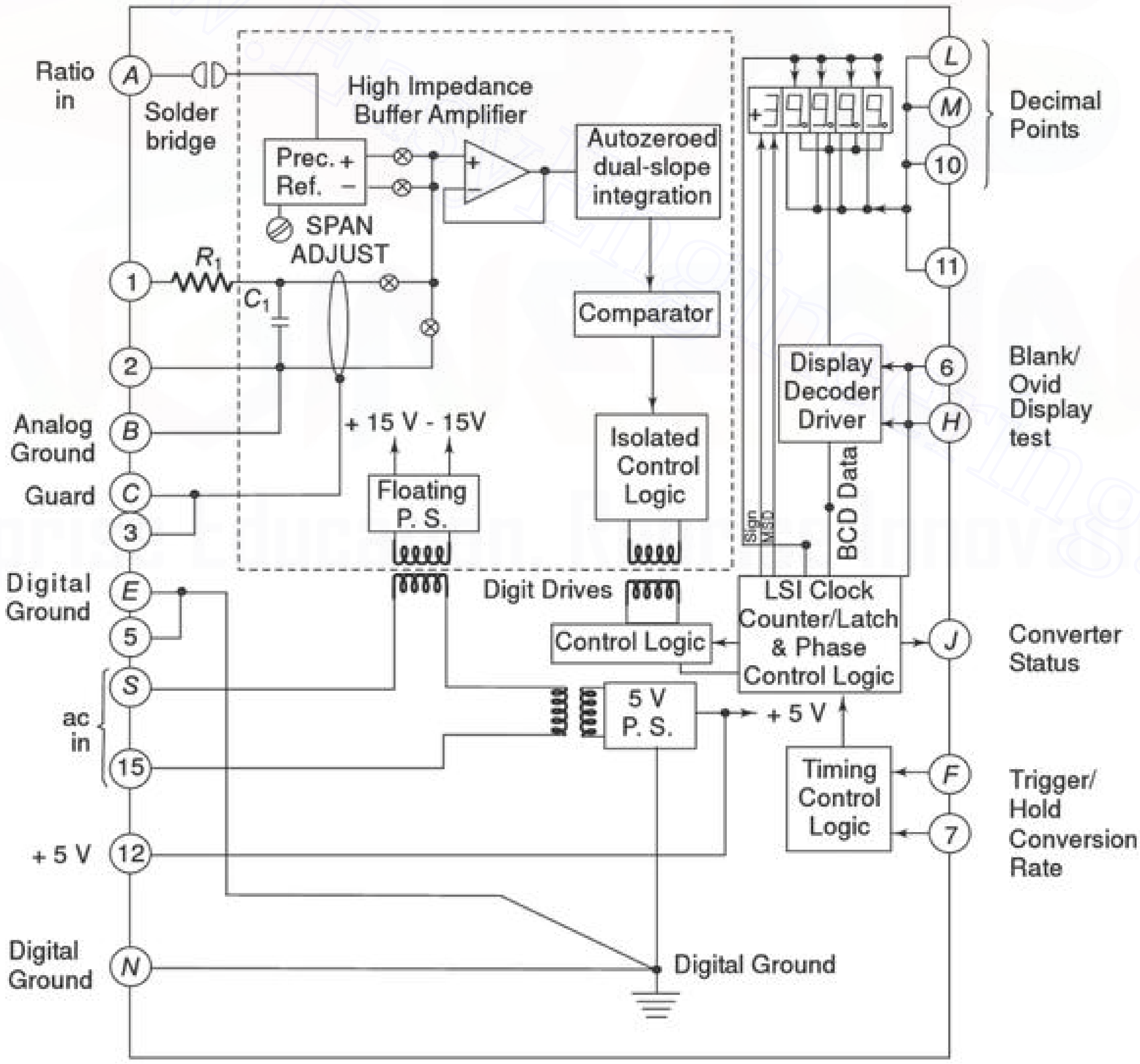


Fig. 6.3 High precision digital panel meter

These meters can be obtained with a tri-state binary coded decimal output. Tri-state outputs provide a high impedance (disconnected) state, in addition to the usual digital high and low. This facilitates interconnection with the microcomputer data buses, since any number of devices can be serviced by a single bus, one at a time, disconnecting all except the two that are communicating with each other.

6.2.2 Bench Type Meters

Bench type meters range from inexpensive hand held units with a 3½ digit readout and 0.5% accuracy, to 5½ digit (200,000 count) devices with 1 μV resolution. Digital nanovoltmeters are designed to measure extremely low voltages and they provide resolution down to about 10 nV (comparable analog meters go to about 1 nV).

Digital picoammeters measure very small currents and can resolve about 1 pA (analog instruments go to 3 femto (10^{-15}) amperes). When extremely high input impedance is required for current, voltage, resistance or charge measurements, an electrometer type of instrument is employed.

Digital electrometer can resolve 10^{-17} A, 10 μV and 1 femto charge and measure resistance as high as 200 T Ω (Tera = 10^{12}). The input impedance can be as high as 10,000 T Ω.

6.2.3 System Type Meters

System type DVMs or DMMs are designed to provide the basic A/D conversion function in data systems assembled by interfacing various peripheral devices with DVM capabilities and their cost vary widely.

A microprocessor is used to provide several mathematical functions in addition to managing the meter operations. A modified dual slope A/D converter is used with selectable integration times, ranging from 0.01 to 100 power lines cycle. At maximum speed (330 readings per second) accuracy is ± 0.1%, while 0.57 readings per second gives a 6½ digit resolution and 0.001% accuracy. Ac and dc voltages and resistance modes are available. The mathematical functions include the following.

1. Null
2. First reading is subtracted from each successive reading and the difference is displayed. (The first reading can be manually entered from the key-board.)
3. The function STAT accumulates reading and calculates mean and variance, (STAT-Statistics).
4. With dBm (*R*), the user enters the resistance and then all readings are displayed as power dissipated in *R* in decibel units (referred to 1 mV).
5. With THMS°F (voltmeter in ohms range), the temperature of a thermistor probe is displayed in degrees Fahrenheit or Centigrade (THMS - Temperature of Thermistor)

6. The function $(X - Z)/Y$ provides offsetting and scaling with user entered Z and Y constants (where X is the reading).
7. The function $100 \times (X - Y)/Y$ determines the percentage deviation, and 20 log X/Y displays X in decibels relative to the value of Y. An internal memory (RAM) can be used to store the results of measurements and programs for taking the measurements.

DIGITAL FREQUENCY METER 6.3

Principle of Operation The signal waveform is converted to trigger pulses and applied continuously to an AND gate, as shown in Fig. 6.4. A pulse of 1 s is applied to the other terminal, and the number of pulses counted during this period indicates the frequency.

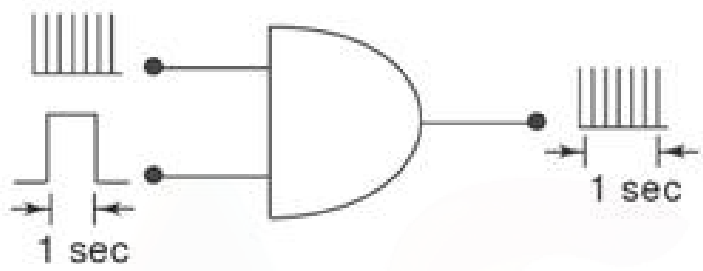


Fig. 6.4 Principle of digital frequency measurement

The signal whose frequency is to be measured is converted into a train of pulses, one pulse for each cycle of the signal. The number of pulses occurring in a definite interval of time is then counted by an electronic counter. Since each pulse represents the cycle of the unknown signal, the number of counts is a direct indication of the frequency of the signal (unknown). Since electronic counters have a high speed of operation, high frequency signals can be measured.

6.3.1 Basic Circuit of a Digital Frequency Meter

The block diagram of a basic circuit of a digital frequency meter is shown in Fig. 6.5.

Fig. 6.5 Basic circuit of a digital frequency meter

The signal may be amplified before being applied to the Schmitt trigger. The Schmitt trigger converts the input signal into a square wave with fast rise and fall times, which is then differentiated and clipped. As a result, the output from the Schmitt trigger is a train of pulses, one pulse for each cycle of the signal.

The output pulses from the Schmitt trigger are fed to a START/STOP gate. When this gate is enabled, the input pulses pass through this gate and are fed directly to the electronic counter, which counts the number of pulses.

When this gate is disabled, the counter stops counting the incoming pulses. The counter displays the number of pulses that have passed through it in the time interval between start and stop. If this interval is known, the unknown frequency can be measured.

6.3.2 Basic Circuit for Frequency Measurement

The basic circuit for frequency measurement is as shown in Fig. 6.6. The output of the unknown frequency is applied to a Schmitt trigger, producing positive pulses at the output. These pulses are called the counter signals and are present at point *A* of the main gate. Positive pulses from the time base selector are present at point *B* of the START gate and at point *B* of the STOP gate.

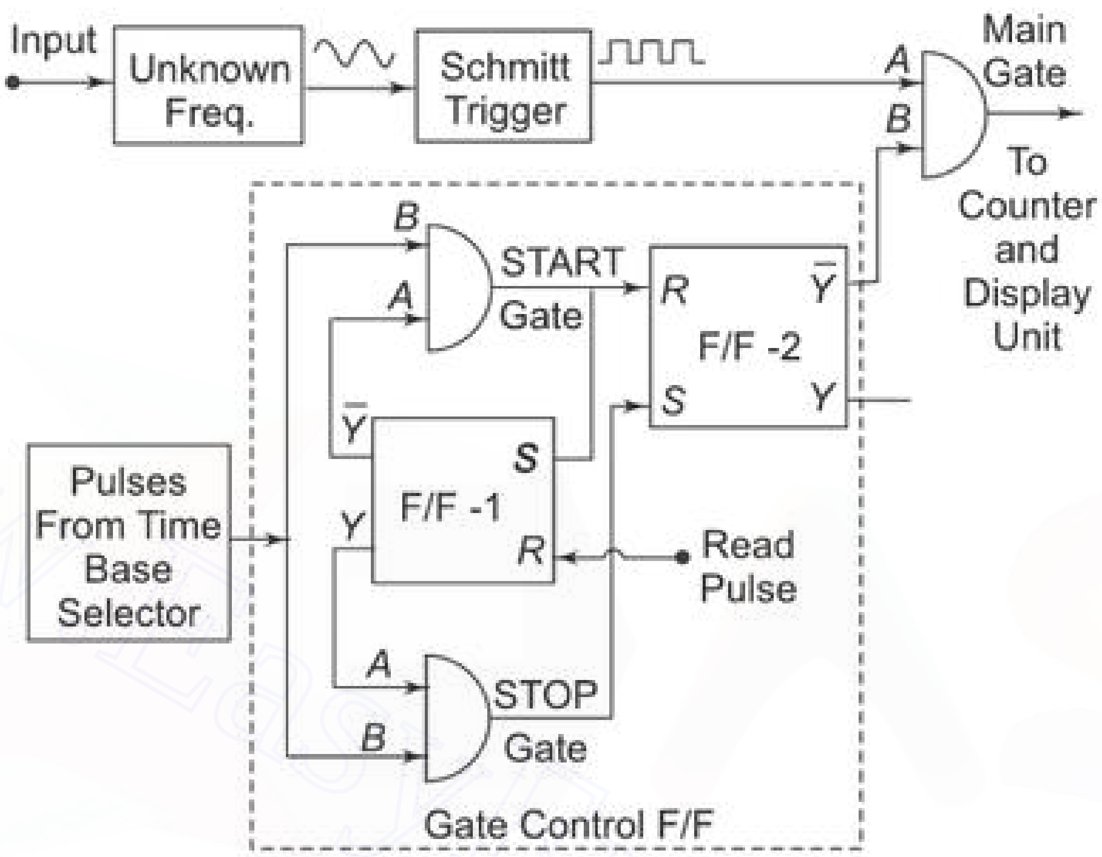


Fig. 6.6 Basic circuit for measurement of frequency showing gate control F/F

Initially the Flip-Flop (F/F–1) is at its logic 1 state. The resulting voltage from output *Y* is applied to point *A* of the STOP gate and enables this gate. The logic 0 stage at the output $\bar{Y}$ of the F/F–1 is applied to the input A of the START gate and disables the gate.

As the STOP gate is enabled, the positive pulses from the time base pass through the STOP gate to the Set (S) input of the F/F–2 thereby setting F/F–2 to the 1 state and keeping it there.

The resulting 0 output level from $\bar{Y}$ of F/F–2 is applied to terminal *B* of the main gate. Hence no pulses from the unknown frequency source can pass through the main gate.

In order to start the operation, a positive pulse is applied to (read input) reset input of F/F–1, thereby causing its state to change. Hence $\bar{Y} = 1$, $Y = 0$, and as a result the STOP gate is disabled and the START gate enabled. This same read pulse is simultaneously applied to the reset input of all decade counters, so that they are reset to 0 and the counting can start.

When the next pulse from the time base arrives, it is able to pass through the START gate to reset F/F–2, therefore, the F/F–2 output changes state from 0 to 1, hence $\bar{Y}$ changes from 0 to 1. This resulting positive voltage from $\bar{Y}$ called the gating signal, is applied to input *B* of the main gate thereby enabling the gate.

Now the pulses from the unknown frequency source pass through the main gate to the counter and the counter starts counting. This same pulse from the

START gate is applied to the set input of F/F–1, changing its state from 0 to 1. This disables the START gate and enables the STOP gate. However, till the main gate is enabled, pulses from the unknown frequency continue to pass through the main gate to the counter.

The next pulse from the time base selector passes through the enabled STOP gate to the set input terminal of F/F–2, changing its output back to 1 and $\overline{Y} = 0$. Therefore the main gate is disabled, disconnecting the unknown frequency signal from the counter. The counter counts the number of pulses occurring between two successive pulses from the time base selector. If the time interval between this two successive pulses from the time base selector is 1 second, then the number of pulses counted within this interval is the frequency of the unknown frequency source, in Hertz.

The assembly consisting of two F/Fs and two gates is called a gate control F/F. The block diagram of a digital frequency meter is shown in Fig. 6.7.

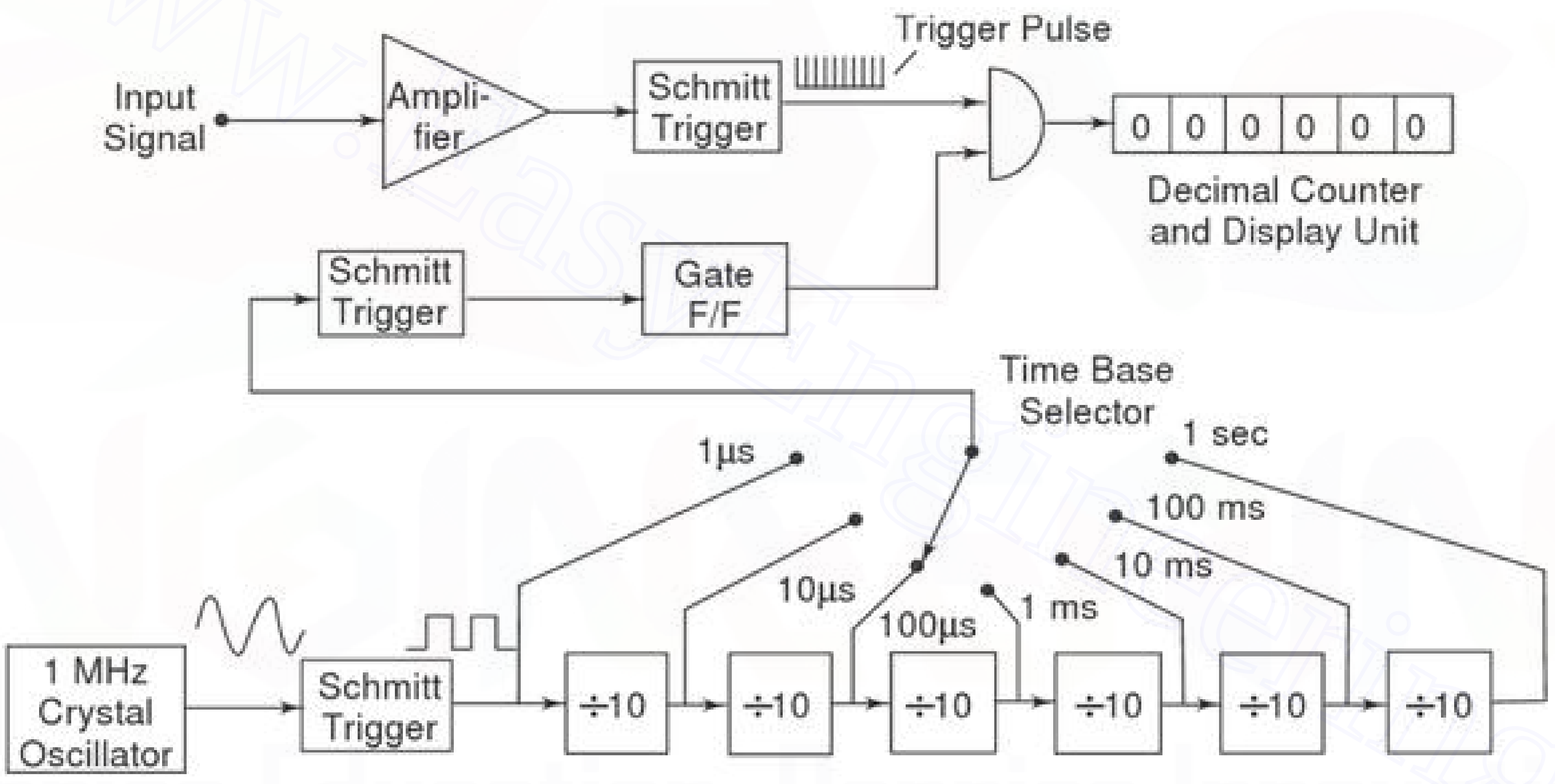


Fig. 6.7 Block diagram of a digital frequency meter

The input signal is amplified and converted to a square wave by a Schmitt trigger circuit. In this diagram, the square wave is differentiated and clipped to produce a train of pulses, each pulse separated by the period of the input signal. The time base selector output is obtained from an oscillator and is similarly converted into positive pulses.

The first pulse activates the gate control F/F. This gate control F/F provides an enable signal to the AND gate. The trigger pulses of the input signal are allowed to pass through the gate for a selected time period and counted. The second pulse from the decade frequency divider changes the state of the control F/F and removes the enable signal from the AND gate, thereby closing it. The decimal counter and display unit output corresponds to the number of input pulses received during a precise time interval; hence the counter display corresponds to the frequency.

6.3.3 High Frequency Measurement (Extending the Frequency Range)

The direct count range of digital frequency meter (DFM) extends from dc to a few 100 MHz. The limitations arises because of the counters used along with the DFM. The counters cannot count at the speed demanded by high frequency measurement.

This range of a few 100 MHz covers only a small portion of the frequency spectrum. Therefore, techniques other than direct counting have been used to extend the range of digital frequency meters to above 40 GHz. The input frequency is reduced before it is applied to a digital counter. This is done by special techniques. Some of the techniques used are as follows.

1. Prescaling The high frequency signal by the use of high speed is divided by the integral numbers such as 2, 4, 6, 8 etc. divider circuits, to get it within the frequency range of DFM (for example synchronous counters).

2. Heterodyne Converter The high frequency signal is reduced in frequency to a range within that of the meter, by using heterodyne techniques.

3. Transfer Oscillator A harmonic or tunable LF continuous wave oscillator is zero beat (mixed to produce zero frequency) with the unknown high frequency signal. The LF oscillator frequency is measured and multiplied by an integer which is equal to the ratio of the two frequencies, in order to determine the value of the unknown HF.

4. Automatic Divider The high frequency signal is reduced by some factor, such as 100:1, using automatically tuned circuits which generates an output frequency equal to 1/100th or 1/1000th of the input frequency.

DIGITAL MEASUREMENT OF TIME 6.4

Principle of Operation The beginning of the time period is the start pulse originating from input 1, and the end of the time period is the stop pulse coming from input 2.

The oscillator runs continuously, but the oscillator pulses reach the output only during the period when the control F/F is in the 1 state. The number of output pulses counted is a measure of the time period.

6.4.1 Time Base Selector

It is clear that in order to know the value of frequency of the input signal, the time interval between the start and stop of the gate must be accurately known. This is called time base.

The time base consist of a fixed frequency crystal oscillator, called a clock oscillator, which has to be very accurate. In order to ensure its accuracy, the crystal is enclosed in a constant temperature oven. The output of this constant frequency oscillator is fed to a Schmitt trigger, which converts the input sine wave to an output consisting of a train of pulses at a rate equal to the frequency of the clock oscillator. The train of pulses then passes through a series of frequency divider decade assemblies connected in cascade. Each decade divider consists of a decade counter and divides the frequency by ten. Outputs are taken from each decade frequency divider by means of a selector switch; any output may be selected.

The circuit of Fig. 6.8 consists of a clock oscillator having a 1 MHz frequency. The output of the Schmitt trigger is 10^6 pulses per second and this point corresponds to a time of 1 microsecond. Hence by using a 6 decade frequency divider, a time base with a range of 1 μs – 10 μs – 100 μs – 1 ms – 10 ms – 100 ms – 1 s can be selected using a selector switch.

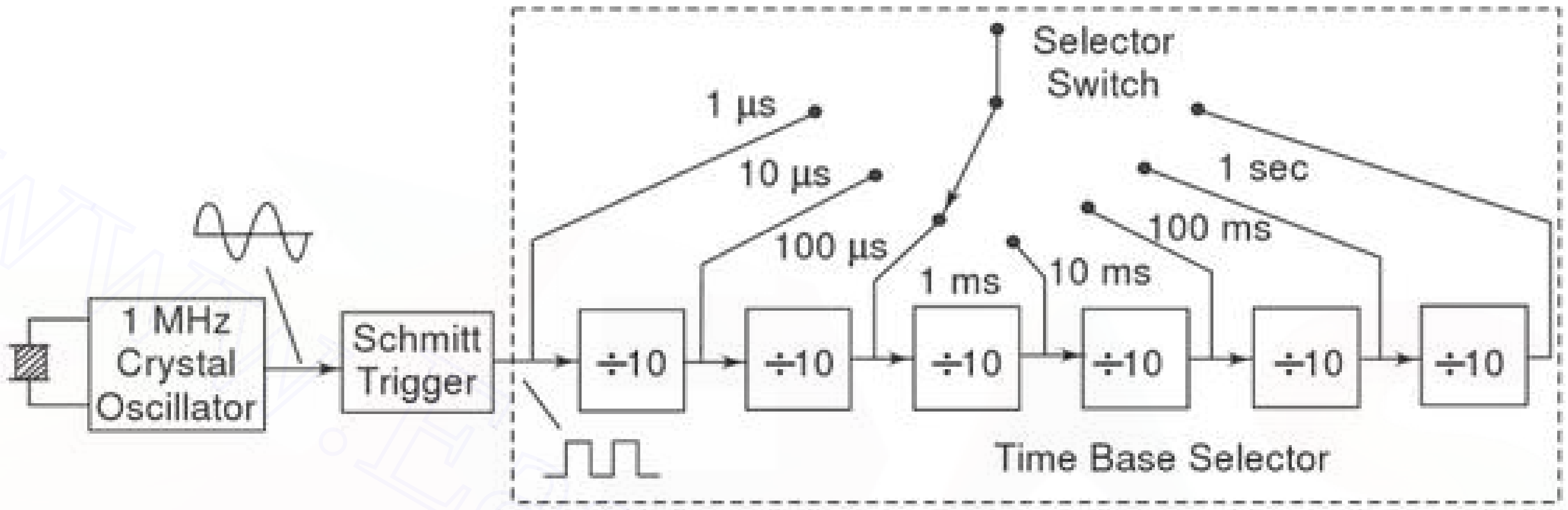


Fig. 6.8 Time base selector

6.4.2 Measurement of Time (Period Measurement)

In some cases it is necessary to measure the time period rather than the frequency. This is especially true in the measurement of frequency in the low frequency range. To obtain good accuracy at low frequency, we should take measurements of the period, rather than make direct frequency measurements. The circuit used for measuring frequency (Fig. 6.7) can be used for the measurement of time period if the counted signal and gating signal are interchanged.

Figure 6.9 shows the circuit for measurement of time period. The gating signal is derived from the unknown input signal, which now controls the enabling and disabling of the main gate. The number of pulses which occur during one period of the unknown signal are counted and displayed by the decade counting assemblies. The only disadvantage is that for measuring the frequency in the low frequency range, the operator has to calculate the frequency from the time by using the equation $f = 1/T$.

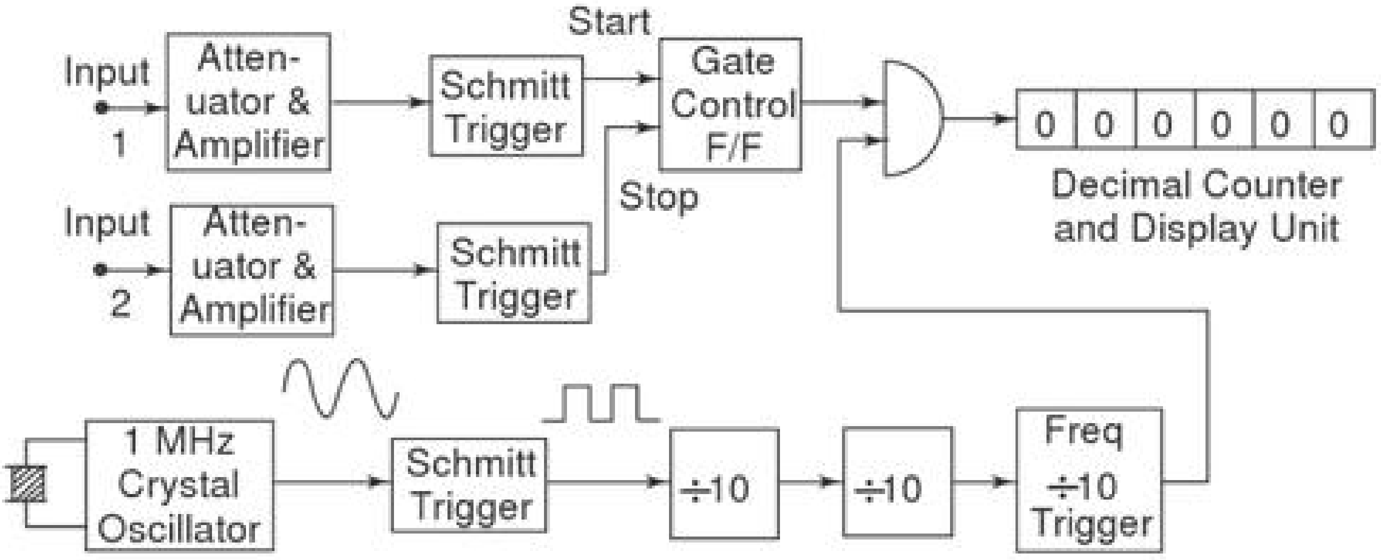


Fig. 6.9 Basic block diagram of time measurement

For example, when measuring the period of a 60 Hz frequency, the electronic counter might display 16.6673 ms, hence the frequency is

$$f = \frac{1}{T} = \frac{1}{16.6673 \times 10^{-3}} = 59.9977 \text{ Hz}.$$

The accuracy of the period measurement and hence of frequency can be greatly increased by using the multiple period average mode of operation. In this mode, the main gate is enabled for more than one period of the unknown signal. This is obtained by passing the unknown signal through one or more decade divider assemblies (DDAs) so that the period is extended by a factor of 10,000 or more.

Hence the digital display shows more digital of information, thus increasing accuracy. However, the decimal point location and measurement units are usually changed each time an additional decade divider is added, so that the display is always in terms of the period of one cycle of the input signal, even though the measurements may have lasted for 10,100 or more cycles.

Figure 6.10 show the multiple average mode of operation. In this circuit, five more decade dividing assemblies are added so that the gate is now enabled for a much longer interval of time than it was with single DDA.

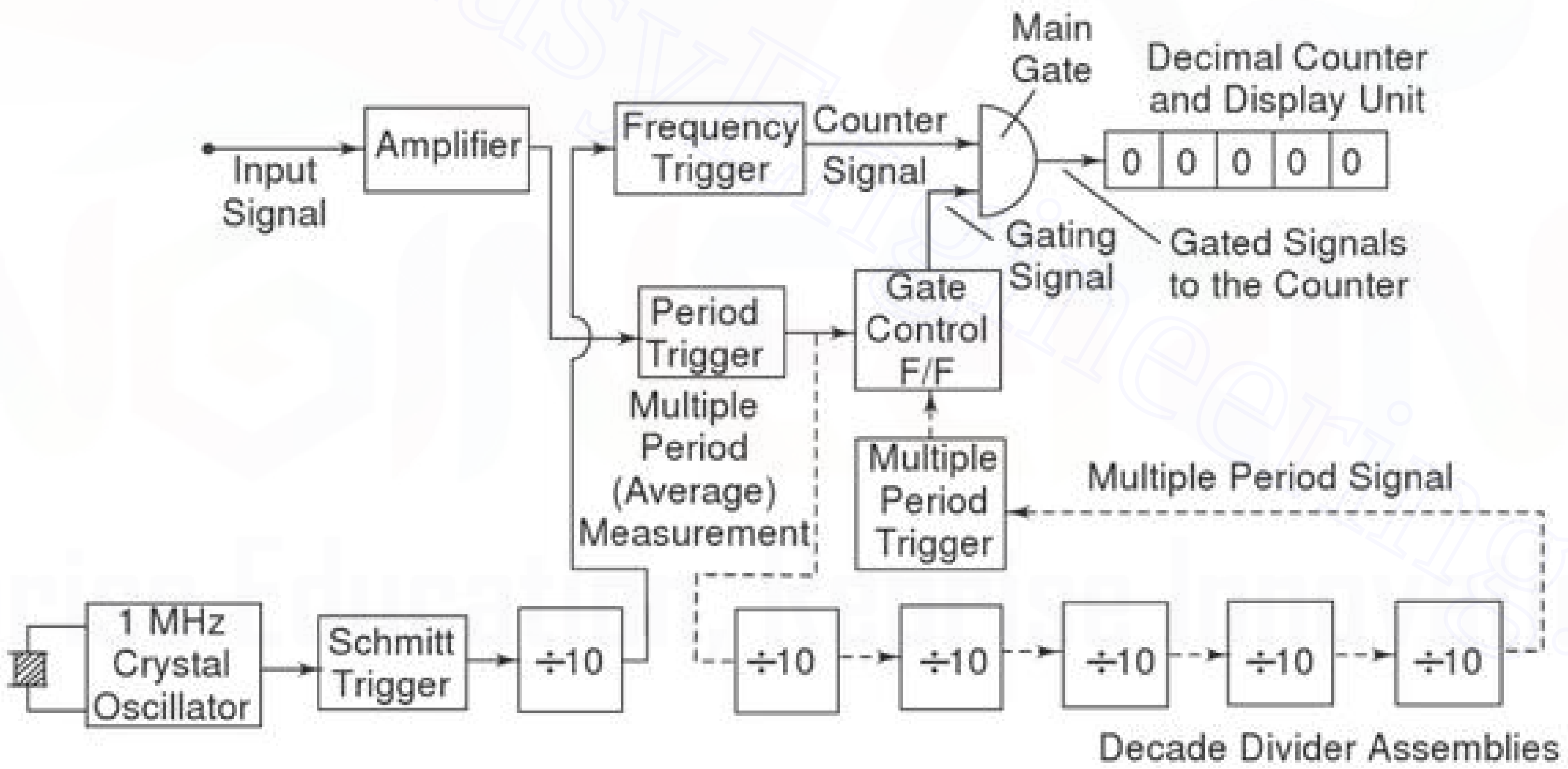


Fig. 6.10 Block diagram of a single and multiple period (average) measurement

6.4.3 Ratio and Multiple Ratio Measurement

The ratio measurement involves the measurement of the ratio of two frequencies. The measurement in effect is a period measurement. A low frequency is used as gating signal while the high frequency is the counted signal. Hence the low frequency takes the place of the time base. The block diagram for the ratio measurements and multiple ratio is shown in Fig. 6.11.

The number of cycles of high frequency signal f_1 which occur during the period of lower frequency signal f_2 are counted and displayed by the decimal counter and display unit. In multiple ratio measurements the period of low frequency signal is extended by a factor of 10,100, etc. by using DDAs.

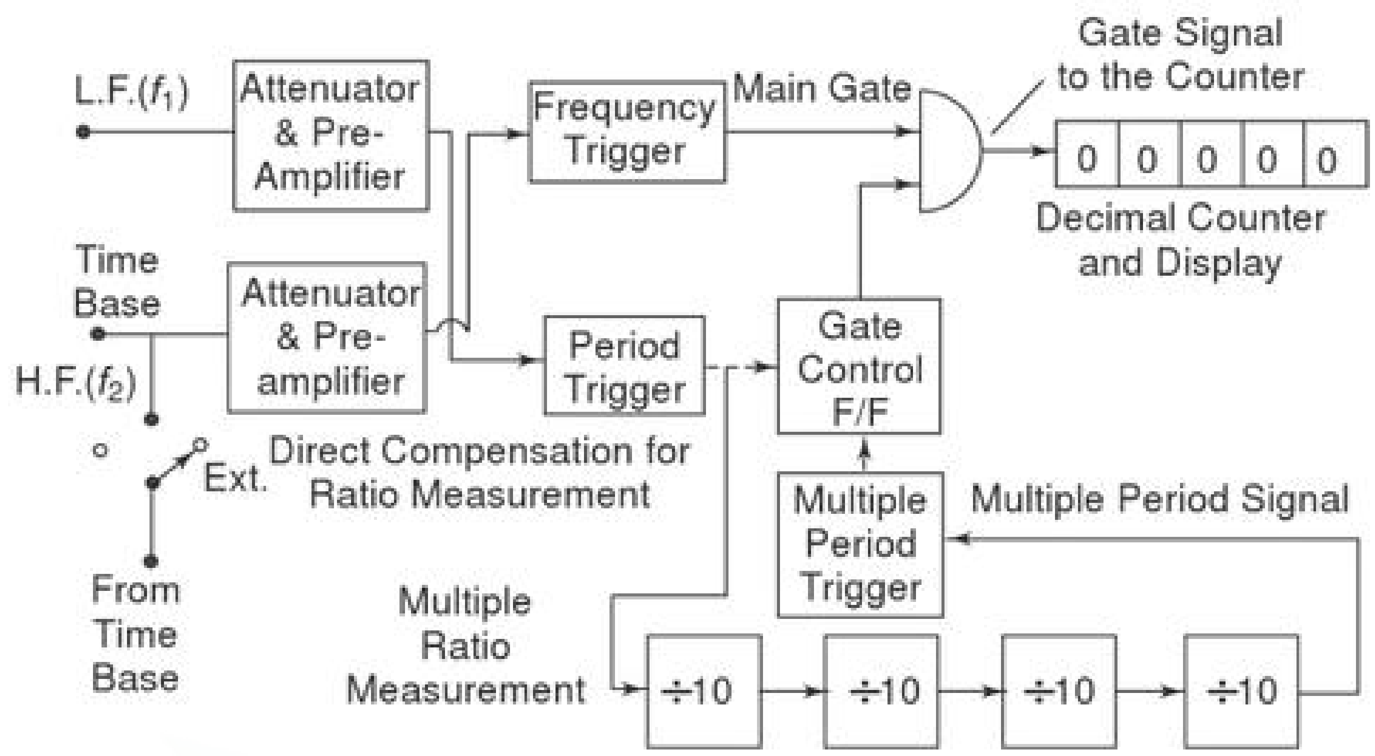


Fig. 6.11 Block diagram for ratio and multiple ratio measurement

UNIVERSAL COUNTER 6.5

All measurements of time period and frequency by various circuits can be assembled together to form one complete block, called a Universal Counter Timer.

The universal counter uses logic gates which are selected and controlled by a single front panel switch, known as the function switch. A simplified block diagram is shown in Fig. 6.12.

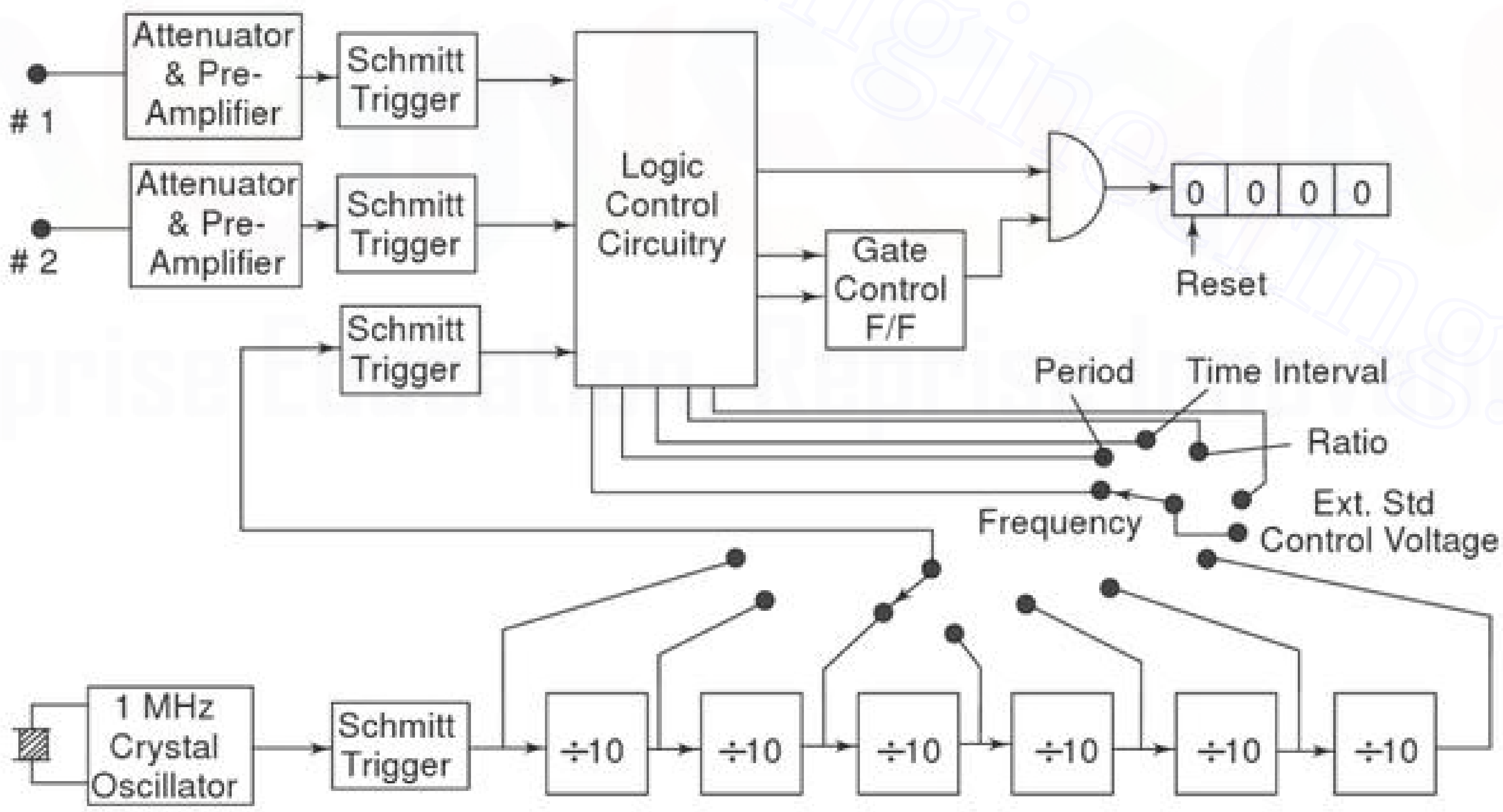


Fig. 6.12 Block diagram of universal counter-timer

With the function switch in the frequency mode, a control voltage is applied to the specific logic gate circuitry. Hence, the input signal is connected to the counted signal channel of the main gate.

The selected output from the time base dividers is simultaneously gated to the control F/F, which enables or disables the main gate. Both control paths are latched internally to allow them to operate only in proper sequence.

When the function switch is on the period mode, the control voltage is connected to proper gates of the logic circuitry, which connects the time base signals to the counted signal channel of the main gate. At the same time the logic circuitry connects the input to the gate control for enabling or disabling the main gate. The other function switches, such as time interval ratio and external standards perform similar functions. The exact details of switching and control procedures vary from instrument to instrument.

DECADE COUNTER 6.6

A decade counter is a circuit of flip-flops (F/Fs) in cascade, which counts in the base 10 (decimal number system). This means that there is a sequence of ten distinct counts in increasing order. Three F/Fs used in cascade progress through 8 distinct states (binary numbers from 000 to 111), while 4 F/Fs in cascade progress through 16 distinct states (binary numbers 0000 to 1111). Hence to get a count of 10, a minimum of 4 F/Fs are required (because 8 distinct states are less while 16 are too many for a decade counter). This problem can be overcome by using 4 F/Fs in cascade and resetting the output of each F/F to 0 after the desired 10 counts. Figure 6.13 (a) shows a decade counter using 4 negative edged triggered F/Fs in cascade.

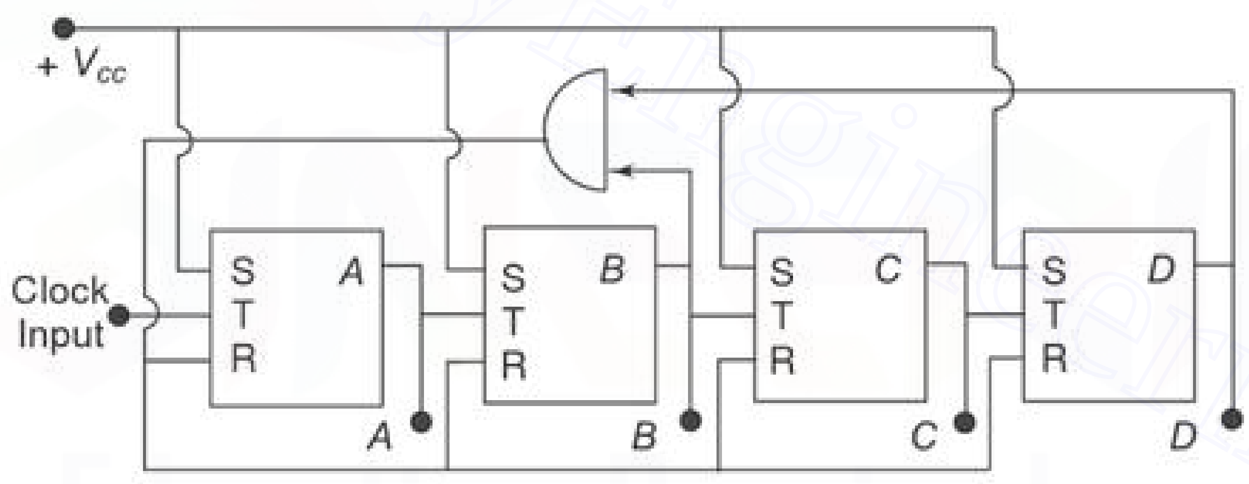


Fig. 6.13 (a) Decade counter

The outputs of the F/F B and D are high (equal to binary 1) after 10 pulses have been applied to the counter. Therefore, the output signal of the decade counter is 1010. This output has to be reset on the very next pulse which is done by the use of an AND gate that resets all F/F's to 0, when the outputs of B and D are 1. The waveform shown in Fig. 6.13 (b) shows the pulse train applied to the trigger input (clock) of the decade counter (shown in Fig. 6.13(a)) and the output waveform of each F/F.

At the beginning all the F/Fs are reset to 0000. The clock pulse is applied to the trigger input T of the F/F. Since this is a negative edged triggered F/F, at the negative edge or falling edge of the trigger input the F/F A will toggle, and hence the output of F/F A changes to level 1; all other F/Fs undergo no change. The outputs from the F/Fs will be 0001. At the next clock pulse the F/F A will toggle back to 0, and the output of F/F A falls from 1 to 0 and is applied to the T input of the next F/F B, toggling it. The output of the F/F B changes to 1 and the output of the decade counter goes to 0010.

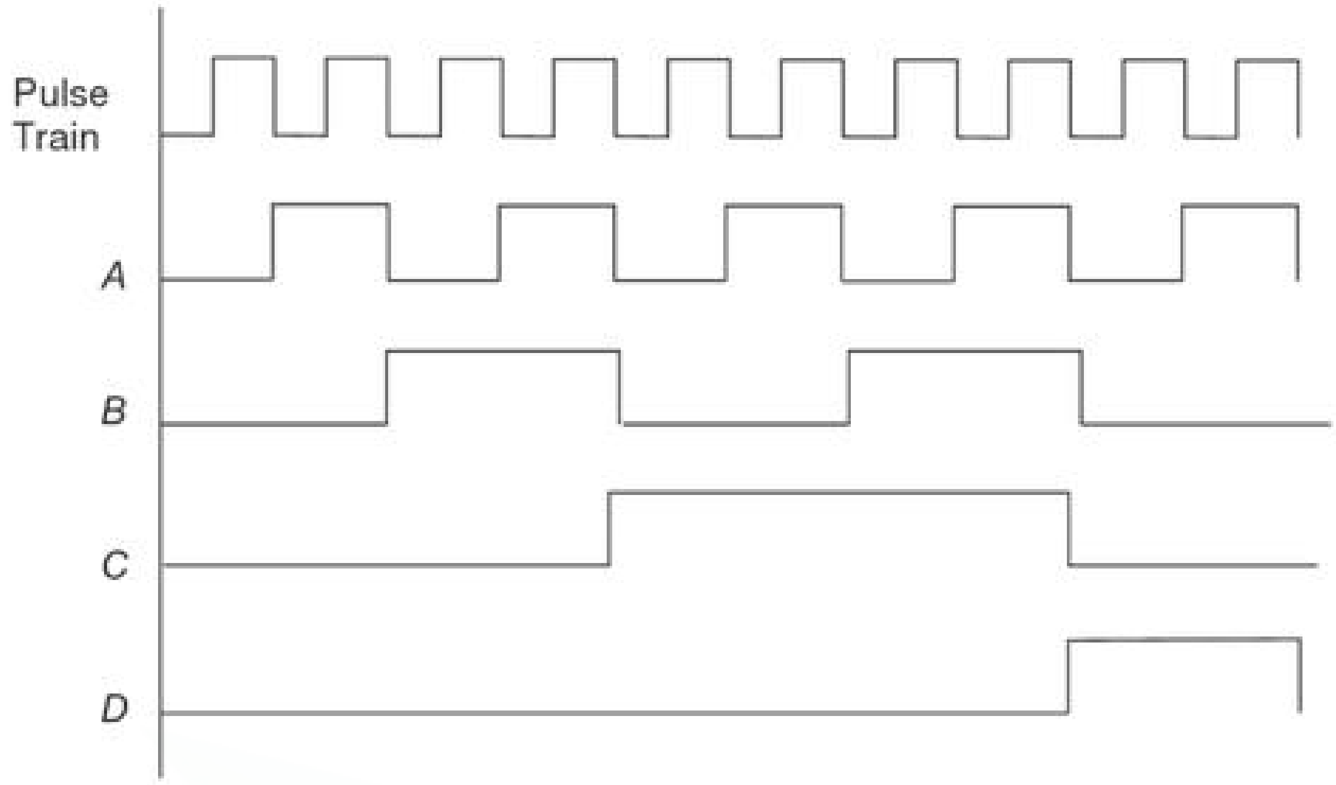


Fig. 6.13 (b) Waveforms of a decade counter

Similarily, as the clock progresses, the F/F toggles in a straight sequence up to 10 (binary 1010). On the very next pulse the AND gate is enabled, which makes the reset input of F/F B high. As soon as the clock pulse arrives, all F/Fs are reset to 0 and the output of the decade counter goes back to 0000. Therefore, by using the AND gate the counter is reset at the tenth pulse.

If some indicator device, such as a lamp or LED has to be driven, the signal must be encoded in the decimal system. This can be done by the use of AND gates. The output of the F/Fs is applied to the AND gates. The AND gates inputs are set to a unique set of conditions that occur only once during the ten trigger pulses. Therefore, each of the 10 lights is ON for only one particular pulse, which allows us to determine at a glance how many pulses have been counted. An F/F divides its input frequency by two. It can be seen from the waveform of Fig. 6.13(b) that the F/F acts as a frequency divider.

Large scale integration (LSI) has made it possible to incorporate the entire decade counter divider circuit with binary to decimal encoding in one or more IC's.

ELECTRONIC COUNTER 6.7

The decade counter can be easily incorporated in a commercial test instrument called an electronic counter. A decade counter, by itself, behaves as a totaliser by totalling the pulses applied to it during the time interval that a gate pulse is present. Typical modes of operation are totalising, frequency, period, ratio, time interval and averaging.

6.7.1 Totalising

In the totalising mode, as shown in Fig. 6.14, the input pulses are counted (totalised) by the decade counter as long as the switch is closed. If the

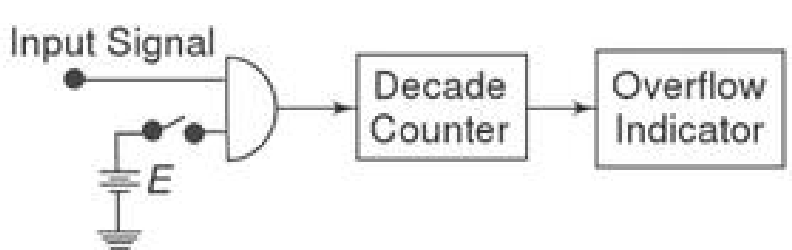


Fig. 6.14 Block diagram of the totalising mode of an electronic counter

count pulse exceeds the capacity of the decade counter, the overflow indicator is activated and the counter starts counting again.

6.7.2 Frequency Mode

If the time interval in which the pulses are being totalised is accurately controlled, the counter operates in the frequency mode. Accurate control of the time interval is achieved by applying a rectangular pulse of known duration to the AND gate, as shown in Fig. 6.15, in place of the dc voltage source. This technique is referred to as gating the counter. A block diagram of an electronic counter operating in the frequency mode is shown in Fig. 6.15. The frequency of the input signal is computed as

$$f = \frac{N}{t}$$

where f = frequency of the input signal
N = pulse counted
t = duration of the gate pulse

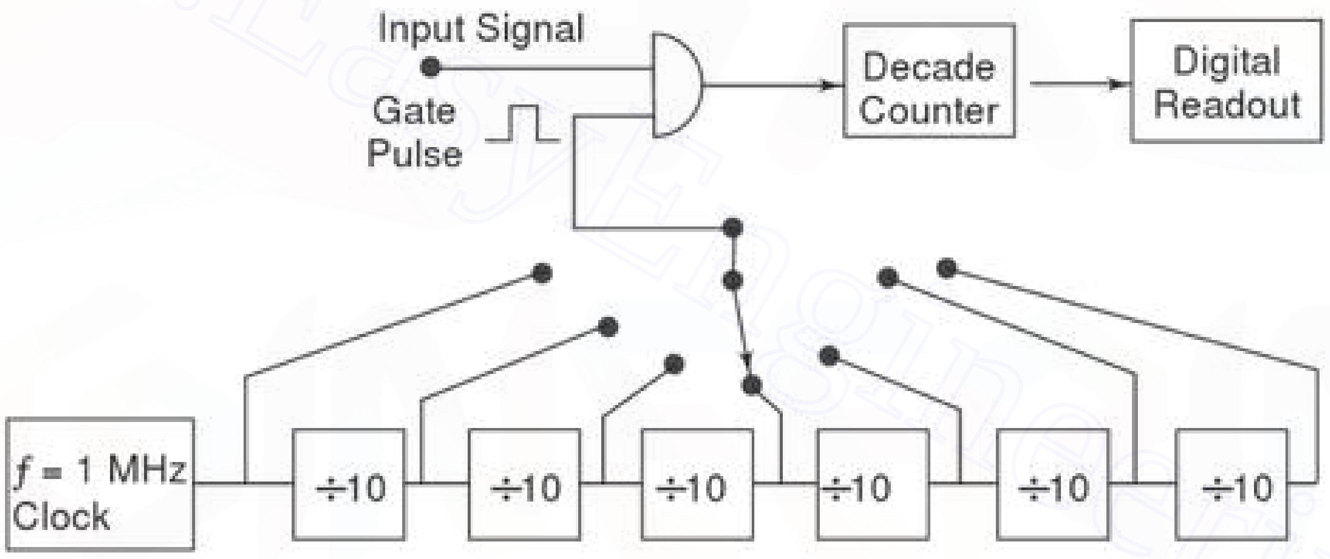


Fig. 6.15 Block diagram of electronic counter frequency mode

6.7.3 Ratio Mode

The ratio mode of operation simply displays the numerical value of the ratio of the frequencies of the two signals.

The low frequency signal is used in place of the clock to provide a gate pulse. The number of cycles of the high frequency signal, which are stored in the decade counter during the presence of an externally generated gate pulse, is read directly as a ratio of the frequency. A basic circuit for the ratio mode of operation is shown in Fig. 6.16.

6.7.4 Period Mode

In some applications, it is desirable to measure the period of the signal rather than its frequency. Since the period is the reciprocal of the frequency, it can easily be measured by

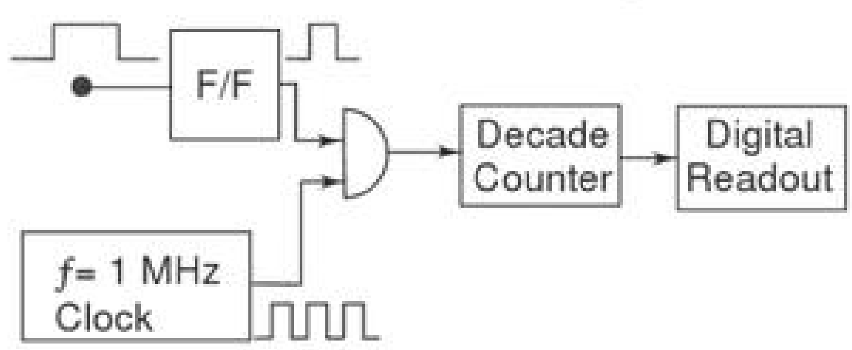


Fig. 6.16 Block diagram of electronic counter in period mode

using the input signal as a gating pulse and counting the clock pulses, as shown in Fig. 6.16.

The period of the input signal is determined from the number of pulses of known frequency or known time duration which are counted by the counter during one cycle of the input signal. The period is computed as

$$T = \frac{N}{f}$$

where N = pulse counted
f = frequency of the clock

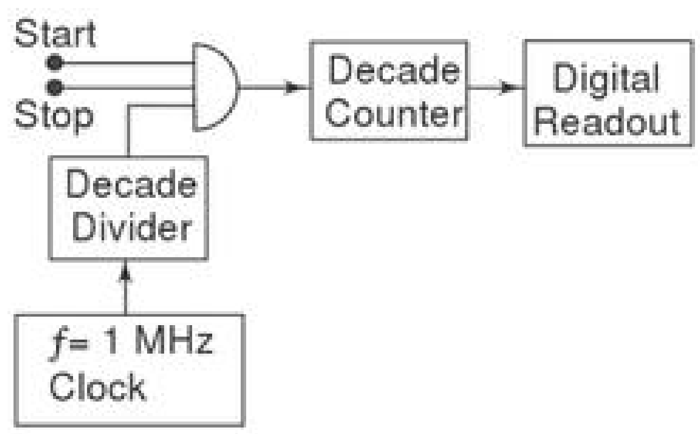


Fig. 6.17 Block diagram of electronic counter in time interval mode

6.7.5 Time Interval Mode

The time interval mode of operation measures the time elapsed between two events. The measurement can be done using the circuit of Fig. 6.17.

The gate is controlled by two independent inputs, the start input, which enables the gate, and the stop input which disables it. During the time interval between the start and stop signal, clock pulses accumulate in the register, thus providing an indication of the time interval between the start and stop of the event.

Electronic counters find many applications in research and development laboratories, in standard laboratories, on service benches and in everyday operations of many electronics installations.

Counters are used in communication to measure the carrier frequency, in a digital system to measure the clock frequency, and so on.

DIGITAL MEASUREMENT OF FREQUENCY (MAINS) 6.8

The conventional method of measuring the frequency of an electrical signal consists of counting the number of cycles of the input electrical signal during a specified gate interval. The length of the gate interval decides the resolution of the measurement. The shorter the gate interval, the lesser is the resolution. Now, for frequencies of the order of kHz and above, it is possible to get a resolution of 0.1% better with a nominal gate time of 1 (sec). But for low frequencies, in order to obtain a resolution of even 0.5%, the gate time has to be considerably larger. For example, consider the case when the input electrical signal frequency is around 50 Hz. In order to obtain a resolution of 0.1 Hz, the gate interval has to be 10 seconds and in order to obtain a resolution of 0.01 Hz, the gate interval has to be 100 s. These gate periods of 10 s and 100 s are too long and in many cases it is desirable to obtain an indication of the frequency in far less time. Hence, direct or ordinary frequency counters are at a great disadvantage when it comes to low frequency measurements.

For the mains frequency monitor, the frequency range of interest is rather narrow, (50 ± 5%) Hz. The technique employed in the measurement of mains frequency, yields only a parabolic calibration curve. But within the narrow frequency range, which in this case is (50 ± 5%) Hz, the calibration is conveniently flat. Hence, the error due to the non-linear calibration is less than 0.2% at a frequency deviation as large as 5% from the centre frequency, which is 50 Hz. The error is 0.02% at a frequency deviation as large as 2% from the centre frequency and as the frequency approaches the centre value of 50 Hz, the error approaches zero.

The principle that backs up this technique is as follows.

Consider the relationship between the frequency and time period of the input electrical signal, $f = 1/T$. For an ac power line, the desired frequency is 50 Hz; let us denote it as F_{50}. If we denote the corresponding period by T_{50}, then T_{50} = 1/50 s = 20 ms. Now, let us further denote any frequency x as F_x and the corresponding period as T_x. Now, we introduce a new time scale for measuring the period of the electrical input signal whose frequency measurement is desired. Let us formulate the relationship between the MKS scale and the new scale as 20 ms = 50 ku (ku = kilounit), where ku is the unit of the new time scale. Therefore, 1 s = 50 × (1/20) × 1000 = 2500 ku.

Let us determine the periods corresponding to various frequencies from 45 Hz to 55 Hz in terms of ku.

$$T_{45} = 1/45 \text{ s} = 2500/45 \text{ ku} = 55.55 \text{ ku}$$
$$T_{46} = 1/46 \text{ s} = 2500/46 \text{ ku} = 54.35 \text{ ku}$$
$$T_{47} = 1/47 \text{ s} = 2500/47 \text{ ku} = 53.19 \text{ ku}$$
$$T_{48} = 1/48 \text{ s} = 2500/48 \text{ ku} = 52.08 \text{ ku}$$
$$T_{49} = 1/49 \text{ s} = 2500/49 \text{ ku} = 51.02 \text{ ku}$$
$$T_{50} = 1/50 \text{ s} = 2500/50 \text{ ku} = 50.00 \text{ ku}$$
$$T_{51} = 1/51 \text{ s} = 2500/51 \text{ ku} = 49.02 \text{ ku}$$
$$T_{52} = 1/52 \text{ s} = 2500/52 \text{ ku} = 48.08 \text{ ku}$$
$$T_{53} = 1/53 \text{ s} = 2500/53 \text{ ku} = 47.16 \text{ ku}$$
$$T_{54} = 1/54 \text{ s} = 2500/54 \text{ ku} = 46.29 \text{ ku}$$
$$T_{55} = 1/55 \text{ s} = 2500/55 \text{ ku} = 44.44 \text{ ku}$$

Now within this narrow frequency range of 45 – 55 Hz, we can form an empirical relation between the frequency and period of signals, as $F_x = 100 - T_x$, where F_x is the frequency in Hz and T_x is the period in ku.

In order to determine the frequency of the input electrical signal, the period of the input signal has to be measured in terms of ku and then subtracted from 100. If an indication of the frequency F_x correct to 1 Hz (resolution is 1 Hz), is sufficient, then it is enough if the period T_x of the input signal is measured correct to 1 ku. In order to obtain 4 digit indication, the period T_x of the input signal has to be measured correct to 0.01 ku. To determine the period of the input electrical (power line) signal in terms of 0.01 ku, we need a reference signal whose period is 0.01 ku. This signal is obtained from a stable crystal controlled reference oscillator. The number of cycles of this reference signal during 1 cycle of the input signal gives the period T_x in terms of 0.07 ku. Rather than employing separate circuitry to determine the period and then subtracting it from 100, an UP/DOWN counter is used in the down counted mode. Thus the processes of counting the period and doing the subtraction are done simultaneously by the same circuitry.

The schematic diagram shown in Fig. 6.18, is the circuitry of the digital mains frequency measurement, consisting of the input wave shaper, reference clock generator, sequence control logic unit, counter display and intermediate latch circuitry.

Let us analyse the circuit, assuming the input signal is exactly 50 Hz. When the reference clock frequency is 1 MHz, there will be 20,000 pulses in the 20 ms period. These 20,000 pulses are divided by the other two flip-flops by a factor of 4, to get 5000 pulses in the measuring period of 20 ms. Now these pulses are counted down in the 10000 modulo counter and are displayed.

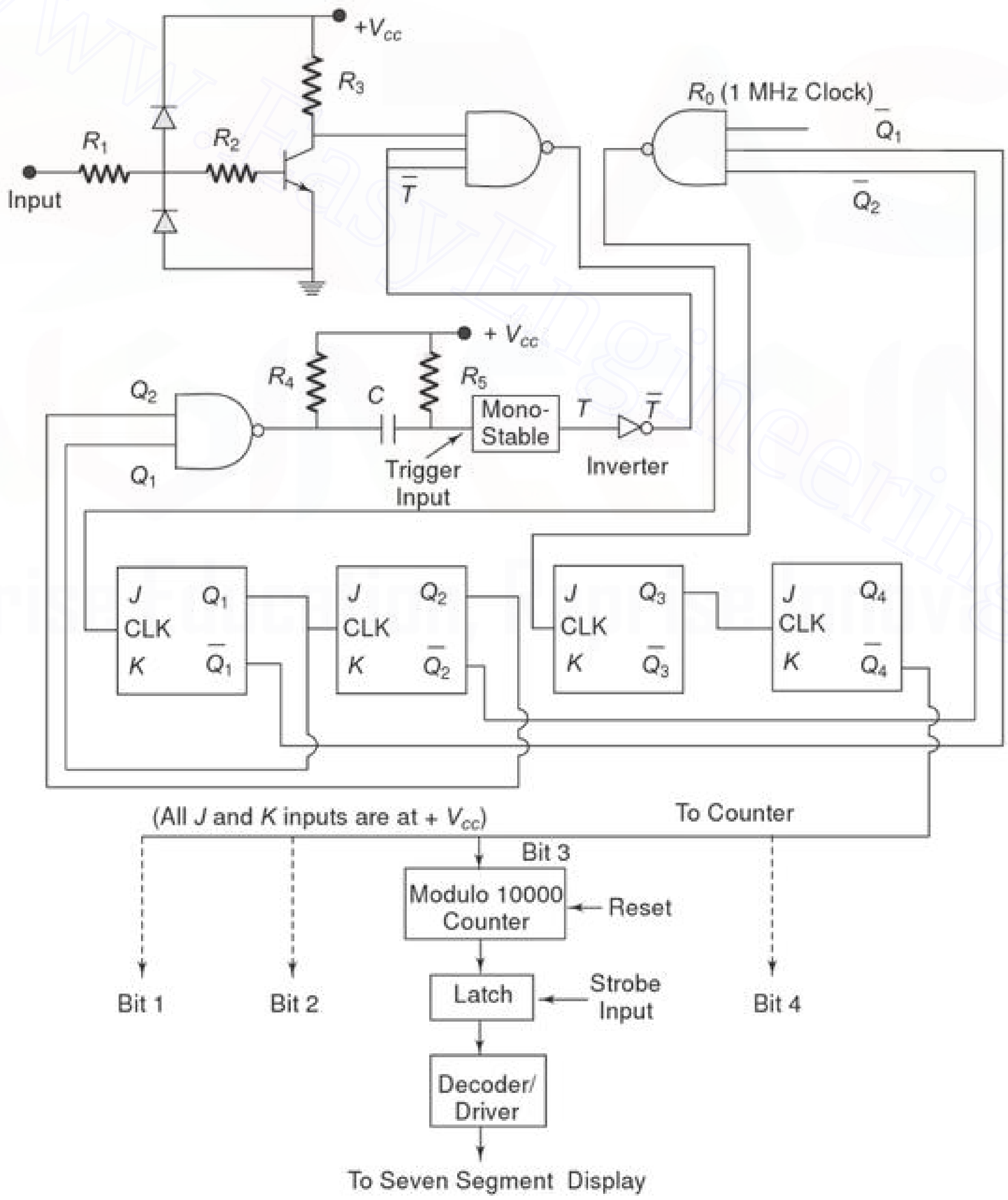


Fig. 6.18 Digital measurement of mains frequency

Let us consider the case, when the input signal frequency is 48 Hz. The period i.e. 1/48 s = 20.83 ms. Within this period, the number of pulses will be 5208. (For 20 ms the count is 5000, hence for 20.83 ms the count is

$$\frac{5000 \times 20.83 \text{ ms}}{20 \text{ ms}} = 5208$$

Therefore, 20.83 ms the count is 5208). Now, these pulses are counted down and the display reading is 10000 – 5208 = 4792; 48 Hz is displayed as 47.92 Hz.

DIGITAL TACHOMETER 6.9

The technique employed in measuring the speed of a rotating shaft is similar to the technique used in a conventional frequency counter, except that the selection of the gate period is in accordance with the rpm calibration.

Let us assume, that the rpm of a rotating shaft is R. Let P be the number of pulses produced by the pick up for one revolution of the shaft. Therefore, in one minute the number of pulses from the pick up is $R \times P$. Then, the frequency of the signal from the pick up is $(R \times P)/60$. Now, if the gate period is G s the pulses counted are $(R \times P \times G)/60$. In order to get the direct reading in rpm, the number of pulses to be counted by the counter is R. So we select the gate period as $60/P$, and the counter counts

$$\frac{(R \times P \times 60)}{60 \times P} = R \text{ pulses}$$

and we can read the rpm of the rotating shaft directly. So, the relation between the gate period and the number of pulses produced by the pickup is $G = 60/P$. If we fix the gate period as one second (G = 1 s), then the revolution pickup must be capable of producing 60 pulses per revolution.

Figure 6.19 shows a schematic diagram of a digital tachometer.

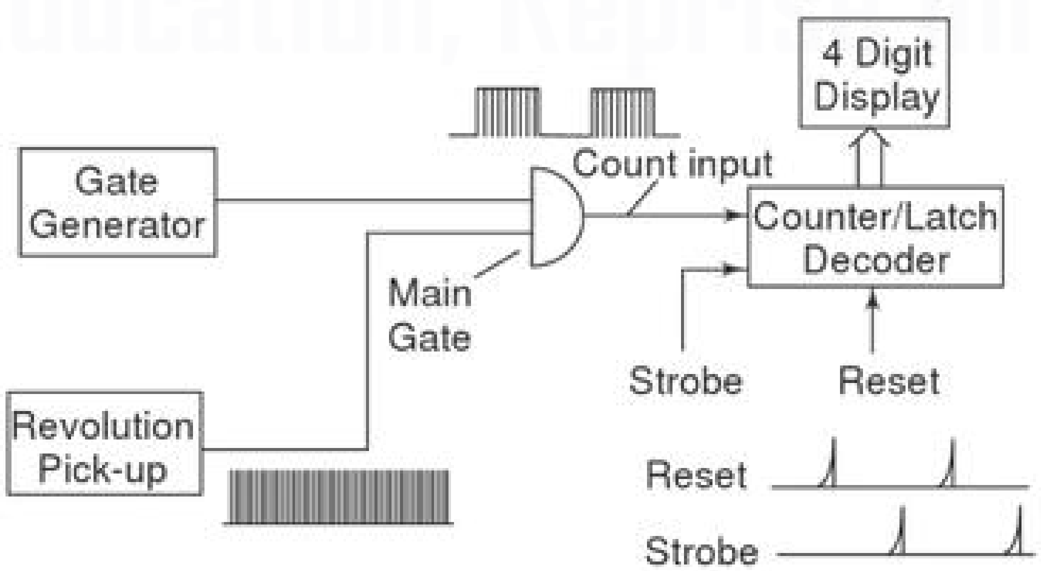


Fig. 6.19 Basic block diagram of a digital tachometer

DIGITAL pH METER 6.10

The measurement of hydrogen ion activity (pH) in a solution can be accomplished with the help of a pH meter. For those unfamiliar with the terminology, a very brief review is included.

pH is a quantative measure of acidity. If the pH is less than 7, the solution is acidic (the lower the pH, the greater the acidity). A neutral solution has a pH of 7 and alkaline (basic) solutions have a pH greater than 7.

The pH unit is defined as

$$pH = -\log(\text{concentration of } H^+)$$

where H^+ is the hydrogen or hydronium ion. (Analog pH meters are discussed in Chapter 10.)

A digital pH meter differs from an ordinary pH meter, in this the meter is replaced by an analog to digital converter (ADC) and a digital display. A frequently used ADC for this application is the dual slope converter. A basic block diagram of a digital pH meter is shown in Fig. 6.20.

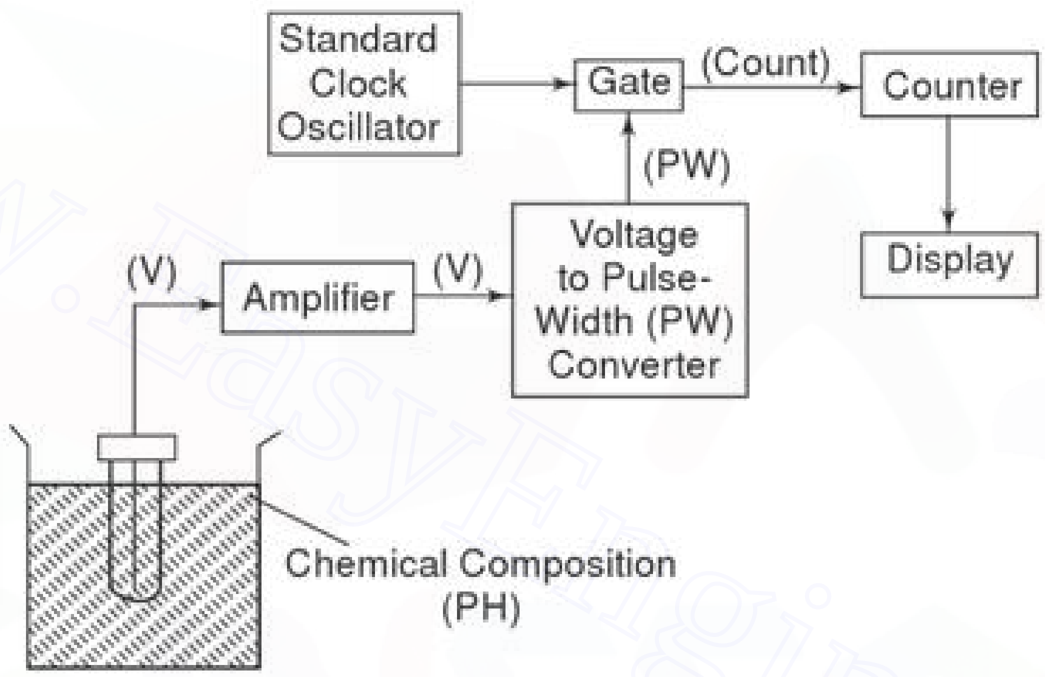


Fig. 6.20 Digital pH meter

The dual slope circuit produces a pulse which has a duration proportional to the input signal voltage, that is, a T pulse width signal. The pulse width is converted to a digital signal using the pulse to turn an oscillator On or Off, generating a count digital signal. The count signal is in turn counted or converted to a parallel digital signal for display by the counter.

AUTOMATION IN DIGITAL INSTRUMENTS 6.11

One of the advantages of digital multimeters is their ease of operation. The reading is easy to take and does not lend itself to errors of interpretation. Moreover, the number of ranges is limited because the ranges move in steps of 10 (instead of the $\sqrt{10}$ steps used for analog instruments). Demand from users for simple forms of computation signalling and control, and advances in digital circuitry have led to further development, in which more and more automatic functions have been incorporated in digital voltmeters. Nearly all instruments today have automatic polarity display and automatic decimal point positioning, while many have automatic ranging and zeroing too.

This automation includes automatic polarity indication, automatic ranging, and automatic zeroing.

1. Automatic Polarity Indication The polarity indication is generally obtained from the information in the ADC. For integrating ADCs, only the polarity of the integrated signal is of importance. The polarity should thus be measured at the very end of the integration period (see Fig. 6.21). As the length of the integration period is determined by counting a number of clock pulses, it is logical to use the last count or some of the last counts to start the polarity measurement. The output of the integrator is then used to set the polarity flip-flop, the output of which is stored in memory until the next measurement is made.

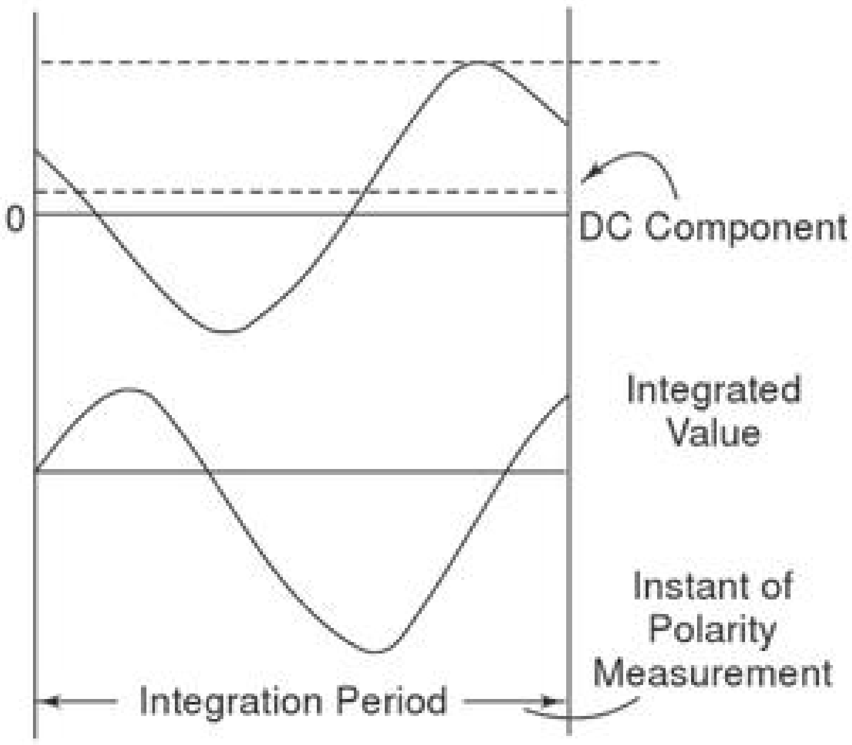


Fig. 6.21 Polarity of integrated signal has to be measured at very end of integration period

2. Automatic Ranging The object of automatic ranging is to get a reading with optimum resolution under all circumstances (e.g. 170 mV should be displayed as 170.0 and not as 0.170). Let us take the example of a 3½ digit display, i.e. one with a maximum reading of 1999. This maximum means that any higher value must be reduced by a factor of 10 before it can be displayed (e.g. 201 mV as 0201). On the other hand, any value below 0200 can be displayed with one decade more resolution (e.g. 195 mV as 195.0). In other words, if the display does not reach a value of 0200, the instrument should automatically be switched to a more sensitive range, and if a value of higher than 1999 is offered, the next less sensitive range must be selected.

Generally the lower limit is taken lower than 0200 (example 0180). Otherwise, a voltage exhibiting slight fluctuations around 2000 would be displayed successively as 1999.9, 0200 and 0201, which would be confusing. By introducing an overlap in the ranges (see Fig. 6.22), we ensure that all values are displayed in the same range (in the above example, as 0199, 0200 or 0201). Values around 0180 also give a stable display e.g. 1798, 1800 and 1807).

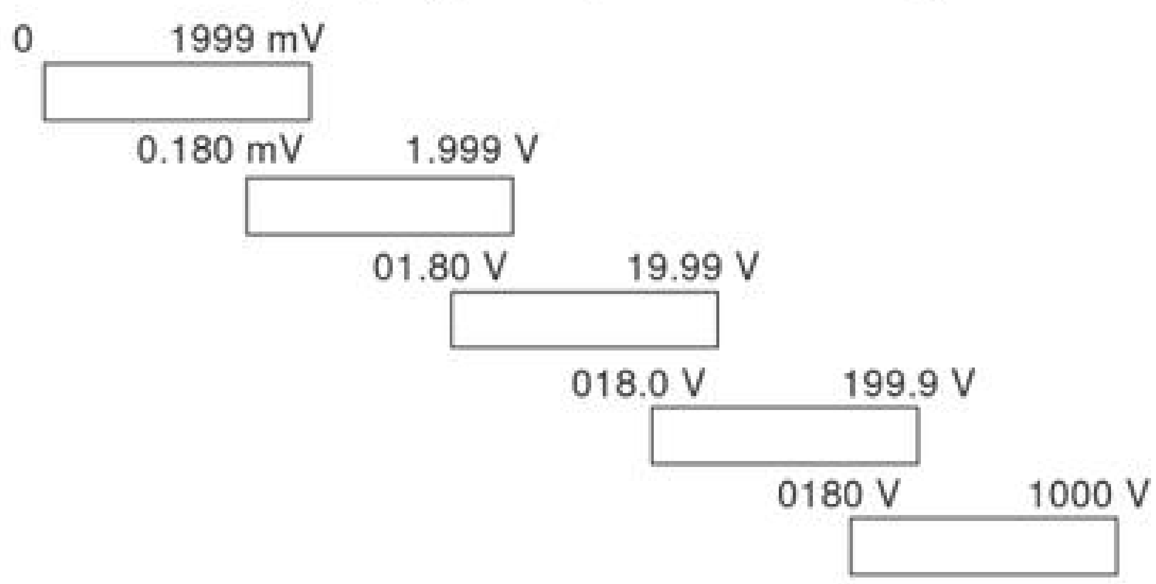


Fig. 6.22 Example of overlapping ranges in automatic ranging instruments

The design of an automatic ranging system is indicated in the block diagram in Fig. 6.23.

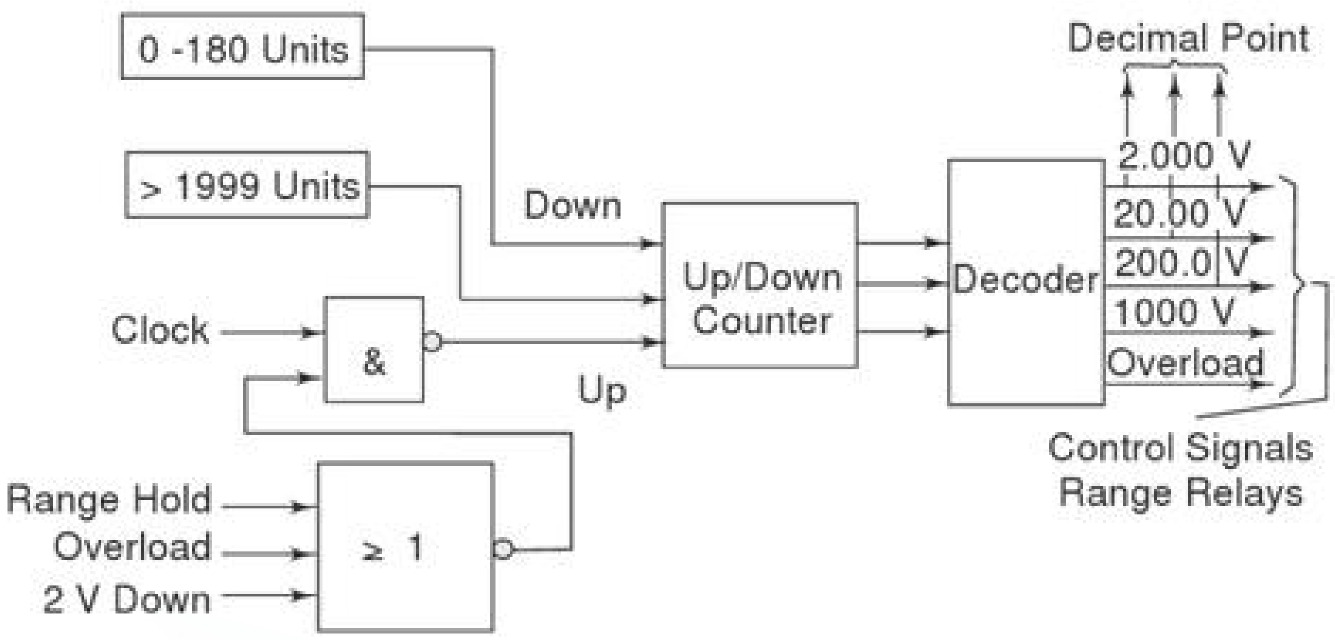


Fig. 6.23 Block diagram of automatic ranging system

The information contained in the counter of the ADC yields a control pulse for down ranging when the count is less than 180 and one for up ranging when the count exceeds 1999 units. The Up/Down counter of the automatic ranging circuit reacts to this information at the moment that a clock pulse (a pulse at the end of the measuring period, also used to transfer new data to memory), is applied, and the new information is used to set the range relays via the decoder. At the same time the decimal point in the display is adapted to the new range, when more than range step has to be made, several measuring periods are needed to reach the final result. Clock pulses, and so automatic ranging, can be inhibited, for example, by a manual range hold command, by a signal that exceeds the maximum range (only for up counts), and course by reaching the most sensitive range, but then only for down counts.

3. Automatic Zeroing Each user of a voltmeter expects the instrument to indicate zero when the input is short-circuited. In a digital voltmeter with a maximum reading of 1999, a zero error of 0.05% of full scale deflection is sufficient to give a reading of 0001. For this reason, and in the interests of optimum accuracy with low valued readings, a zero adjustment is necessary. To increase the ease of operation, many instruments now contain an automatic zeroing circuit.

In a system used in several multimeters, the zero error is measured just before the real measurement and stored as an analog signal. A simplified circuit diagram of a circuit that can be used for this purpose is given in Fig. 6.24, for a dual slope ADC.

Before the real measurement is made, switches S_3, S_4 and S_5 are closed, say for 50 ms, thus grounding the input, giving the integrator a short RC time, and connecting the output of the comparator to capacitor C. This capacitor is now charged by the offset voltages to the amplifier, the integrator and the comparator. When switches S_3, S_4 and S_5 are opened again to start the real measurement, the total offset voltage of the circuit (equal to zero error) is stored in this capacitor, and the real input voltage is measured correctly.

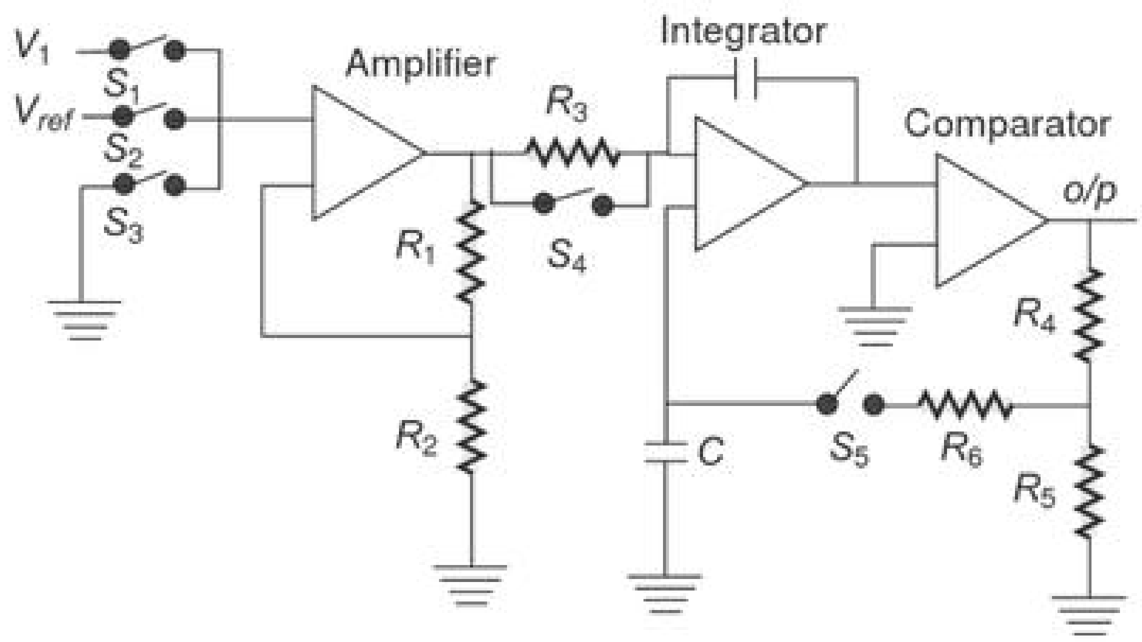


Fig. 6.24 Simplified circuit diagram of automatic zeroing circuit that can be used with dual slope ADC

6.11.1 Fully Automatic Digital Instrument

A multimeter with automatic polarity indication, automatic zero correction and automatic ranging (of course coupled with automatic decimal point indication) only needs a signal applied to its input, and a command as to what quantity (V_{dc}, V_{ac}, I or R) to measure; it does all the rest itself.

The digital part of a typical instrument is organised so as to produce a display or a digital output signal, as shown in Fig. 6.25. Before a measurement can begin, the functions of the instrument must be set, that is, we must select the quantity to be measured (e.g. voltage), the ranging mode (automatic or manual), and the start mode (internal or with an external trigger signal). This can be done by the front panel controls, or via a remote control input. In both cases, the signals are fed to the function control unit, while the information on ranging is passed to the range control unit.

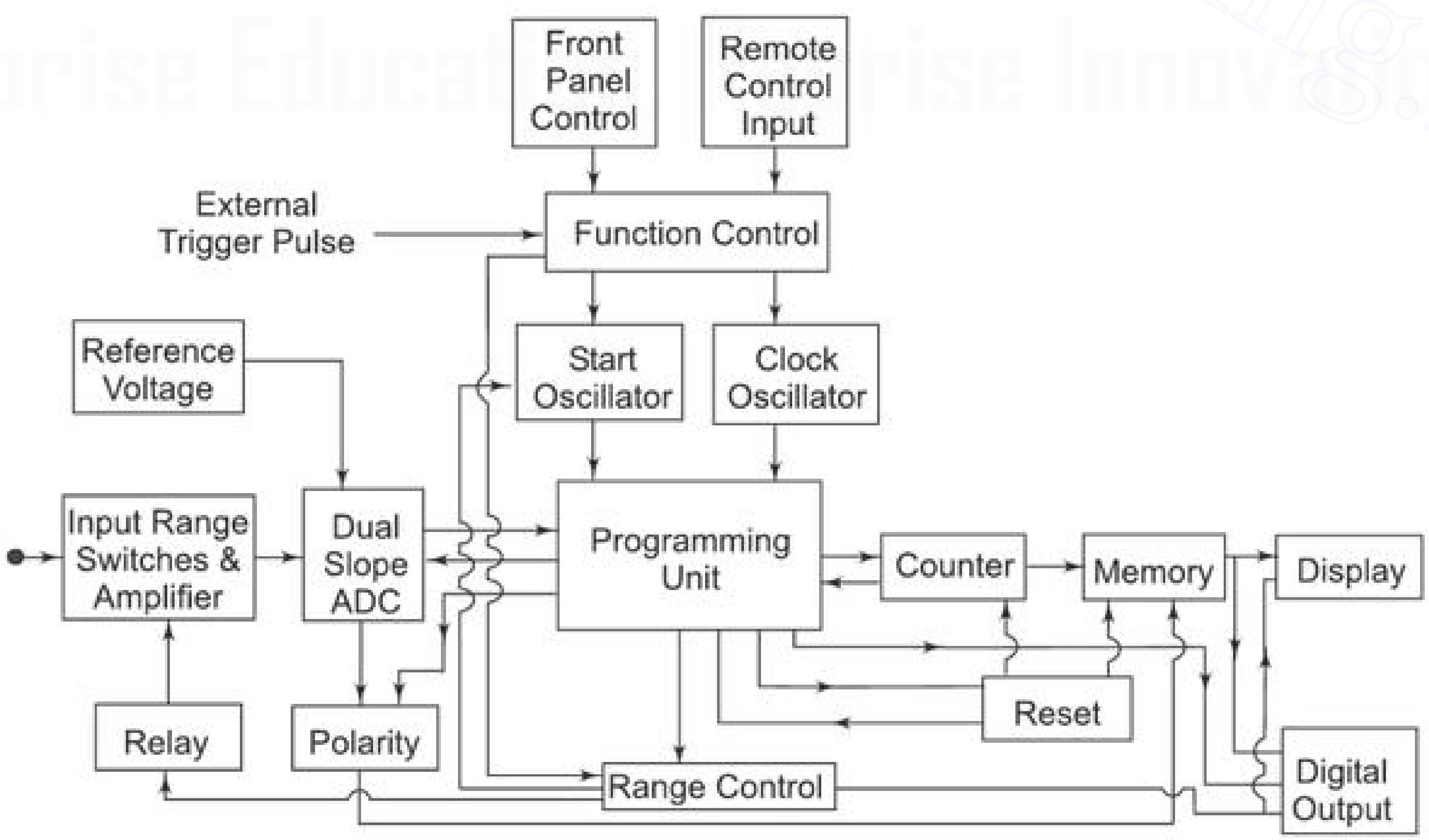


Fig. 6.25 Block diagram of an automatic instrument

Let us assume that in the instrument in question, the ADC is of the dual slope integration type, and that a choice can be made between the combinations given in Table 6.1.

Table 6.1

Measurements	*Integration Time*	*Clock Frequency*
4	100 ms	200 kHz
20	20 ms	1 MHz
200	2 ms	1 MHz

It will be clear that as the number of measurements per second increases, the integration time must be reduced and that it is useful to increase the clock frequency at the same time to maintain good resolution. To select the desired combination, information on the number of measurements per second must be fed to the start oscillator and clock oscillator. The latter constantly supplies clock pulses to the programming unit. The former is free running when the DVM is set for internal start, but it waits for an external trigger signal when the DVM is set for external control. Let us now follow (see Fig. 6.25) the various steps involved in the performance of a measurement, for the case that the instrument is set for automatic ranging and external triggering.

An incoming trigger pulse causes the start oscillator to deliver a pulse to the programming unit, and a measurement is started. The programming unit starts both the counter and the ADC. The ADC is connected to the input. The counter counts the clock pulses to determine the integration time and sends two signals back to the programming unit, one just before the end of the integration period, and the other at the end of this period. The first signal is used by the programming unit to activate the polarity detector, which determines the polarity of the integrated signal, while the second serves to switch the ADC input from the reference signal. At the same time, the counter is reset to zero and starts counting the down integration time of the ADC until it is stopped by the zero-detector signal of the ADC. At that moment, the programming unit compares the counter reading with the automatic ranging limits, and passes an up or down signal to the range control, if necessary. This unit switches the input range switches via a relay and triggers the start oscillator for a new measurement in a more sensitive or less sensitive range. In the meantime, the programming unit will also have reset the counter. This process continues until a measurement which is within the automatic ranging limits has been made. The programming unit then transfers the new data from the counter to the memory, together with the polarity information so as to make them available to the display unit and the digital output. Finally, the programming unit delivers a transfer pulse to the digital output, to warn an instrument connected to this output (e.g. a printer) that new data has been made available.

DIGITAL PHASE METER 6.12

The simplest technique to measure the phase difference between two signals employs two flip-flops. The signals to be fed must be of the same frequency. First, the signals must be shaped to a square waveform without any change in their phase positions, by the use of a zero crossing detector. The process of measuring the phase difference can be illustrated by the schematic diagram shown in Fig. 6.26.

The block diagram consists of two pairs of preamplifier's, zero crossing detectors, J-K F/Fs, and a single control gate. Two signals having phases P_o and P_x respectively are applied as inputs to the preamplifier and attenuation circuit. The frequency of the two inputs is the same but their phases are different.

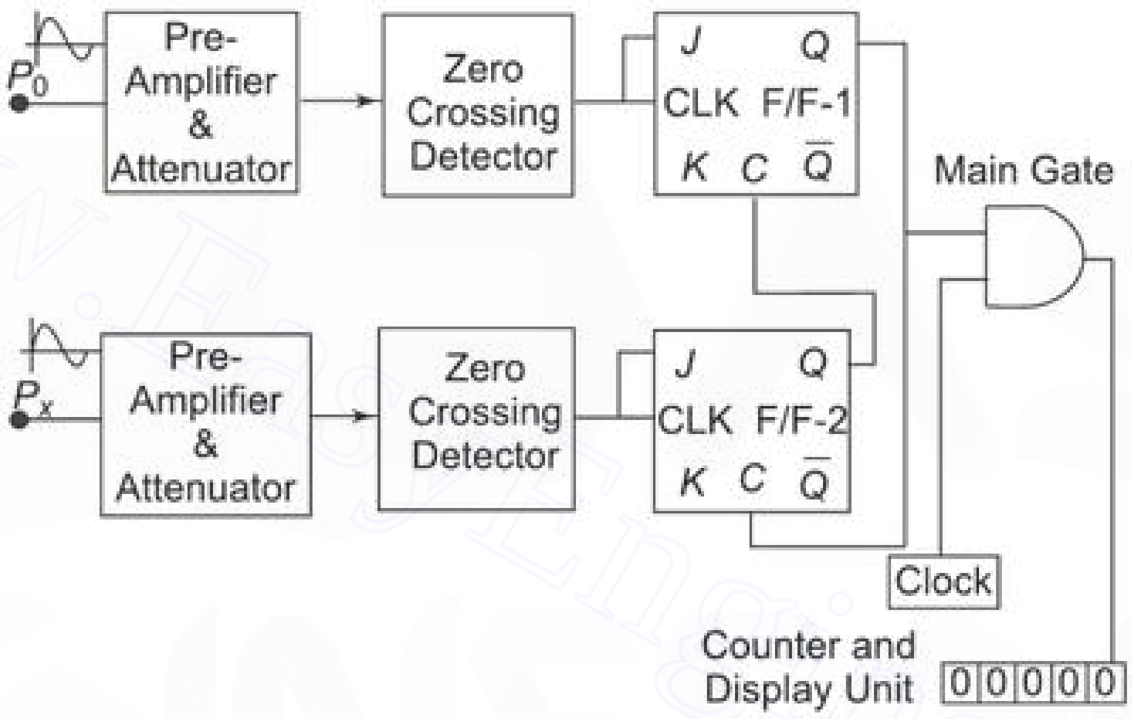


Fig. 6.26 Digital phase meter

As the P_o input signal increases in the positive half cycle, the zero crossing detector changes its state when the input crosses zero (0) giving a high (1) level at the output. This causes the J–K F/F–1 to be set (1), that is, the output (Q) of F/F–1 goes high. This high output from the F/F–1 enables the AND gate, and pulses from the clock are fed directly to the counter. The counter starts counting these pulses. Also this high output level of F/F–1 is applied to the clear input of F/F–2 which makes the output of the F/F–2 go to zero (0).

Now as the input P_x which has a phase difference with respect to P_o, crosses zero (0) in the positive half cycle, the zero detector is activated, causing its output to go high (1). This high input in turn toggles the J–K F/F–2, making its output go high. This output (Q) of F/F–2 is connected to the clear input of F/F–1 forcing the F/F–1 to reset. Hence the output of F/F–1 goes to zero (0). The AND gate is thus disabled, and the counter stops counting.

The number of pulses counted while enabling and disabling the AND gate is in direct proportion to the phase difference, hence the display unit gives a direct readout of the phase difference between the two inputs having the same frequency f.

If the input signal frequency is *f*, then the clock frequency must be 360 times the input frequency for accurate measurements.

DIGITAL CAPACITANCE METER 6.13

Since the capacitance is linearly proportional to the time constant, when a capacitor is charged by a constant current source and discharged through a fixed resistance, we can use a 555 timer along with some digital test equipment to measure capacitances.

One obvious way is to measure the time period of the oscillations. By choosing the right size of charging resistance, we can get a reading directly in microfarads or *nanofarads*. Unlike many capacitance measuring schemes, this one easily handles electrolytics up to the tens of thousands of microfarads.

A better way is to measure only the capacitor discharge time, as shown in Fig. 6.27. With this method, any leakage in the capacitor under test will make the capacitor appear smaller in value than it actually is, and is an effective indicator of how the test capacitor will behave in most timing and bypass circuits.

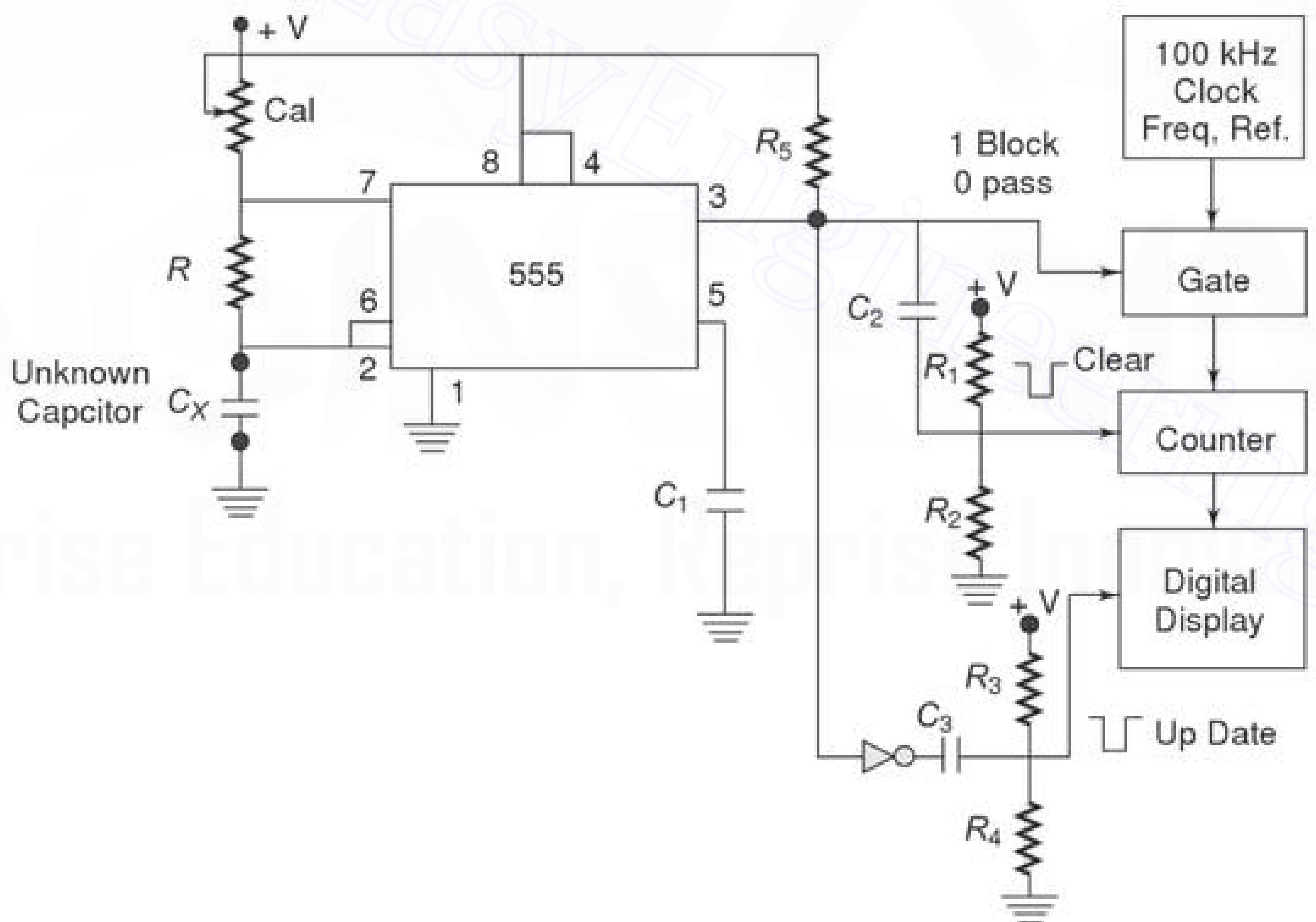


Fig. 6.27 Block diagram of a basic digital capacitance meter

In this circuit, the 555 timer is used as an astable multivibrator. At the peak of the charging curve, a digital counter is reset and a clock of 100 kHz pulses is turned on and routed to the counter. When the discharge portion of the cycle is completed, the display is updated and the value of the capacitor is readout. By selecting the proper reference frequency and charging currents, one can obtain a direct digital display of the value of the capacitance.

Be sure to properly shield the leads and keep them short for low capacity measurements, since the 50 Hz hum can cause some slight instability.

MICROPROCESSOR-BASED INSTRUMENTS 6.14

Digital instruments are designed around digital logic circuits without memory.

The use of microprocessors as an integral part of measuring instruments has given rise to a whole new class of instruments, called intelligent instruments.

Figure 6.28 shows a block diagram of a microprocessor based impedance measuring instrument. The operation makes interface with the instrument via the IEEE 488 bus to allow control by, or to make the measurement available to, a large external computer system. The timing clock signal and the ac test signal are provided by frequency division of the oscillator signal.

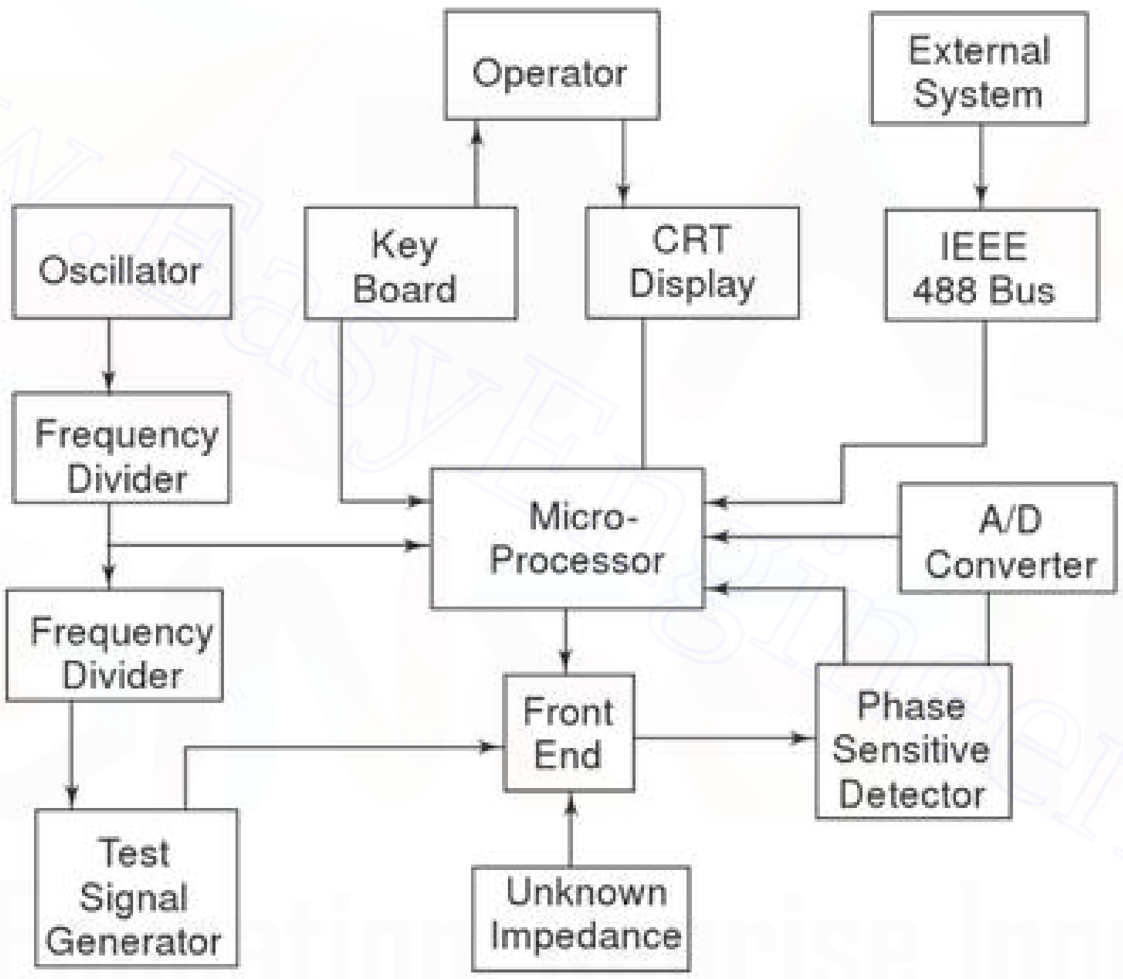


Fig. 6.28 Block diagram of a μp (microprocessor) based instrument

The front end circuit applies the test signal to the unknown impedance and an standard impedance provides an output signal, proportional to the voltage across each, to the phase sensitive detector. Signal transfer is controlled by the microprocessor. The phase sensitive detector, which is also controlled by the microprocessor, converts the ac inputs of the impedance in vector form to a dc output. The A/D converter provides the digital data,which is used by the microprocessor to compute the value of the unknown impedance. This is then displayed on the CRT or sent as output to the IEEE 488 bus.

THE IEEE 488 BUS 6.15

The purpose of IEEE 488 bus is to provide digital interfacing between programmable instruments. There are many instrumentation systems in which interactive instruments, under the command of a central controller, provide superior error-free results when compared with conventional manually operated systems.

Problems such as impedance mismatch, obtaining cables with proper connectors and logic level compatibility are also eliminated by designing the system around a bus-compatible instrument.

The basic structure of an IEEE 488 bus showing interfacing between interactive instruments is given in Fig. 6.29.

Every device in the system must be able to perform at least one of the roles, namely talker, listener or controller. A talker can send data to other devices via the bus. Some devices, such as programmable instruments, can both listen and talk.

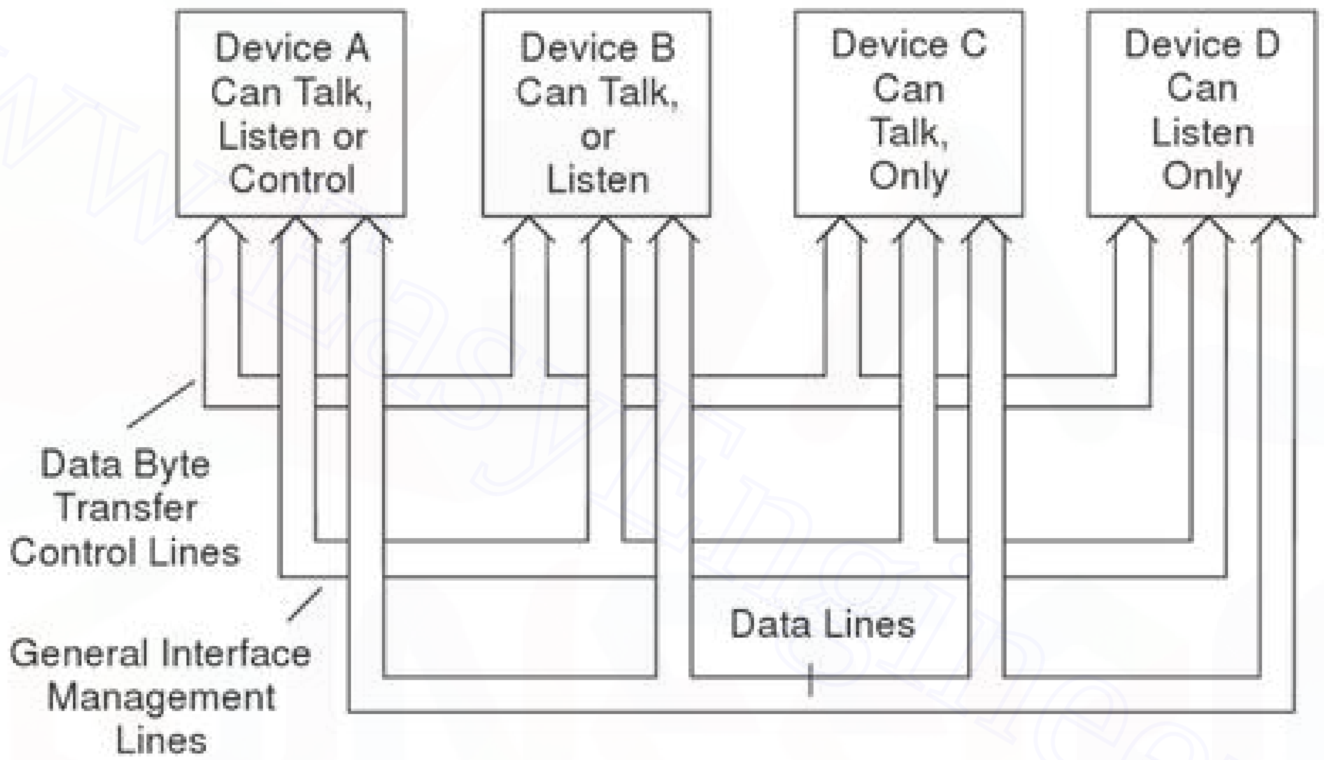


Fig. 6.29 Block Diagram of devices interfaced with IEEE 488 bus

In the listen mode it may receive an instruction to make a particular measurement and in the talk mode it may send its measurand. A controller manages the operation of the bus system. It controls data gathering and transfer by designating which devices talk or listen as well as controlling specific actions within other devices.

Review Questions

1. State the advantages of digital instruments over analog instruments.
2. Explain the operation of a basic digital multimeter.
3. Describe with a diagram the working of a digital multimeter.
4. Explain how current can be measured by digital multimeter. Explain how resistance can be measured by a DMM.
5. Describe the operation of current to voltage converter.
6. Explain with a diagram the working of a digital panel meter.
7. Stae the difference between DMM and DPM.
8. State different types of digital meters.
9. Explain the working principle of a digital frequency meter.

10. Explain with the help of block diagram the operation of a DFM.
11. State the function and explain the operation of a gate control flip-flop.
12. State the function and explain the operation of a time base selector.
13. Explain with a diagram the basic principle of operation of digital time measurement.
14. Describe with the help of a block diagram the operation of digital time measurement.
15. Explain with a diagram the operation of period measurement.
16. What is a universal counter ? How can it be used to measure the following:
    (i) Frequency (ii) Time
    (iii) Period (iv) Ratio
17. Describe with the help of a block diagram the operation of a universal counter-timer.
18. What is an electronic counter ? How can it be used to measure the following:
    (i) Totalising (ii) Frequency
    (iii) Period mode (iv) Ratio mode
    (v) Time interval mode,
19. Explain with a diagram the operation of a digital measurement of mains frequency.
20. On what principle does a digital tachometer operate? Explain with a diagram the working of a digital tachometer.
21. Explain with a diagram the working of a digital pH meter. How is pH measured?
22. On what principle does a digital capacitance meter operate? Describe with a diagram the operation of a digital capacitance meter.
23. How is automation in digital instruments obtained? Why are the ranges in digital instruments overlapped?
24. How can measurements of impedance be obtained using microprocessors?

Multiple Choice Questions

1. A time base selector is used to select
   (a) frequency (b) time
   (c) amplitude (d) voltage
2. A time base selector basically consists of
   (a) LC oscillator
   (b) RC oscillator
   (c) crystal oscillator
   (d) Wien bridge oscillator
3. Schmitt trigger used in digital measurement time converts input to
   (a) square wave
   (b) sine wave
   (c) pulses
   (d) sawtooth wave.
4. A frequency meter is used to measure
   (a) frequency
   (b) ratio
   (c) time interval
   (d) phase
5. Frequency dividers used in the frequency counter divide the frequency by
   (a) 10 (b) 2
   (c) 100 (d) 20

Further Reading

1. Malvino and Leach, *Digital Principles*, McGraw-Hill, New York.
2. Larry D. Jones and A. Foster Chin, *Electronic Instruments and Measurements*, John Wiley & Sons, 1987.
3. Malmstadt, Enke and Others, *Instrumentation for Scientist*.
4. E.O. Doebelin, *Measurement Systems: Applications and Design*, 4th Edition, 1990, McGraw-Hill.

Chapter 7

Oscilloscope

INTRODUCTION 7.1

The Cathode Ray Oscilloscope (CRO) is probably the most versatile tool for the development of electronic circuits and systems.

The CRO allows the amplitude of electrical signals, whether they are voltage, current, or power, to be displayed as a function of time.

The CRO depends on the movement of an electron beam, which is bombarded (impinged) on a screen coated with a fluorescent material, to produce a visible spot. If the electron beam is deflected on both the conventional axes, i.e. X-axis and Y-axis, a two-dimensional display is produced.

The beam is deflected at a constant rate relative of time along the X-axis and is deflected along the Y-axis in response to an stimulus, such as a voltage. This produces a time-dependent variation of the input voltage.

The oscilloscope is basically an electron beam voltmeter. The heart of the oscilloscope is the Cathode Ray Tube (CRT) which makes the applied signal visible by the deflection of a thin beam of electrons. Since the electron has practically no weight, and hence no inertia, therefore the beam of electrons can be moved to follow waveforms varying at a rate of millions of times/second. Thus, the electron beam faithfully follows rapid variations in signal voltage and traces a visible path on the CRT screen. In this way, rapid variations, pulsations or transients are reproduced and the operator can observe the waveform as well as measure amplitude at any instant of time.

Since it is completely electronic in nature, the oscilloscope can reproduce HF waves which are too fast for electro mechanical devices to follow. Thus, the oscilloscope has simplified many tests and measurements. It can also be used in any field where a parameter can be converted into a proportional voltage for observation, e.g. meteorology, biology, and medicine.

The oscilloscope is thus a kind of voltmeter which uses beam instead of a pointer, and kind of recorder which uses an electron beam instead of a pen.

BASIC PRINCIPLE 7.2

7.2.1 Electron Beam

To understand the principle of an oscilloscope, let us consider a torch which is focussed on a piece of cardboard (held perpendicular to the torch). The light beam will make a bright spot where it strikes the cardboard or screen. Hold the torch still, the spot remains still, move the torch, the spot also moves. If the movement is slow, the eye can follow the movement, buf if it is too fast for the eye to follow, persistence of vision causes the eye to see the pattern traced by the spot. Hence when we wave the torch from side to side, a horizontal line is traced; we can similarly have a vertical line or a circle. Hence, if the torch is moved in any manner at a very rapid rate, light would be traced, just like drawing or writing.

A similar action takes place in the CRT of an oscilloscope. The torch is replaced by an electron gun, the light beam by a narrow electron beam, and the cardboard by the external flat end of a glass tube, which is chemically coated to form a fluorescent screen. Here the electron gun generates the beam which moves down the tube and strikes the screen. The screen glows at the point of collision, producing a bright spot.

When the beam is deflected by means of an electric or magnetic field, the spot moves accordingly and traces out a pattern.

The electron gun assembly consists of the indirectly heated cathode with its heater, the control grid, and the first and second anodes.

The control grid in the CRT is cylindrical, with a small aperture in line with the cathode. The electrons emitted from the cathode emerge from this aperture as a slightly divergent beam. The negative bias voltage applied to the grid, controls the beam current. The intensity (or brightness) of the phosphorescent spot depends on the beam current. Hence this control grid bias knob is called or labelled as intensity.

The diverging beam of electrons is converged and focussed on the screen by two accelerating anodes, which form an electronic lens. Further ahead of the grid cylinder is another narrow cylinder, the first anode. It is kept highly positive with respect to the cathode. The second anode is a wider cylinder following the first. Both the cylinders have narrow apertures in line with the electron beam. The second anode is operated at a still higher positive potential and does most of the accleration of the beam. The combination of the first anode cylinder and the wider second anode cylinder produces an electric field that focuses the electron beam on the screen, as a lens converges a diverging beam of light.

The electronic lens action is controlled by the focus control. If this control is turned to either side of its correct focussing position, the spot on the screen becomes larger and blurred. Bringing it back to its correct position brightens and concentrates the spot. With this proper focus, the small spot can be deflected to produce sharp narrow lines that trace the pattern on the CRT screen.

The electron beam may be deflected transversely by means of an electric field (electrostatic deflection) or a magnetic field (electromagnetic deflection).

Most oscilloscopes use electrostatic deflection, since it permits high frequency operation and requires negligible power. Electromagnetic deflection is most common in TV picture tubes.

Electrons are negatively charged particles, they are attracted by a positive charge or field and repelled by a negative charge. Since the electron beam is a stream of electrons, a positive field will divert it in one direction and a negative field in the opposite direction. To move the beam in this way in the CRT, deflecting plates are mounted inside the tube and suitable deflecting voltages are applied to them.

These plates are arranged in two pairs; H_1 and H_2 for deflecting the beam horizontally, and V_1 and V_2 for deflecting it vertically. Leads are taken out for external connections. The beam passes down the tube between the four plates, as shown in Fig. 7.1.

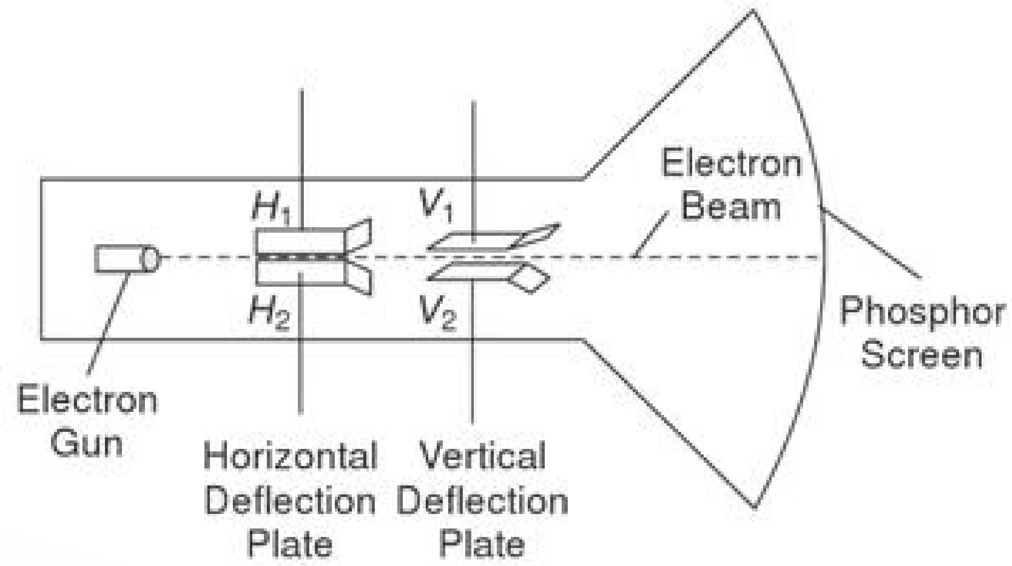


Fig. 7.1 Basic diagram of a CRT

When the plates are at zero voltage the beam is midway between them and the spot is in the centre of the screen. When H_1 is made positive with respect to the cathode (and all other plates are at zero voltage), it attracts the beam and the spot moves horizontally to the left. When H_2 is made positive, it attracts the beam and the spot moves horizontally to the right. Similarly when V_1 is made positive, the spot moves vertically upwards and when V_2 is made positive it moves vertically downwards. In each of these deflections, the displacement of the beam, and therefore, the distance travelled by the spot, is proportional to the voltage applied at the plates.

Figure 7.2 shows the various positions of the electron beam for different voltages applied to the two pairs of plates. If a negative voltage is applied to any plate, the beam will be repelled rather than attracted and the deflection will be in the opposite direction. For example, if V_1 is made negative, the beam will be deflected vertically downward.

As mentioned before, when a spot moves too rapidly for the eye to follow it traces a line. The same happens when a rapidly pulsating or ac voltage is applied to the deflecting plates, the beam is moved back and forth so rapidly that the spot traces a line. When a positive pulsating voltage is applied to H_1 (or negative pulsating to H_2) the spot traces a horizontal line from the centre to the left. Similarly when a positive pulsating voltage is applied to H_2 (or negative to H_1), the spot traces a horizontal line from the centre to the right. Similarly, when the pulsating voltage is applied to V_1, we get a vertical line from the centre upwards and when applied to V_2, we get a vertical line from the centre downwards.

Now, when an alternating voltage is applied to H_1 or H_2, the spot moves from the centre to one side, back to the centre and on to the other side, back again and so on, tracing a line that passes through the centre of the screen (because of the attraction and repulsion of the beam by the positive and negative ac half cycles). Hence, a horizontal line is traced when an ac voltage is applied to either horizontal plates. Similarly, a vertical line is traced when an ac voltage is applied to the vertical plates.

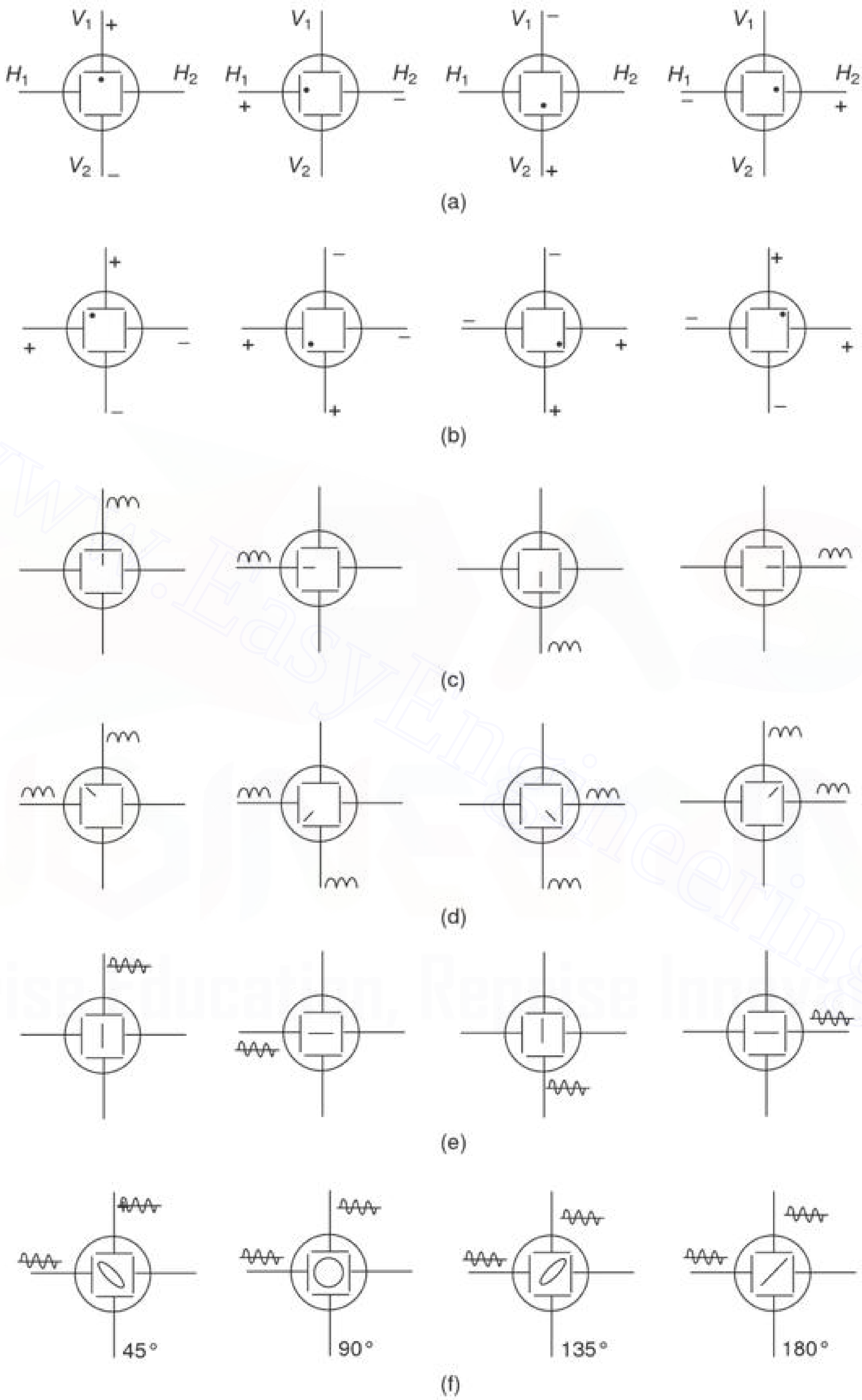


Fig. 7.2 (a) Applying dc voltage to vertical and horizontal plates (b) Applying dc voltage to both vertical and horizontal plates (c) Applying pulsating dc to vertical or horizontal plates (d) Applying pulsating dc to both vertical and horizontal (e) Applying a sine wave to vertical or horizontal (f) Applying phase-shifted sine waves to vertical and horizontal plates

Now, let us see what happens to the beam when voltage is applied simultaneously to both vertical and horizontal plates.

When voltage is applied to the vertical and horizontal plates simultaneously, the deflection of the beam is proportional to the resultant of the two voltages and the position of the beam is inbetween the horizontal and vertical axis of the screen.

Suppose a steady voltage is applied to one horizontal and one vertical plate. When these two deflection voltages are equal, the position of the spot is 45°. The angle is greater than 45° (spot close to *V*-axis) when the vertical voltage is greater than the horizontal, and less than 45° (spot close to the *H*-axis) when the horizontal voltage is greater than the vertical voltage. When the two voltages are reversed in polarity, the deflection is in the opposite direction.

If instead of a steady voltage a pulsating positive voltage is applied to the same plates as before, a tilt of 45° is obtained from the horizontal if the two voltages are equal and in phase. The tilt is greater than 45° if the vertical voltage is greater than the horizontal voltage, and less than 45° if the horizontal voltage is greater than the vertical voltage. When a negative voltage is applied to both plates, the trace extends in the opposite direction. When an alternating voltage in phase is applied to the plates, the tilt of the trace is 45° from the horizontal when the two voltages are equal, it traces a straight line at an angle of 45 degrees. Again the tilt is greater than 45° if the vertical voltage is greater, and less than 45° if the horizontal voltage is greater.

The ac trace has equal length from the centre of screen to either tip, when the ac is symmetrical. When it is asymmetrical, the shorter part corresponds to the lower voltage half cycle.

A single trace is obtained only when the phase angles are 0°, 180°, or 360°. At other phase angles a double line trace is obtained at equal voltages, the pattern becomes an ellipse with a right tilt for angle between 0–90°, a circle at 90° and an ellipse with a left tilt between 90–180°. Again, a left tilt between 180–270°, a circle at 270°, an ellipse with lift tilt between 270–360°.

CRT FEATURES 7.3

Electrostatic CRTs are available in a number of types and sizes to suit individual requirements. The important features of these tubes are as follows.

1. Size Size refers to the screen diameter. CRTs for oscilloscopes are available in sizes of 1, 2, 3, 5, and 7 inches. 3 inches is most common for portable instruments.

For example a CRT having a number 5GP1. The first number 5 indicates that it is a 5 inch tube.

Both round and rectangular CRTs are found in scopes today. The vertical viewing size is 8 cm and horizontal is 10 cm.

2. Phosphor The screen is coated with a fluorescent material called phosphor. This material determines the colour and persistence of the trace, both of which are indicated by the phosphor.

The trace colours in electrostatic CRTs for oscilloscopes are blue, green and blue green. White is used in TVs, and blue-white, orange, and yellow are used for radar.

Persistence is expressed as short, medium and long. This refers to the length of time the trace remains on the screen after the signal has ended.

The phosphor of the oscilloscope is designated as follows.

P1 — Green medium
P2 — Blue green medium
P5 — Blue very short
P11 — Blue short

These designations are combined in the tube type number. Hence 5GP1 is a 5 inch tube with a medium persistence green trace.

Medium persistence traces are mostly used for general purpose applications.

Long persistence traces are used for transients, since they keep the fast transient on the screen for observation after the transient has disappeared.

Short persistence is needed for extremely high speed phenomena, to prevent smearing and interference caused when one image persists and overlaps with the next one.

P11 phosphor is considered the best for photographing from the CRT screen.

3. Operating Voltages The CRT requires a heater voltage of 6.3 volts ac or dc at 600 mA.

Several dc voltages are listed below. The voltages vary with the type of tube used.

(i) Negative grid (control) voltage – 14 V to – 200 V.
(ii) Positive anode no. 1 (focusing anode) – 100 V to – 1100 V
(iii) Positive anode no. 2 (accelerating anode) 600 V to 6000 V
(iv) Positive anode no. 3 (accelerating anode) 200 V to 20000 V in some cases

4. Deflection Voltages Either ac or dc voltage will deflect the beam. The distance through which the spot moves on the screen is proportional to the dc, or peak ac amplitude. The deflection sensitivity of the tube is usually stated as the dc voltage (or peak ac voltage) required for each cm of deflection of the spot on the screen.

5. Viewing Screen The viewing screen is the glass face plate, the inside wall of which is coated with phosphor. The viewing screen is a reetangular screen having graticules marked on it. The standard size used nowadays is 8 cm × 10 cm (8 cm on the vertical and 10 cm on horizontal). Each centimeter on the graticule corresponds to one division (div). The standard phosphor colour used nowadays is blue.

7.3.1 Basic Principle of Signal Display (Function of the Sweep Generator)

The amplitude of a voltage may be directly measured on a calibrated viewing screen from the length of the straight line trace it produces. This is entirely satisfactory for dc voltage.

But the straight line tells little, or practically nothing, about the waveform of an ac voltage, pulsating voltage or transient. What is required is a graph of the voltage traced on the screen by the ac spot (a graph of amplitude versus time).

To obtain such a display the signal voltage is applied to the vertical plates (directly or through the vertical amplifier) and it moves the spot vertically to positions, corresponding to the instantaneous values of the signal. Simultaneously, the spot is moved horizontally by a sweep voltage applied to the horizontal plates. The combined action of these two voltages causes the spot to produce a trace on the screen. The horizontal sweep voltage produces the time base by moving the spot horizontally with time, while the signal moves the spot vertically in proportional to the voltage at a particular instant of time.

There are two important sweep generator requirements.

1. The sweep must be linear (the sweep voltage must rise linearly to the maximum value required for full screen horizontal deflection of the spot).
2. The spot must move in one direction only, i.e. from left to right only, else the signal will be traced backwards during the return sweep. This means that the sweep voltage must drop suddenly after reaching its maximum value. These requirements call for a sweep voltage having a linear sawtooth waveform, as shown in Fig. 7.3.

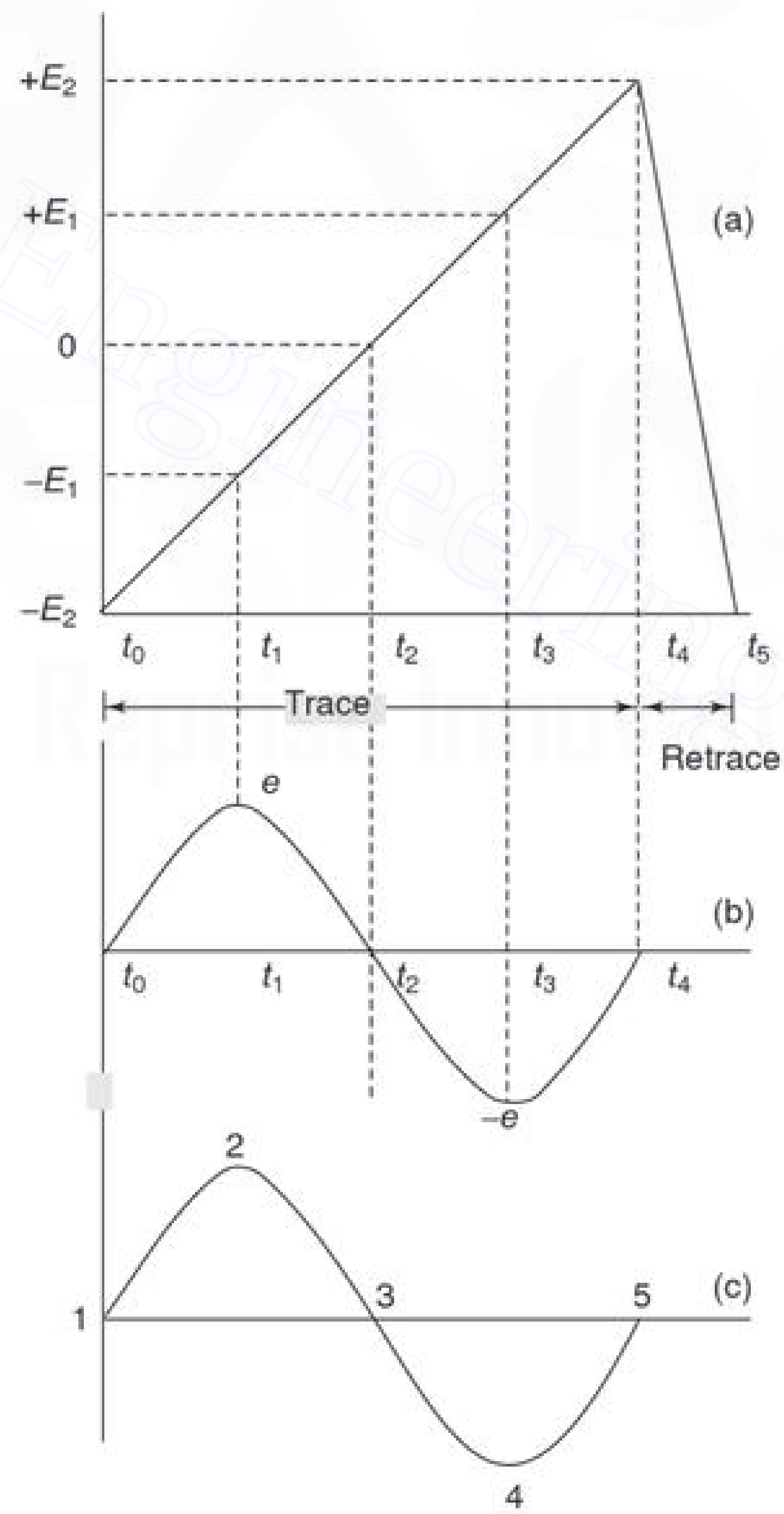


Fig. 7.3 Waveform of sweep voltage

Now at time t_0, the sweep voltage is $-E_2$, and the negative horizontal voltage moves the spot to point 1 on the screen. At this instant, the signal voltage is 0, so the spot rests at the left end of the zero line on the screen.

At time t_1, the linearly increasing sawtooth reaches $-E_1$, which, being more positive than $-E_2$, moves the spot to the screen, point 2. At this instant, the signal voltage is e, the +ve peak value, so the point represents its maximum upward deflection of the spot. At time t_2, the sawtooth voltage is 0, there is no horizontal deflection and the spot is at the centre, point 3. At this instant, the signal voltage is 0, so there is no vertical deflection either. At time t_3, the sawtooth voltage is $+E_1$, moving the spot to point 4.

At this instant, the signal is $-e$, the –ve peak value, so point 4 is the maximum downward deflection of the spot. At time t_4, the sawtooth voltage is $+E_2$, moving the spot to point 5. Now the signal voltage is 0, so the spot is not vertically deflected. Between t_4 and t_5, the sawtooth voltage falls quickly through 0 to its initial value of $-E_2$, snapping the spot back to point 1, in time to sweep forward on the next cycle of signal voltage. When sweep and signal frequencies are equal, a single cycle appears on the screen, when the sweep is lower than the signal, several cycles appear (in the ratio of the two frequencies), and when sweep is higher than signal, less than one cycle appears. The display is stationary only when the two frequencies are either equal or integral multiples of each other. At other frequencies the display will drift horizontally. A sawtooth sweep voltage is generated by a multivibrator, relaxation oscillator or pulse generator. The upper frequency generated by internal devices in the oscilloscope is 50–100 kHz in audio instruments, 500–1000 kHz in TV service instruments and up to several MHz in high quality laboratory instruments. In some oscilloscopes the sweep is calibrated in Hz or kHz, and in others it is calibrated in time units (μs, ms, s). The different types of sweep generated are as follows:

1. Recurrent Sweep When the sawtooths, being an ac voltage alternates rapidly, the display occurs repetitively, so that a lasting image is seen by the eye. This repeated operation is recurrent sweep.

2. Single Sweep The signal under study produces a trigger signal, which in turn produces a single sweep.

3. Driven Sweep The sawtooth oscillator is a free running generator when operated independently. There is a chance that the sweep cycle may start after the signal cycle, thereby missing a part of the signal. Driven sweep removes this possibility because it is fixed by the signal itself. The sweep and signal cycles start at the same time.

4. Triggered Sweep In a recurrent mode, the pattern is repeated again and again. In this mode the voltage rises to a maximum and then suddenly falls to a minimum. The electron beam moves slowly from left to right, retraces rapidly to the left and the pattern is repeated. The horizontal sweep action takes place whether the input signal is applied to the oscilloscope or not, and a horizontal line is displayed on the scope screen.

A triggered sweep, on the other hand, does not start unless initiated by a trigger voltage, generally derived from an incoming signal. In the absence of the input signal, the sweep is held off and the CRT screen is blanked.

The continuous or recurrent sweep uses a free running multivibrator (m/v) which covers a wide frequency range and can be locked into synchronisation by an input signal. Sync takes place when the sweep frequency and the input signal frequency are the same or when the former is a multiple of the latter.

A triggered scope does not use a continuous or recurrent sweep, but uses a monostable multivibrator which is in its off state until a trigger pulse arrives, hence there is no deflection on the screen.

When an input signal is applied, a trigger pulse is generated and applied to the multivibrator, which switches on and produces a sweep signal, and a trace appears on the screen. After a specific voltage, depending on the CRT beam arriving on the RHS, the multivibrator switches back to its off state, causing the beam to return rapidly to the LHS. (The basic difference between recurrent and triggered scopes is that the recurrent sweep locks at the frequency of the input signal, while the triggered scope displays a trace for a specific period of time. Hence, the triggered scope is ON during a specific time interval and will display a waveform or a segment of waveform (e.g. a one shot waveform) regardless of the signal frequency. Hence transients or single clamped oscillations can be observed on the screen.)

Most triggered scopes use a convenient feature of calibrating the sweep speed, in time per cm or division. Sweep frequency is the reciprocal of the time period.

5. Intensity Modulation In some applications an ac signal is applied to the control electrode of the CRT. This causes the intensity of the beam to vary in step with signal alternations. As a result, the trace is brightened during the +ve half cycles and diminished or darkened during –ve half cycles. This process, is called intensity modulation or *Z*-axis modulation (in contrast to *X*-axis for horizontal and *Y*-axis for vertical). It produces bright segments or dots on the trace in response to positive peak or dim segments or holes in response to negative peaks.

BLOCK DIAGRAM OF OSCILLOSCOPE 7.4

The major block circuit shown in Fig. 7.4, of a general purpose CRO, is as follows:

1. CRT
2. Vertical amplifier
3. Delay line
4. Time base
5. Horizontal amplifier
6. Trigger circuit
7. Power supply

The function of the various blocks are as follows.

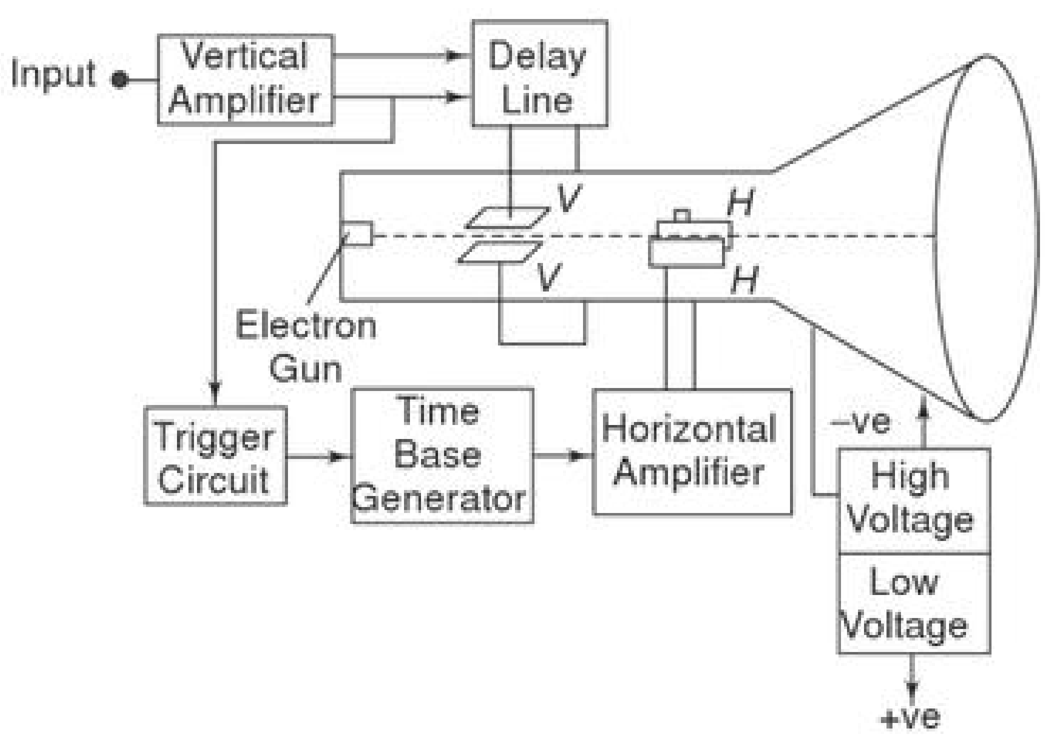


Fig. 7.4 Basic CRO block diagram

1. CRT This is the cathode ray tube which emits electrons that strikes the phosphor screen internally to provide a visual display of signal.

2. Vertical Amplifier This is a wide band amplifier used to amplify signals in the vertical section.

3. Delay Line It is used to delay the signal for some time in the vertical sections.

4. Time Base It is used to generate the sawtooth voltage required to deflect the beam in the horizontal section.

5. Horizontal Amplifier This is used to amplify the sawtooth voltage before it is applied to horizontal deflection plates.

6. Trigger Circuit This is used to convert the incoming signal into trigger pulses so that the input signal and the sweep frequency can be synchronised

7. Power Supply There are two power supplies, a –ve High Voltage (HV) supply and a +ve Low Voltage (LV) supply. Two voltages are generated in the CRO. The +ve volt supply is from + 300 to 400 V. The –ve high voltage supply is from – 1000 to – 1500 V. This voltage is passed through a bleeder resistor at a few mA. The intermediate voltages are obtained from the bleeder resistor for intensity, focus and positioning controls.

Advantages of using –ve HV Supply

(i) The accelerating anodes and the deflection plates are close to ground potential. The ground potential protects the operator from HV shocks when making connections to the plates.

(ii) The deflection voltages are measured wrt ground, therefore HV blocking or coupling capacitor are not needed, but low voltage rating capacitors can be used for connecting the HV supply to the vertical and horizontal amplifiers.

(iii) Less insulation is needed between positioning controls and chasis.

SIMPLE CRO 7.5

The basic block diagram of a simple CRO is shown in Fig. 7.5. The ac filament supplies power to the CRT heaters. This also provides an accurate ac calibrating voltage. CRT dc voltage is obtained from the HV dc supply through voltage dividers $R_1 - R_5$. Included along with this voltage divider is a potentiometer (R_3) which varies the potential at the focusing electrode, known as focus control, and one which varies the control grid voltage, called the intensity control (R_5).

Capacitor C_1 is used to ground the deflection plates and the second anode for the signal voltage, but dc isolates these electrodes from the ground.

Normally S_2 is set to its linear position. This connects the sweep generator output to the horizontal input. The sweep voltage is amplified before being applied to the horizontal deflecting plates.

When an externally generated sweep is desired, S_2 is connected to its external position and the external generator is connected to the input. The sweep synchronising voltage is applied to the internal sweep generator through switch S_1, which selects the type of synchronisation.

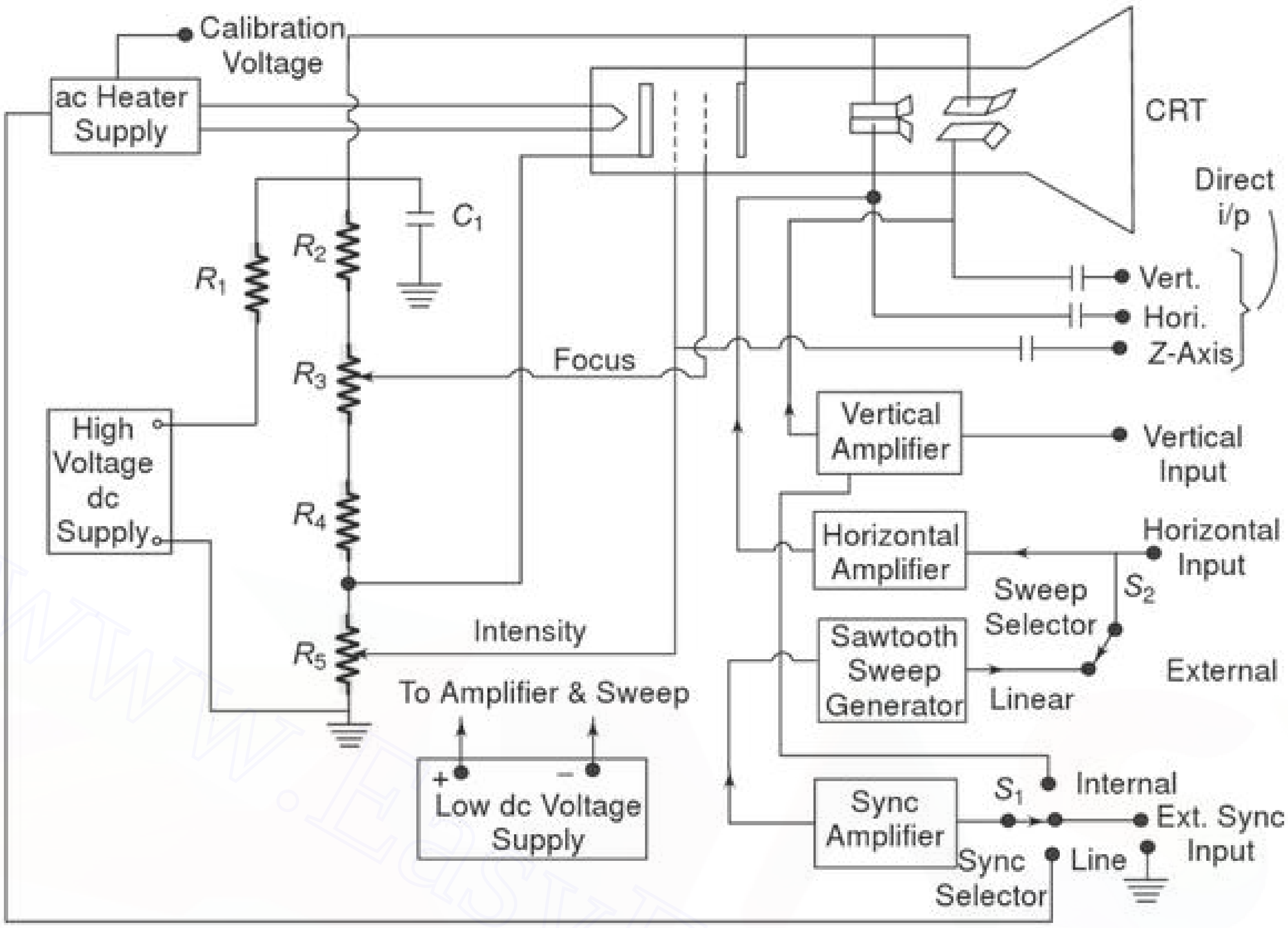


Fig. 7.5 Simple CRO

7.5.1 CRT Showing Power Supply

Figure 7.6 shows the various voltages applied to CRT electrodes. The intensity control controls the number of electrons by varying the control grid voltage. Focusing can be done either electrostatically or electromagnetically. Electrostatic focusing is obtained by using a cylindrical anode, which changes the electrostatic lines of force which controls the beam.

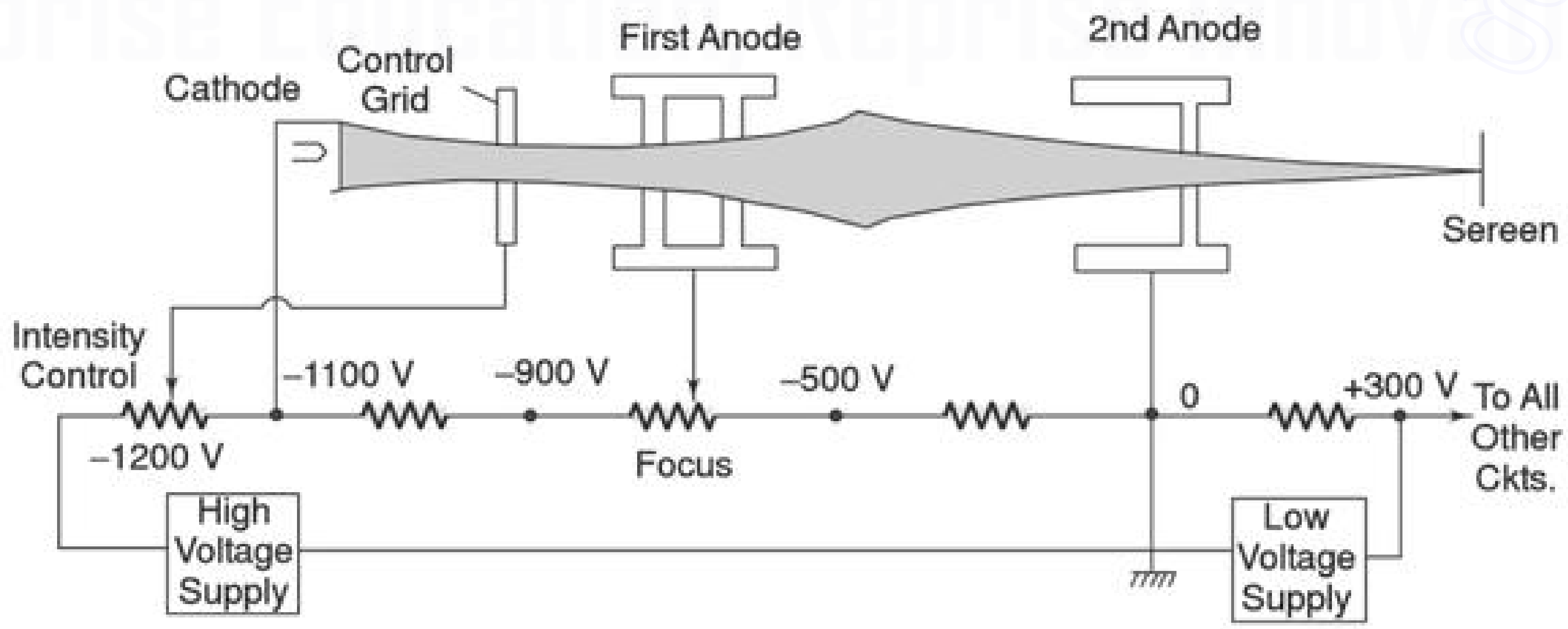


Fig. 7.6 CRT showing power supplies

VERTICAL AMPLIFIER 7.6

The sensitivity (gain) and frequency bandwidth (B.W.) response characteristics of the oscilloscope are mainly determined by the vertical amplifier. Since the gain–

B.W. product is constant, to obtain a greater sensitivity the B.W. is narrowed, or vice-versa.

Some oscilloscopes give two alternatives, switching to a wide bandwidth position, and switching to a high sensitivity position.

Block Diagram of a Vertical Amplifier The block diagram of a vertical amplifier is shown in Fig. 7.7.

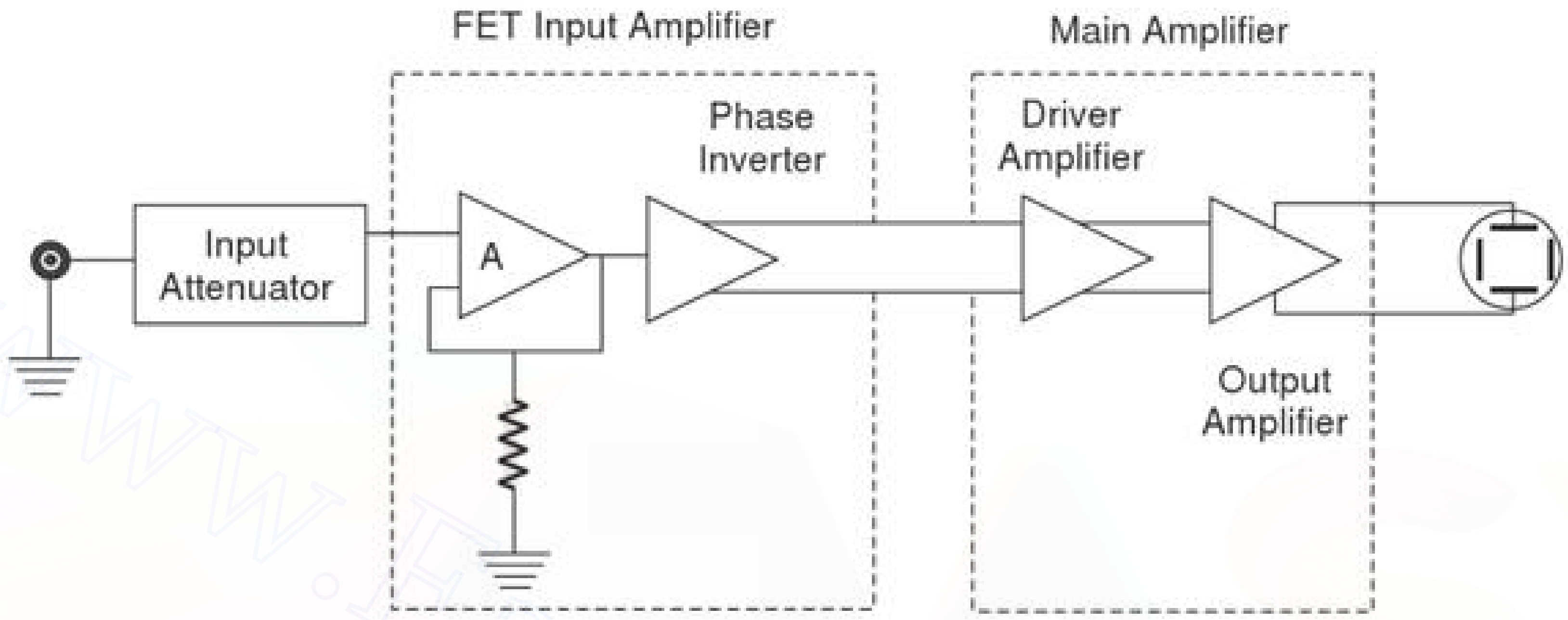


Fig. 7.7 Vertical amplifier

The vertical amplifier consists of several stages, with fixed overall sensitivity or gain expressed in V/div. The advantage of fixed gain is that the amplifier can be more easily designed to meet the requirements of stability and B.W. The vertical amplifier is kept within its signal handling capability by proper selection of the input attenuator switch. The first element of the pre-amplifier is the input stage, often consisting of a FET source follower whose high input impedance isolates the amplifier from the attenuator.

This FET input stage is followed by a BJT emitter follower, to match the medium impedance of FET output with the low impedance input of the phase inverter.

This phase inverter provides two antiphase output signals which are required to operate the push-pull output amplifier. The push-pull output stage delivers equal signal voltages of opposite polarity to the vertical plates of the CRT.

The advantages of push-pull operation in CRO are similar to those obtained from push-pull operation in other applications; better hum voltage cancellation from the source or power supply (i.e. dc), even harmonic suppression, especially the large 2nd harmonic is cancelled out, and greater power output per tube as a result of even harmonic cancellation. In addition, a number of defocusing and non-linear effects are reduced, because neither plate is at ground potential.

HORIZONTAL DEFLECTING SYSTEM 7.7

The horizontal deflecting system consist of a Time Base Generator and an output amplifier.

7.7.1 Sweep or Time Base Generator

A continuous sweep CRO using a UJT as a time base generator is shown in Fig. 7.8. The UJT is used to produce the sweep. When the power is first applied, the UJT is off and the C_T charges exponentially through R_T. The UJT emitter voltage V_E rises towards V_{BB} and when V_E reaches the peak voltage V_P, as shown in Fig. 7.9, the emitter to base '1' (B_1) diode becomes forward biased and the UJT triggers ON. This provides a low resistance discharge path and the capacitor discharges rapidly. The emitter voltage V_E reaches the minimum value rapidly and the UJT goes OFF. The capacitor recharges and the cycle repeats.

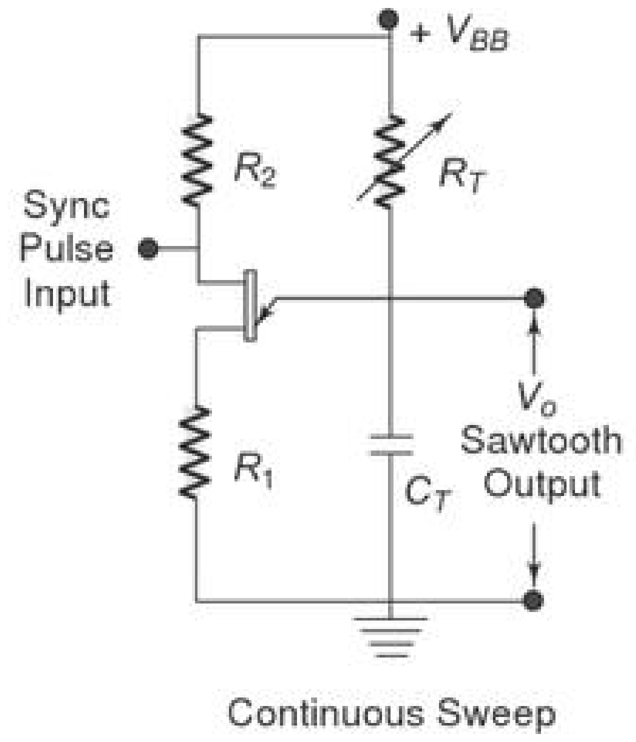


Fig. 7.8 Continuous sweep

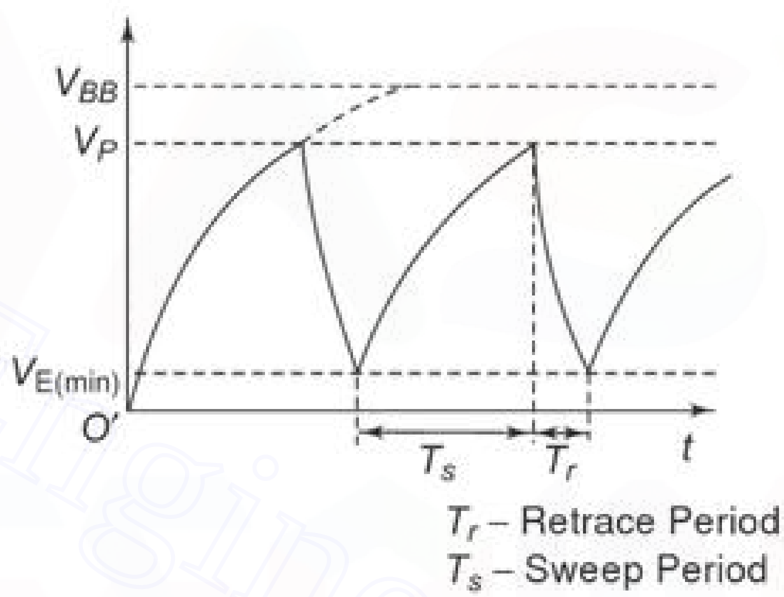


Fig. 7.9 Sawtooth output waveform

To improve sweep linearity, two separate voltage supplies are used, a low voltage supply for UJT and a high voltage supply for the $R_T C_T$ circuit.

R_T is used for continuous control of frequency within a range and C_T is varied or changed in steps for range changing. They are sometimes called as timing resistor and timing capacitor respectively.

The sync pulse enables the sweep frequency to be exactly equal to the input signal frequency, so that the signal is locked on the screen and does not drift.

TRIGGERED SWEEP CRO 7.8

The continuous sweep is of limited use in displaying periodic signals of constant frequency and amplitude. When attempting to display voice or music signals, the pattern falls in and out of sync as the frequency and amplitude of the music varies resulting in an unstable display.

A triggered sweep can display such signals, and those of short duration, e.g. narrow pulses. In triggered mode, the input signal is used to generate substantial pulses that trigger the sweep. Thus ensuring that the sweep is always in step with the signal that drives it.

As shown in Fig. 7.10, resistance R_3 and R_4 form a voltage divider such that the voltage V_D at the cathode of the diode is below the peak voltage V_P for UJT conduction. When the circuit is switched on, the UJT is in the non-conducting stage, and C_T charges exponentially through R_T towards V_{BB} until the diode becomes forward biased and conducts; the capacitor voltage never reaches the peak voltage required for UJT conduction but is clamped at V_D. If now a –ve pulse of sufficient amplitude is applied to the base and the peak voltage V_p is momentarily lowered, the UJT fires. As a result, capacitor C_T discharges rapidly through the UJT until the maintaining voltage of the UJT is reached; at this point the UJT switches off and capacitor C_T charges towards V_{BB}, until it is clamped again at V_D. Figure 7.11 shows the output waveform.

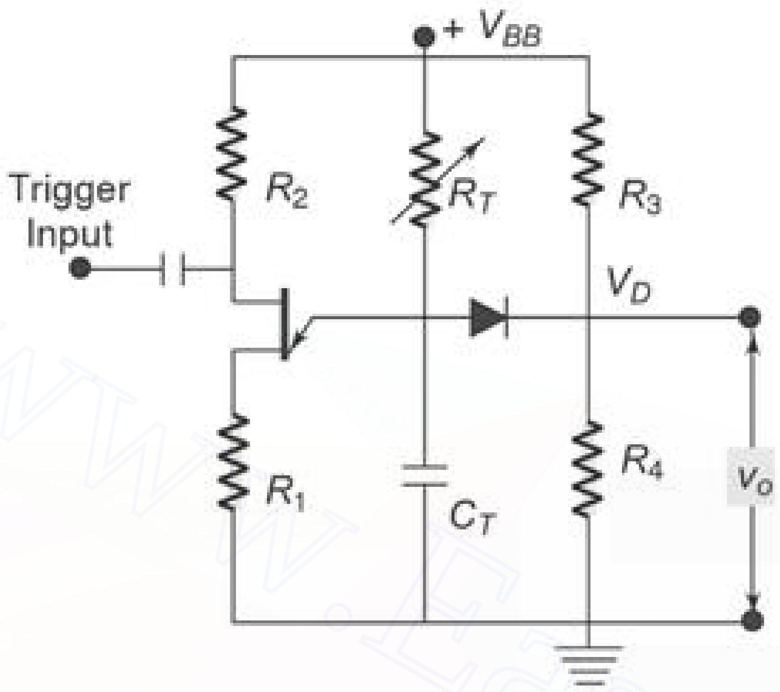


Fig. 7.10 Triggered sweep

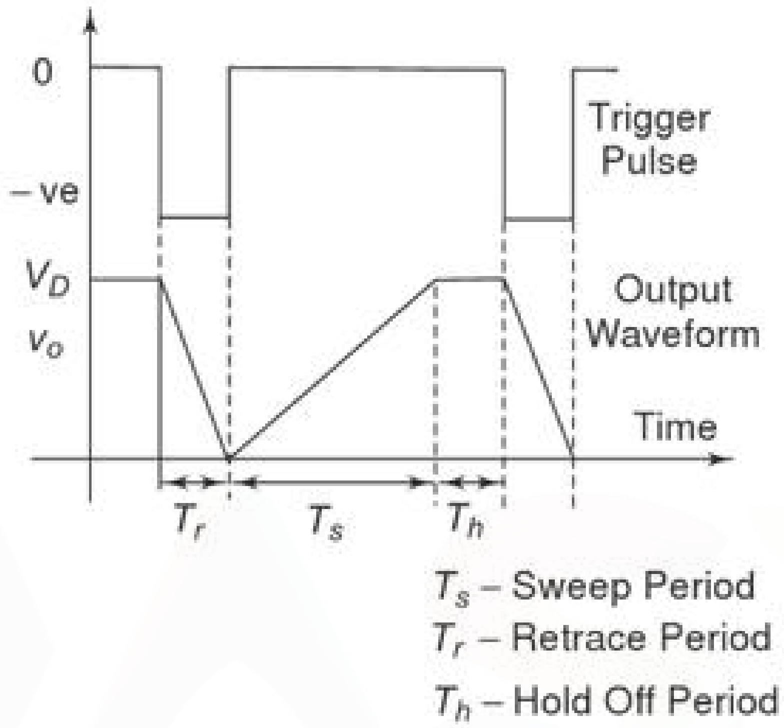


Fig. 7.11 Output waveform

TRIGGER PULSE CIRCUIT 7.9

The trigger circuit is activated by signals of a variety of shapes and amplitudes, which are converted to trigger pulses of uniform amplitude for the precision sweep operation. If the trigger level is set too low, the trigger generator will not operate. On the other hand, if the level is too high, the UJT may conduct for too long and part of the leading edge of the input signal may be lost.

The trigger selection is a 3-position switch, Internal-External-Line, as shown in Fig. 7.12. The trigger input signal is applied to a voltage comparator whose reference level is set by the Trigger Level control on the CRO front panel.

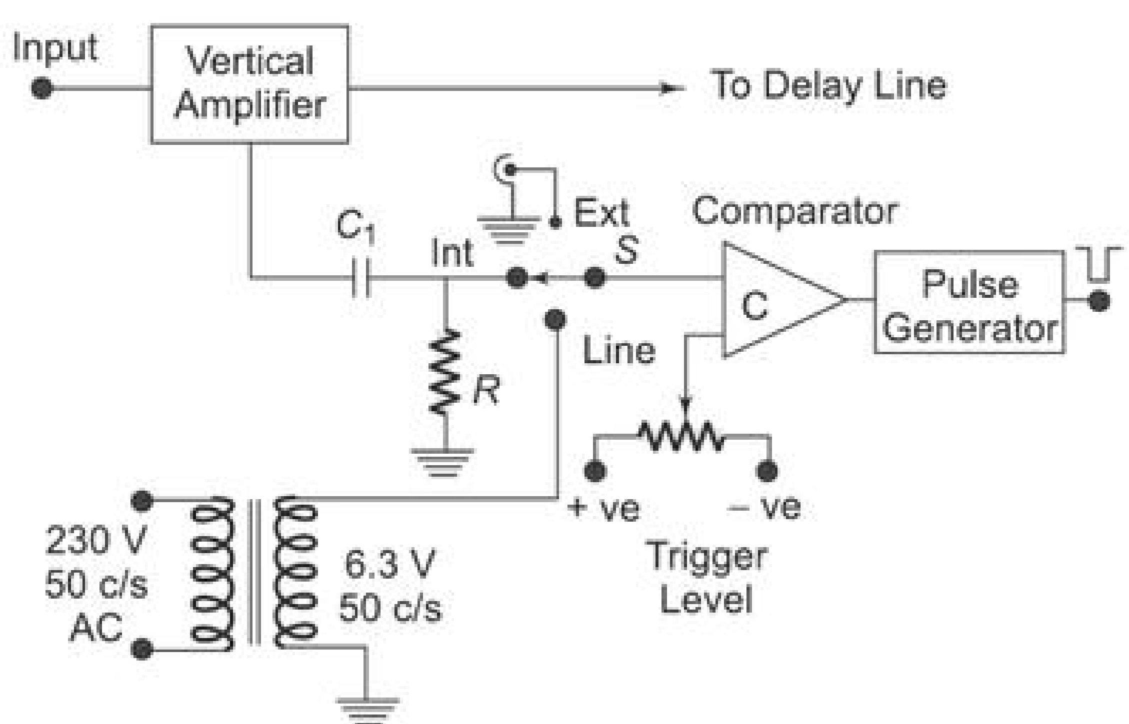


Fig. 7.12 Trigger pulse circuit

The comparator circuit C produces a change in the output whenever the trigger input exceeds the present trigger levels. The pulse generator that follows the comparator produces –ve trigger pulses each time the comparator output crosses its quiescent level, which in turn triggers the sweep generator to start the next sweep. The trigger sweep generator contains the stability or sync control, which prevents the display from jittering or running on the screen. Stability is secured by proper adjustments of the sweep speed. Sweep speed is adjustable by means of a sweep rate control and its multiplier, i.e. range control. The timing resistance R_T is used for sweep rate control and timing capacitor C_T is changed in steps for sweep rate control.

DELAY LINE IN TRIGGERED SWEEP 7.10

Figure 7.13 shows a delay line circuit.

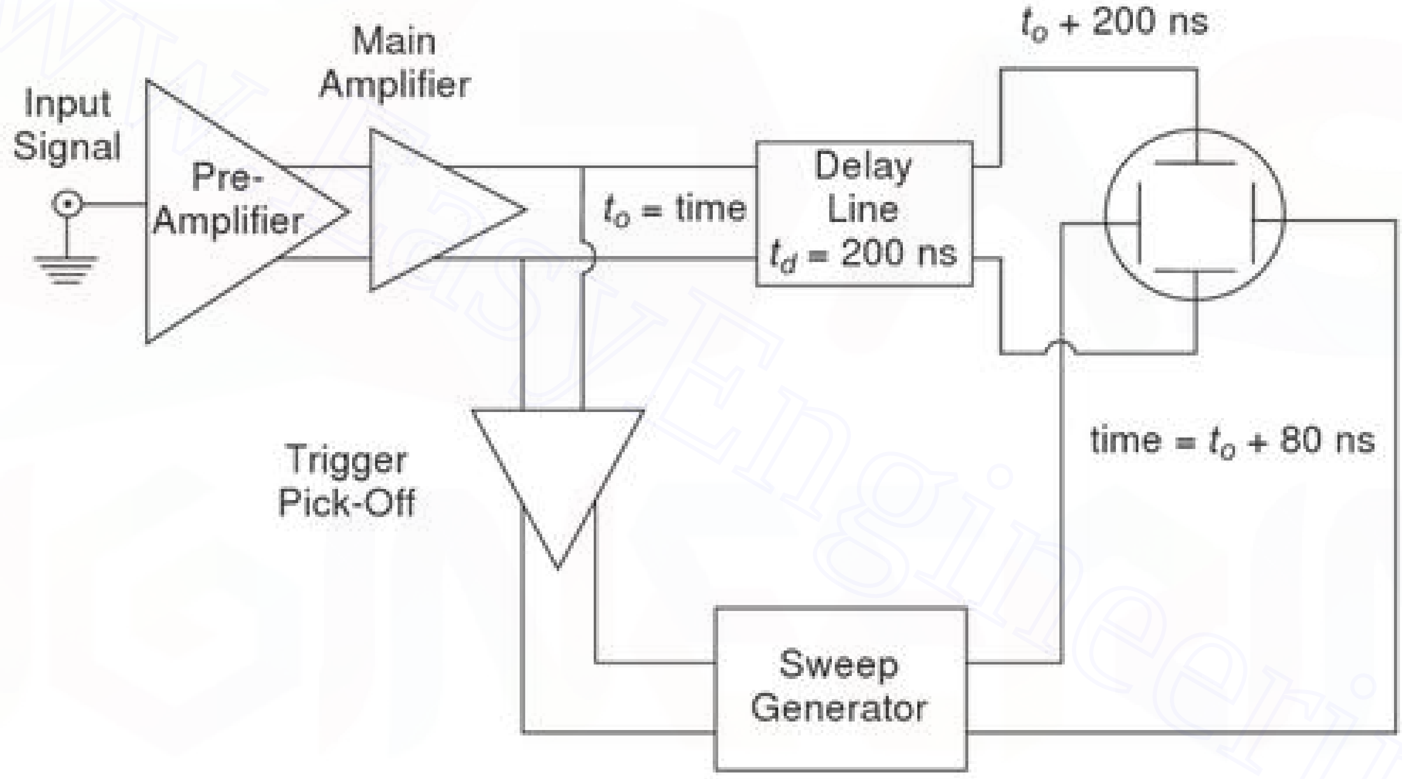


Fig. 7.13 Delay line circuit

Figure 7.14 indicates the amplitude of the signal wrt time and the relative position of the sweep generator output signal. The diagram shows that when the delay line is not used, the initial part of the signal is lost and only part of the signal is displayed. To counteract this disadvantage the signal is not applied directly to the vertical plates but is passed through a delay line circuit, as shown in Fig. 7.13. This gives time for the sweep to start at the horizontal plates before the signal has reached the vertical plates. The trigger pulse is picked off at a time t_o after the signal has passed through the main amplifier. The sweep generator delivers the sweep to the horizontal amplifier and the sweep starts at the HDP at time t_o + 80 ns. Hence the sweep starts well in time, since the signal arrives at the VDP at time t_o + 200 ns.

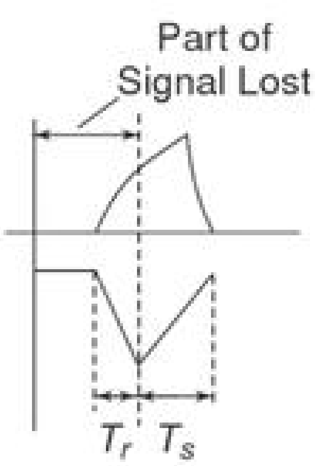


Fig. 7.14 Delay line waveform

SYNC SELECTOR FOR CONTINUOUS SWEEP CRO 7.11

The sync selector is a 3-position switch, Int-Ext-Line. Therefore horizontal sweep can be synchronised with the signals coming from any of the three sources, as shown in Fig. 7.15.

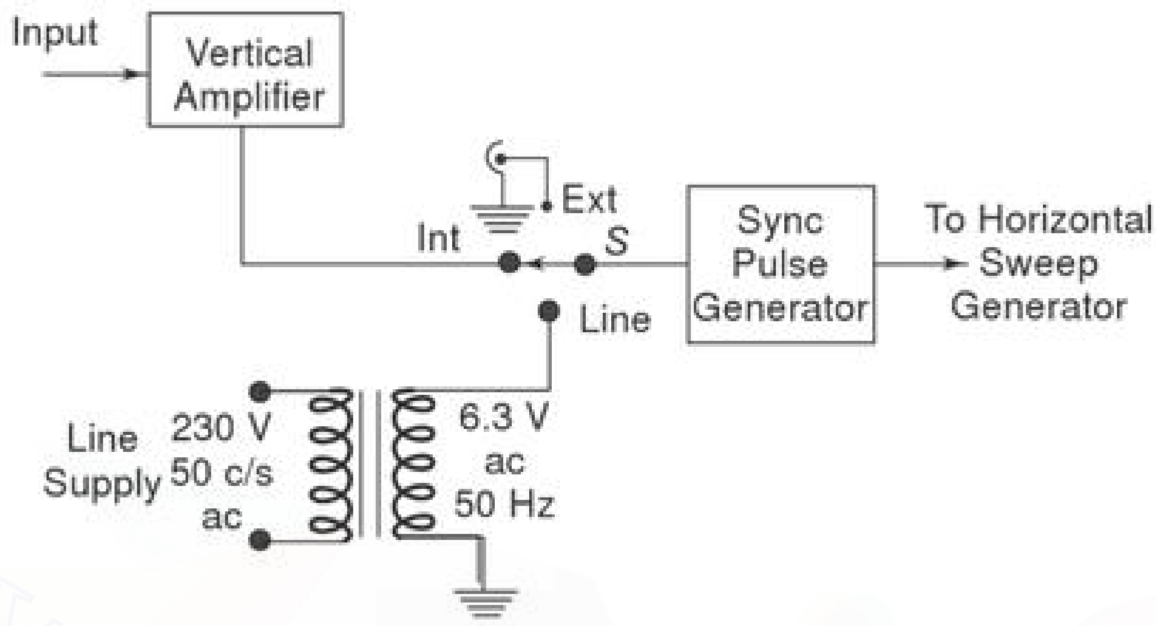


Fig. 7.15 Sync selector

TYPICAL CRT CONNECTIONS 7.12

Figure 7.16 shows various controls and CRT connections.

The following controls are available on CRO panel.

1. Intensity It controls the magnitude of emission of the electron beam, i.e. the electron beam is adjusted by varying the cathode-to-grid bias voltage. This adjustment is done by the 500 kΩ potentiometer.

2. Focus The focusing anode potential is adjusted with respect to the first and final accelerating anodes. This is done by the 2 MΩ potentiometer. It adjusts the negative voltage on the focus ring between –500 V and –900 V.

3. Astigmatism It adjusts the voltage on the acceleration anode with respect to the VDP of the CRT. This arrangement forms a cylindrical lens that corrects any defocusing that might be present. This adjustment is made to obtain the roundest spot on the screen.

4. X-shift or Horizontal Position Control The *X*-position of the spot is adjusted by varying the voltage between the horizontal plates. When the spot is in the center position, the two horizontal plates have the same potential.

5. Y-shift or Vertical Position Control The *Y*-position of the spot is adjusted by varying the voltage between the vertical plates. When the spot is in the center position, the two vertical plates have the same potential.

6. Time Base Control This is obtained by varying the C_T and R_T of the time base generator.

7. Sync Selector It can synchronise the sweep to signals coming internally from the vertical amplifier or an external signal or the line supply i.e. the Int-Ext-Line switch.

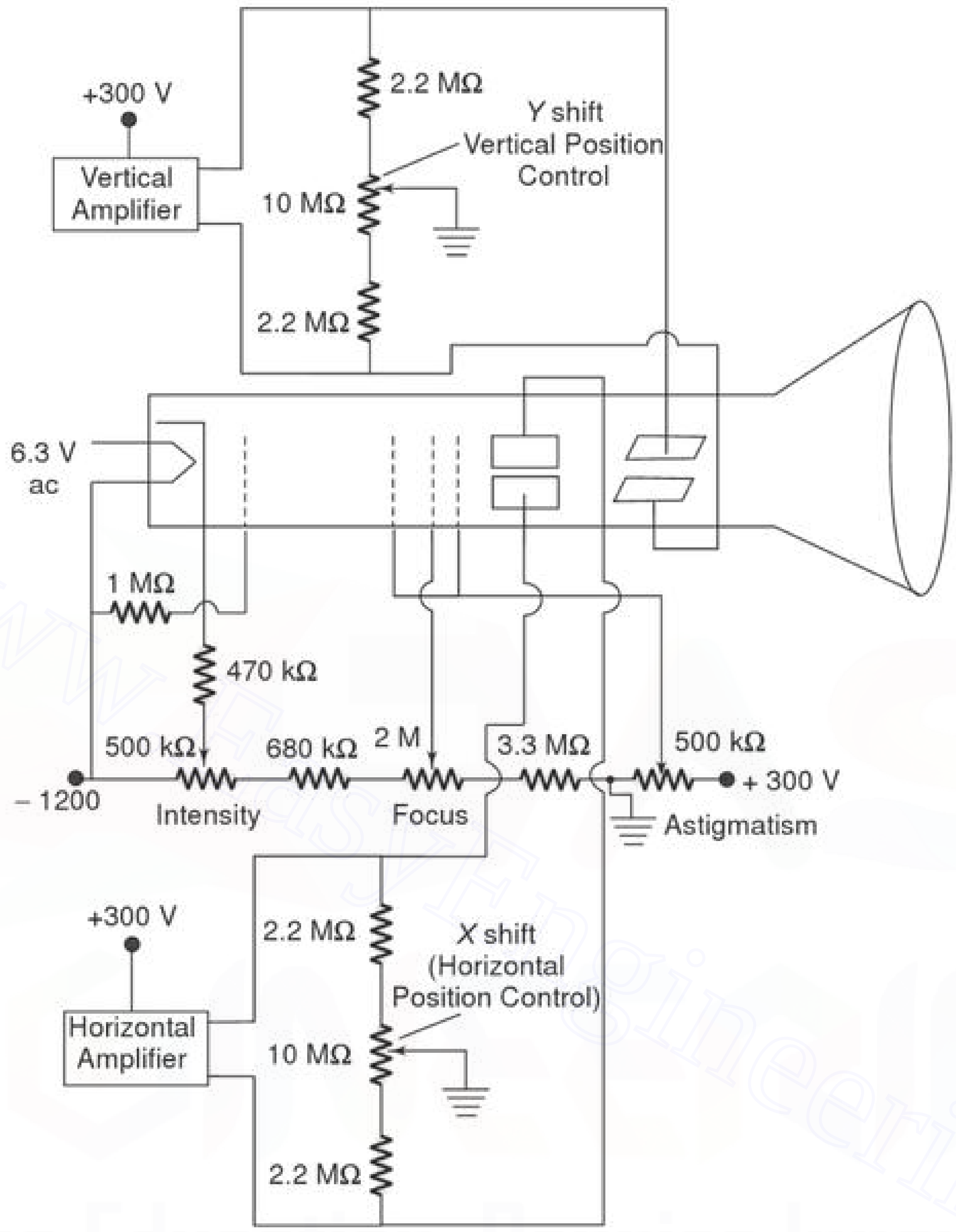


Fig. 7.16 Typical CRT connections

HIGH FREQUENCY CRT OR TRAVELLING WAVE TYPE CRT 7.13

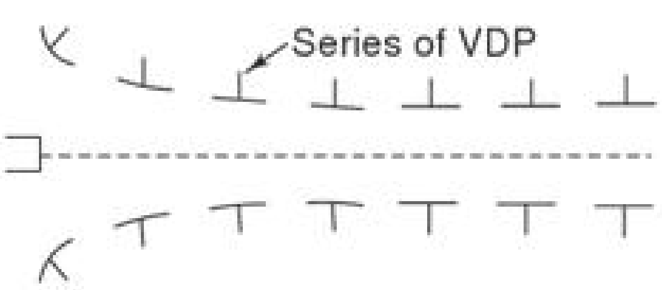


Fig. 7.17 Travelling wave CRO

Figure 7.17 illustrates a high frequency CRT.

In an ordinary CRO, there is only one pair of VDPs. When the signal to be displayed is of a very high frequency, the electron beam does not get sufficient time to pick up the instantaneous level of the signal. Also, at high frequencies the numbers of electrons striking the screen in a given time and the intensity of the beam is reduced. Hence, instead of one set of vertical deflection plates, a series of vertical deflection plates are used. The plates are so shaped and spaced that an electron travelling along the CRT receives from each set of plates an additional deflecting force in proper time sequence. This synchronisation is achieved by making the signal travel from one plate to the next at the same speed as the transit time of the electrons. The signal is applied to each pair of plates, and as the electron beam travels the signal also travels through the delay lines. The time delays are so arranged that the same electrons are deflected by the input signal. In this way the electron beam picks up the level of the input signal. The time delays between the plates correspond exactly to the transit times of the electrons. (In addition, new fluorescent materials have now been developed to increase the brightness at HF.)

7.13.1 Characteristics of a HF CRO or (HF Improvement in a CRO)

1. The vertical amplifier must be designed both for high B.W. and high sensitivity or gain. Making the vertical amplifier a fixed gain amplifier simplifies the design. The input to the amplifier is brought to the required level by means of an attenuator circuit. The final stages is the push-pull stage.
2. The LF CRT is replaced by an HF CRT.
3. A probe is used to connect the signals, e.g. a high *Z* passive probe acts like a compensated attenuator.
4. By using a triggered sweep, for fast rising signals, and by the use of delay lines between the vertical plates, for improvement of HF characteristics.
5. New fluorescent materials that increase the brightness of the display are used.

DUAL BEAM CRO 7.14

Figure 7.18 illustrates a block diagram of a Dual Beam CRO.

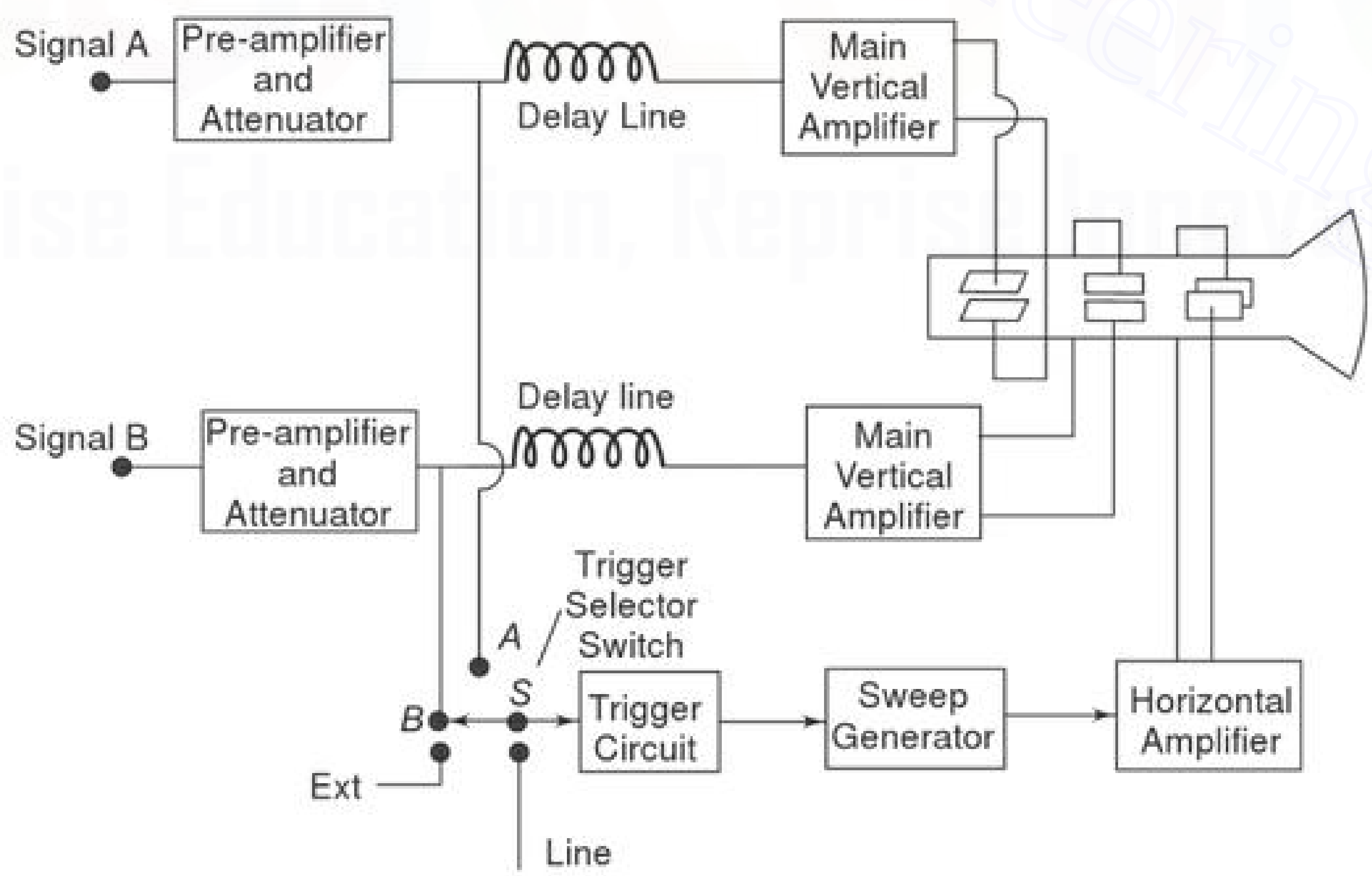


Fig. 7.18 Dual beam CRO

The dual trace oscilloscope has one cathode ray gun, and an electronic switch which switches two signals to a single vertical amplifier. The dual beam CRO uses two completely separate electron beams, two sets of VDPs and a single set of HDPs. Only one beam can be synchronised at one time, since the sweep is the same for both signals, i.e. a common time base is used for both beams. Therefore, the signals must have the same frequency or must be related harmonically, in order to obtain both beams locked on the CRT screen, e.g. the input signal of an amplifier can be used as signal A and its output signal as signal B.

DUAL TRACE OSCILLOSCOPE 7.15

Figure 7.19 (a) shows a block diagram of a dual trace oscilloscope.

This CRO has a single electron gun whose electron beam is split into two by an electronic switch. There is one control for focus and another for intensity. Two signals are displayed simultaneously. The signals pass through identical vertical channels or vertical amplifiers. Each channel has its own calibrated input attenuator and positioning control, so that the amplitude of each signal can be independently adjusted.

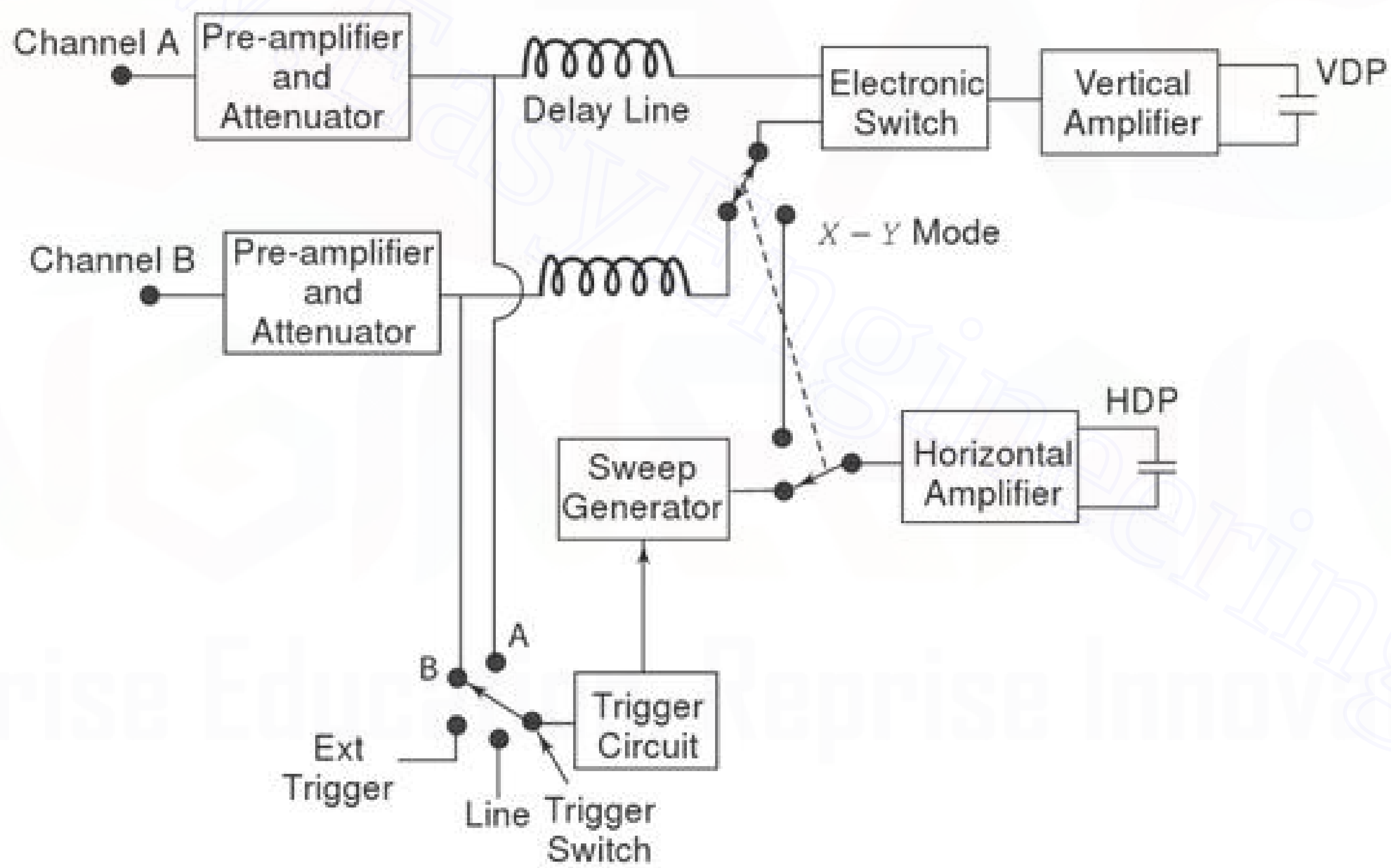


Fig. 7.19 (a) Dual trace oscilloscope

A mode control switch enables the electronic switch to operate in two modes i.e. Alternate and Chop mode. When the switch is in ALTERNATE position, the electronic switch feeds each signal alternately to the vertical amplifier. The electronic switch alternately connects the main vertical amplifier to channels *A* and *B* and adds a different dc component to each signal; this dc component directs the beam alternately to the upper or lower half of the screen. The switching takes place at the start of each new sweep of the sweep generator. The switching rate of the electronic switch is synchronised to the sweep rate, so that the CRT spot traces the channel *A* signal on one sweep and the channel *B* signal on the succeeding sweep [Fig. 7.19 (b)].

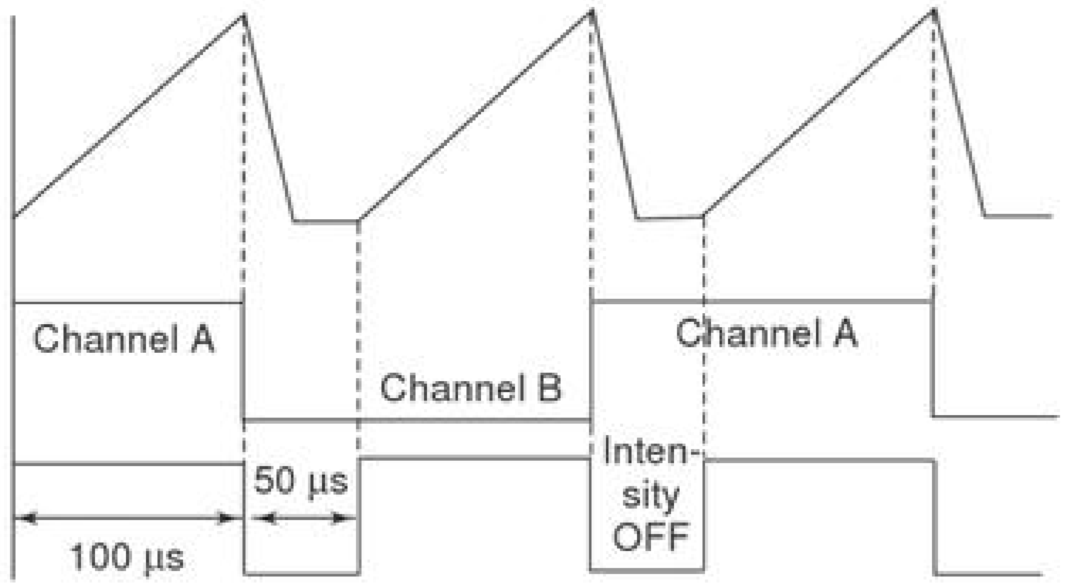


Fig. 7.19 (b) Time relation of a dual-channel vertical amplifier in alternate mode

The sweep trigger signal is available from channels *A* or *B* and the trigger pick-off takes place before the electronic switch. This arrangement maintains the correct phase relationship between signals *A* and *B*.

When the switch is in the CHOP mode position, the electronic switch is free running at the rate of 100–500 kHz, entirely independent of the frequency of the sweep generator. The switch successively connects small segments of *A* and *B* waveforms to the main vertical amplifier at a relatively fast chopping rate of 500 kHz e.g. 1 μs segments of each waveform are fed to the CRT display (Fig. 7.19 (c)).

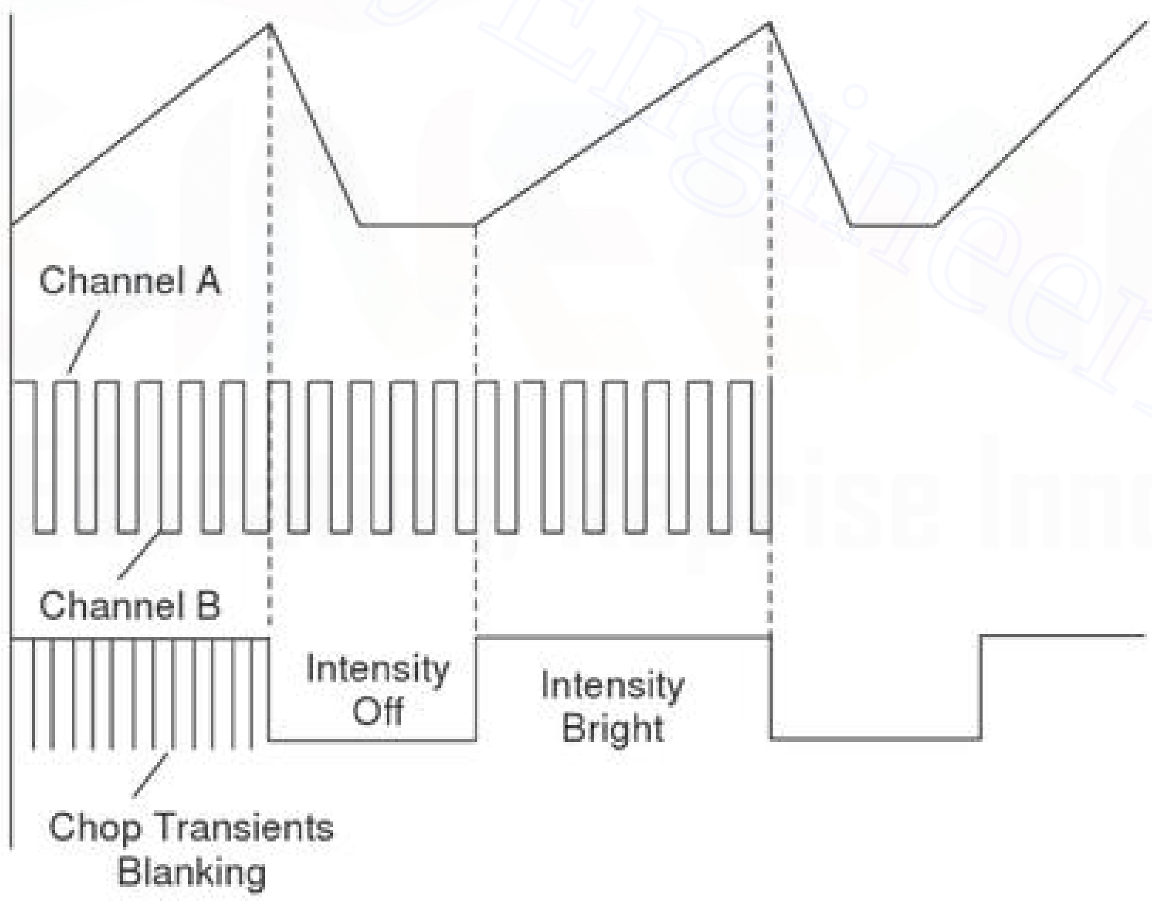


Fig. 7.19 (c) Time relation of a dual-channel vertical amplifier in chop mode

If the chopping rate is slow, the continuity of the display is lost and it is better to use the alternate mode of operation. In the added mode of operation a single image can be displayed by the addition of signal from channels *A* and *B*, i.e. $(A + B)$, etc. In the $X - Y$ mode of operation, the sweep generator is disconnected and channel B is connected to the horizontal amplifier. Since both pre-amplifiers are identical and have the same delay time, accurate $X - Y$ measurements can be made.

7.15.1 Dual Trace Oscilloscope (0–15 MHz) Block Description

Y-Channels *A* and *B* vertical channels are identical for producing the dual trace facility. Each comprises an input coupling switch, an input step attenuator, a source follower input stage with protection circuit, a pre-amplifier from which a trigger signal is derived and a combined final amplifier. The input stage protection circuit consists of a diode, which prevents damage to the FET transistors that could occur with excessive negative input potentials, and a resistor network which protects the input stage from large positive voltage swings.

As the transistors are the balanced pre-amplifier stage, they share the same IC block. The resulting stabilisation provides a measure of correction to reduce the drift inherent in high gain amplifiers. The trigger pick-off signal is taken from one side of the balanced pre-amplifier to the trigger mode switch, where either channel *A* or channel *B* triggering can be selected. The supply for the output of the pre-amplifier stage is derived from a constant current source controlled by the channel switching logic. Under the control of channel switching, signals from *A* and *B* channels are switched to the final amplifier. The combined balanced final amplifier is a direct coupled one to the *Y*-plates of the CRT (refer to Fig. 7.20).

Channel Switching The front panel *A* and *B* channel selection (push button or switch), controls an oscillator in the CHOP mode. For channel switching electronic switching logic and a F/F is used. When either *A* or *B* channels are selected, the F/F is switched to allow the appropriate channel.

In the ALTERNATE mode, a pulse from the sweep-gating multivibrator via the electronic switching logic, switches the F/F, thus allowing *A* and *B* channels for alternate sweeps.

In the CHOP mode, the oscillator is switched via the logic stage to provide rapid switching of the channels via the F/F.

Triggering A triggering signal can be obtained from the vertical amplifier of Channels *A* and *B* from an external source or internally from the mains supply (LINE triggering). The triggering signal is selected and normally fed via the amplifier stage to the pulse shaper, which supplies well defined trigger pulses to the sweep-gating multivibrator for starting the sawtooth generator.

Triggering from the TV line and frame signals can be obtained from the sync separator and peak detector stages. The latter stage is switched into circuit in the TOP position.

Time Base The time base generator circuit operates on the constant current integrator principle.

The sweep-gating multivibrator, triggered by pulses from the differentiator and auto circuits, starts the sawtooth generator. Sweep signals are fed to the final X-amplifier.

A gate pulse is supplied by the sweep-gating multivibrator for unblanking the CRT during the forward sweep. In addition this pulse is supplied to an external socket for probe adjustment via a diode network.

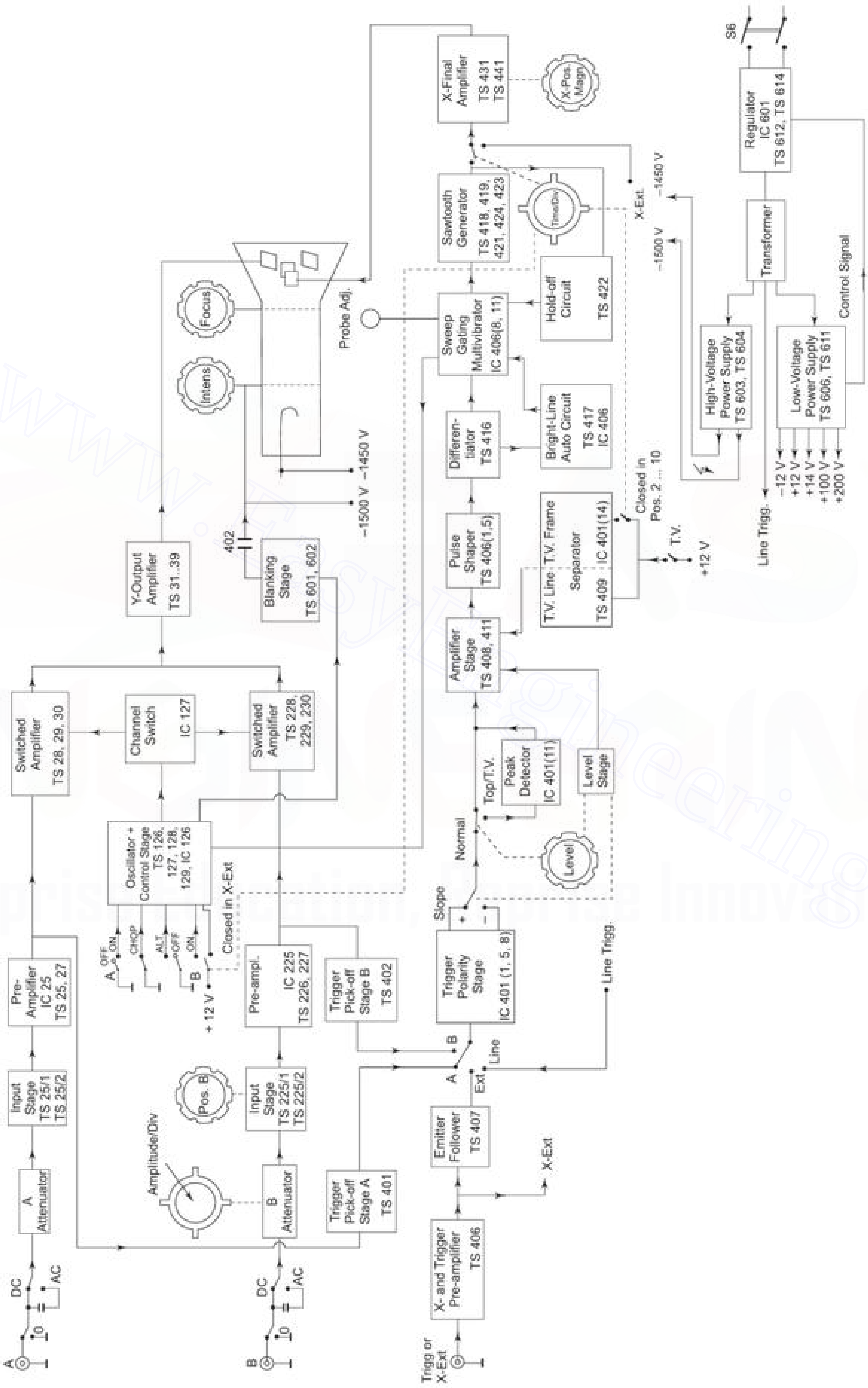


Fig. 7.20 Block diagram of dual trace CRO (Practical)

X-Channel Under the control of diode switching from the TIME/DIV switch, the X-amplifier receives its input signal from either the time base sawtooth generator or from an external source (X-EXT input socket via the *X* and trigger pre-amplifier). The X-MAGN (× 5) circuit is incorporated in the X-final amplifier. The output of this amplifier is direct coupled to the horizontal deflection plates of the CRT.

Cathode-Ray Tube Circuit and Power Supply The high voltages required for the CRT, which has an acceleration potential of 1.5 kV, are generated by a voltage multiplier circuit controlled by a stabilised power supply. The CRT beam current is controlled by:

The intensity potentials network across the Extra High Tension (EHT) supply. During flyback (movement of electron beam from right to left) by the blanking pulses coming from the sawtooth generator via the beam blanking stages to blank the trace during right to left movement of the electron.

Regulation of the mains input voltage is achieved by a diode clipper network controlled by a signal fed back from an LED in the + 14 V rectifier supply.

7.15.2 Dual Trace CRO Specifications

Maximum sensitivity	:	5 mV/div and B.W. 15 MHz
Operating temperature	:	+ 5° to 40°C
CRT	:	
Measuring area	:	8 × 10 Div (1 cm = 1 Div)
Screen type	:	B31 or 3B1
Total acceleration voltage	:	2kV
Vertical Amplifier	:	
Display modes	:	A, A and B, B (chopped in ms) (alternated in μs)
Input coupling	:	AC/DC Bandwidth DC – 0 – 15 MHz (– 3db) AC – 10 Hz – 15 MHz (– 3db)
Deflection accuracy	:	± 5%
Input impedance	:	1 MΩ/35 pF
Maximum rated input voltage	:	400 V (dc + ac peak) (no damage)
Chopper frequency	:	120 kHz approximately
Time Base		
Time coefficients	:	0.2 s/Div to 0.5 s/Div in 2 × 9
	:	calibrated steps (1-2-5 sequence) with
	:	5 × magnifier, max. 0.1 μs/Div
	:	Uncalibrated continuous control 1 : ≥ 2, 5
Coefficient error	:	± 5%
Additional error for × 5 magnifier	:	± 2%

Trigger		
Source		: CH A, B or Ext
Mode		: AC/TV
Sensitivity	Int	: 0.75 Div/0.75 V – Trigger freq. at 100 kHz.
	Ext	: 1 Div/1.0 V – Trigger freq. at 15 MHz.
Trigger frequency		: 10 Hz – 15 MHz
Input impedance		: 1 MΩ/35 pF
Z-Modulation input trace blanking		: TTL high blanks trace
Power Supply		
Voltage range		: 220 V ± 10%
Frequency		: 50 Hz
Power		: 30 VA
Size		: 378 (L) × 348 (W) × 142 (H)
Weight		: 5 kg Approx.
X-Deflection		
Phase shift		: 3 at 10 kHz
Accuracy		: ± 5%
μs/ms		: Slide switch in combination with time base
		: The display is chopped in ms and Alternated in μs

Figure 7.21 illustrates a 30 MHz Dual Trace Oscilloscope with Delayed Sweep and Frequency Counter (I.E. 234).

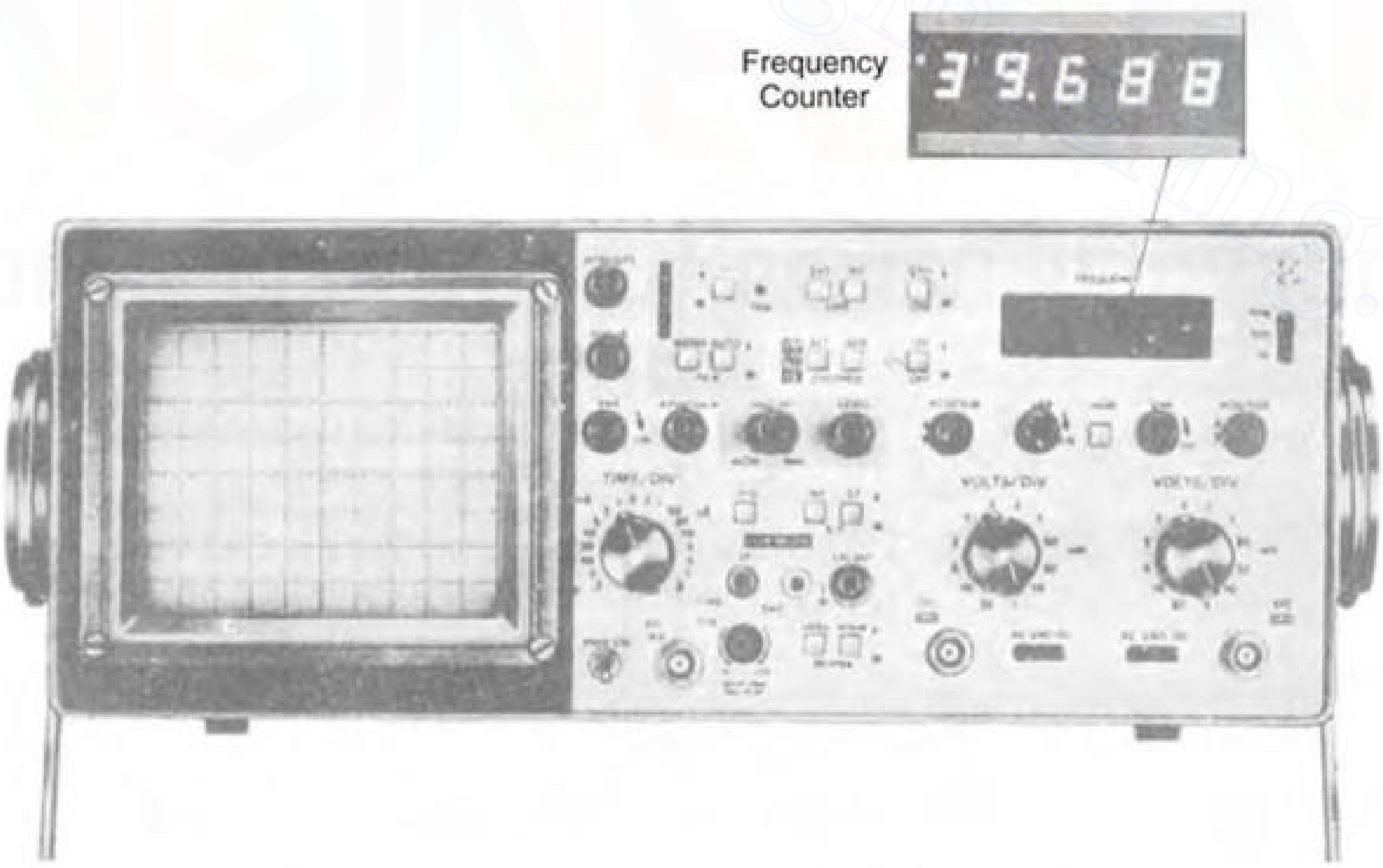


Fig. 7.21 30 MHz Dual trace oscilloscope with delayed sweep and frequency counter
(Courtesy: International Electronics Ltd., Bombay;
Marketed by: Signetics Electronics Ltd.)

ELECTRONIC SWITCH 7.16

The electronic switch is a device that enables two signals to be displayed simultaneously on the screen by a single gun CRT. The basic block diagram of an electronic switch is shown in Fig. 7.22.

Each signal is applied to a separate gain control and gate stage. The gates stage are alternately biased to cut off by square wave signals from the square wave generator. Therefore only one gate stage is in a condition to pass its signal at any given time.

The outputs of both stages are applied directly to the oscilloscope input.

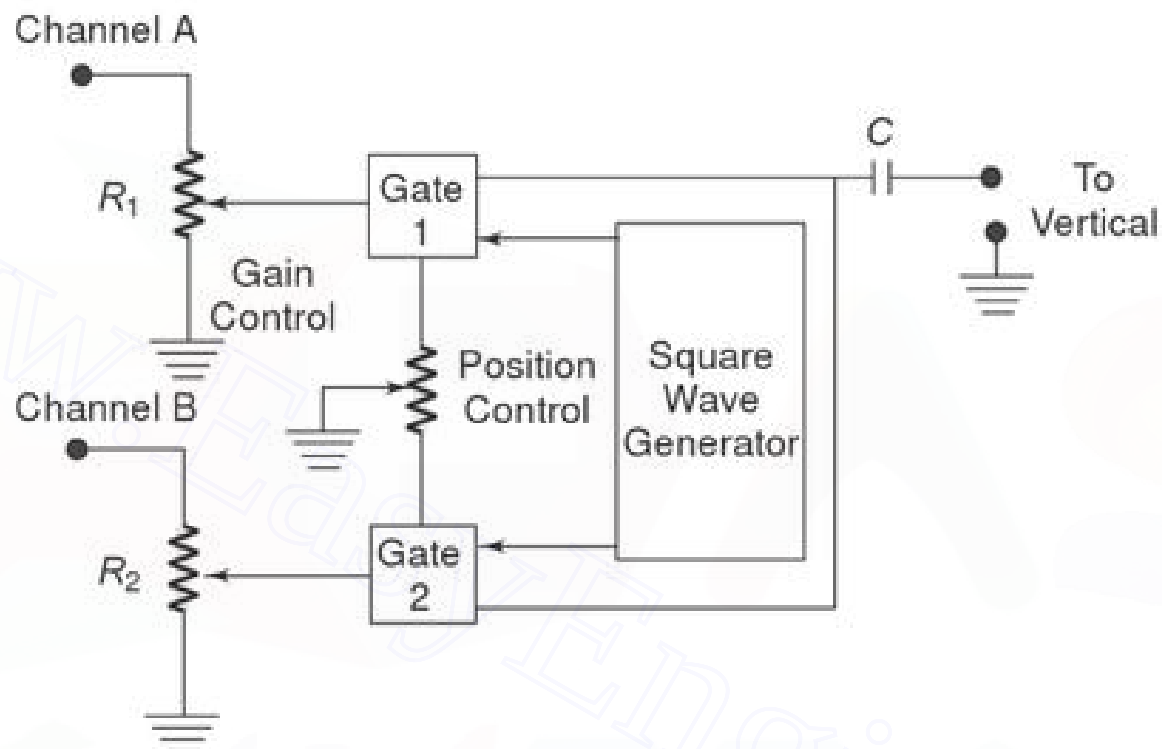


Fig. 7.22 Basic block diagram of an electronic switch

R_1 and R_2 are gain controls used to adjust the amplitudes of Channels A and B.

In the circuit diagram of Fig. 7.23, Q_1 and Q_2 are the amplifiers and Q_3 and Q_4 the switches. Input signal 1 is applied to Q_1 through gain control R_1, and input signal 2 is applied to Q_2 through gain control R_2. The square wave generator

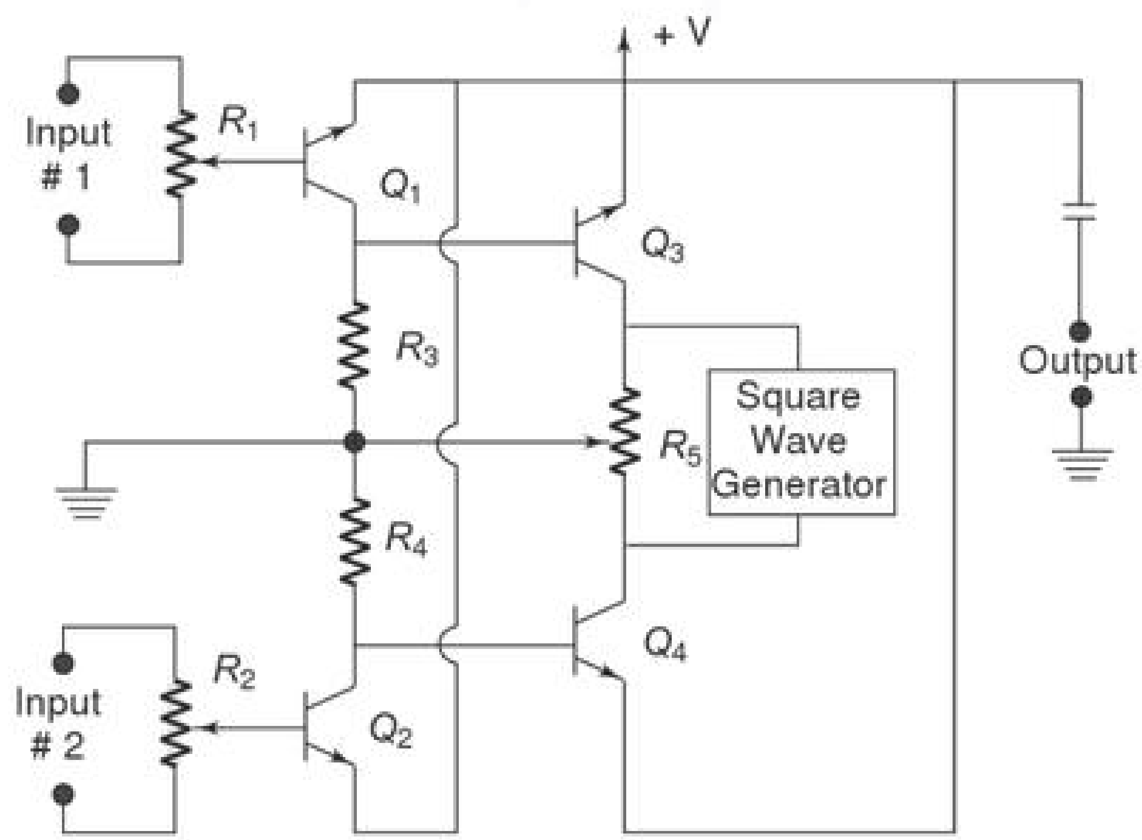


Fig. 7.23 Electronic switch

alternately biases first Q_3 and then Q_4 to cut off. When Q_3 is cut off, Q_4 conducts and transmits signal 2 to the output terminals. When Q_4 is cut off, Q_3 conducts and transmits signal 1 to the output terminals.

When the square wave generator switching frequency is much higher than either signal frequency, bits of each signal are alternately presented to the oscilloscopes vertical input to reproduce the two signals on the screen.

The traces can be moved up or down by the position control R_5. The traces can be overlapped for easy comparison. The heights of the individual signals can be adjusted by means of gain controls R_1 and R_2. The sweep signal produced by this design is very linear and can be calibrated in time per cm or inch, so that accurate time and frequency can be measured.

(VHF) SAMPLING OSCILLOSCOPE 7.17

An ordinary oscilloscope has a B.W. of 10 MHz. The HF performance can be improved by means of sampling the input waveform and reconstructing its shape from the sample, i.e. the signal to be observed is sampled and after a few cycles the sampling point is advanced and another sample is taken. The shape of the waveform is reconstructed by joining the sample levels together. The sampling frequency may be as low as 1/10th of the input signal frequency (if the input signal frequency is 100 MHz, the bandwidth of the CRO vertical amplifier can be as low as 10 MHz). As many as 1000 samples are used to reconstruct the original waveform.

Figure 7.24 shows a block diagram of a sampling oscilloscope. The input waveform is applied to the sampling gate. The input waveform is sampled whenever a sampling pulse opens the sampling gate. The sampling must be synchronised with the input signal frequency. The signal is delayed in the vertical amplifier, allowing the horizontal sweep to be initiated by the input signal. The waveforms are shown in Fig. 7.25.

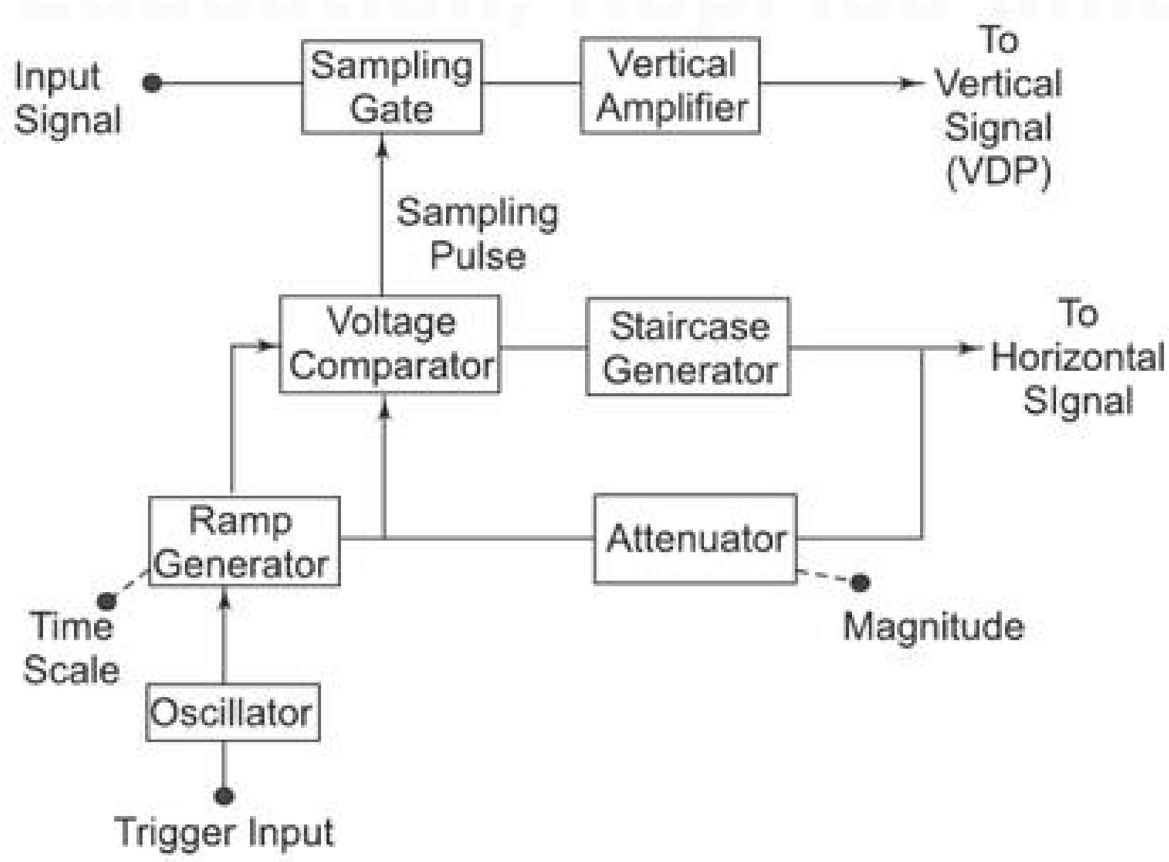


Fig. 7.24 Sampling oscilloscope

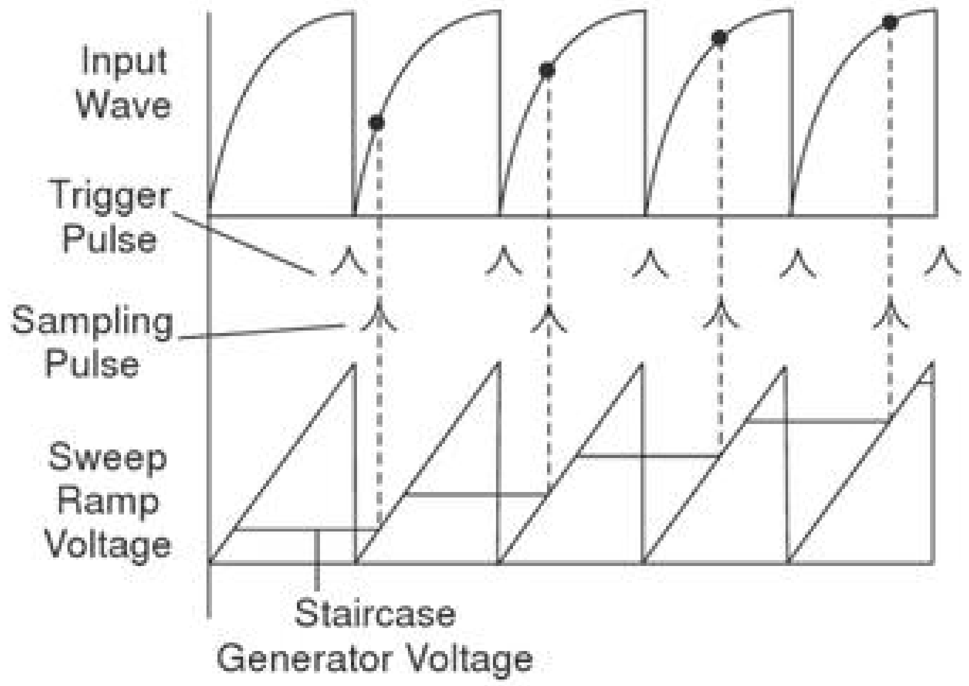


Fig. 7.25 Various waveforms at each block of a sampling oscilloscope

At the beginning of each sampling cycle, the trigger pulse activates an oscillator and a linear ramp voltage is generated. This ramp voltage is applied to a voltage comparator which compares the ramp voltage to a staircase generator. When the two voltages are equal in amplitude, the staircase advances one step and a sampling pulse is generated, which opens the sampling gate for a sample of input voltage.

The resolution of the final image depends upon the size of the steps of the staircase generator. The smaller the size of the steps the larger the number of samples and higher the resolution of the image.

STORAGE OSCILLOSCOPE (FOR VLF SIGNAL) 7.18

Storage targets can be distinguished from standard phosphor targets by their ability to retain a waveform pattern for a long time, independent of phosphor peristence. Two storage techniques are used in oscilloscope CRTs, mesh storage and phosphor storage.

A mesh-storage CRT uses a dielectric material deposited on a storage mesh as the storage target. This mesh is placed between the deflection plates and the standard phosphor target in the CRT. The writing beam, which is the focussed electron beam of the standard CRT, charges the dieletric material positively where hit. The storage target is then bombarded with low velocity electrons from a flood gun and the positively charged areas of the storage target allow these electrons to pass through to the standard phosphor target and thereby reproduce the stored image on the screen. Thus the mesh storage has both a storage target and a phosphor display target. The phosphor storage CRT uses a thin layer of phosphor to serve both as the storage and the display element.

Mesh Storage It is used to display Very Low Frequencies (VLF) signals and finds many applications in mechanical and biomedical fields. The conventional scope has a display with a phosphor peristence ranging from a few micro seconds to a few seconds. The persistence can be increased to a few hours from a few seconds.

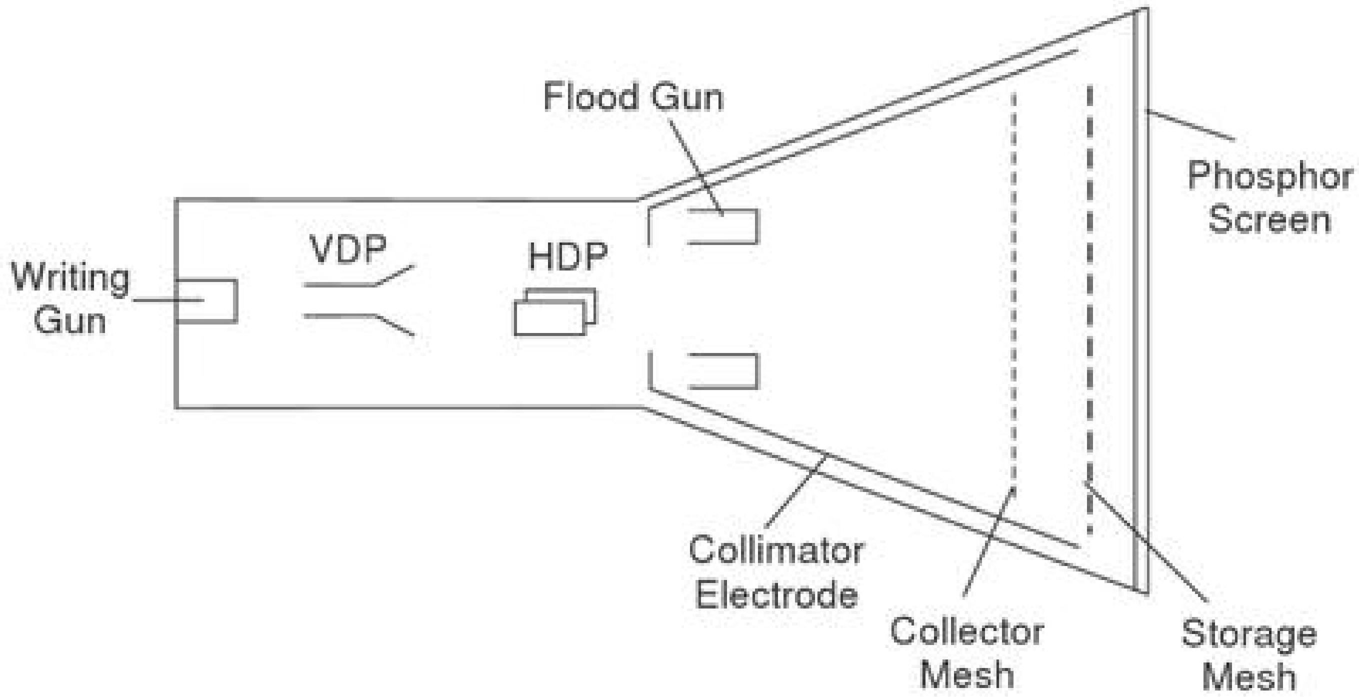


Fig. 7.26 Basic elements of storage mesh CRT

A mesh storage CRT, shown in Fig. 7.26, contains a dielectric material deposited on a storage mesh, a collector mesh, flood guns and a collimator, in addition to all the elements of a standard CRT. The storage target, a thin deposition of a dielectric material such as Magnesium Fluoride on the storage mesh, makes use of a property known as secondary emission. The writing gun etches a positively charged pattern on the storage mesh or target by knocking off secondary emission electrons. Because of the excellent insulating property of the Magnesium Fluoride coating, this positively charged pattern remains exactly in the position where it is deposited. In order to make a pattern visible, a special electron gun, called the flood gun, is switched on (even after many hours). The electron paths are adjusted by the collimator electrode, which constitutes a low voltage electrostatic lens system (to focus the electron beam), as shown in Fig. 7.27. Most of the electrons are stopped and collected by the collector mesh. Only electrons near the stored positive charge are pulled to the storage target with sufficient force to hit the phosphor screen. The CRT will now display the signal and it will remain visible as long as the flood guns operate. To erase the pattern on the storage mesh, a negative voltage is applied to neutralise the stored positive charge.

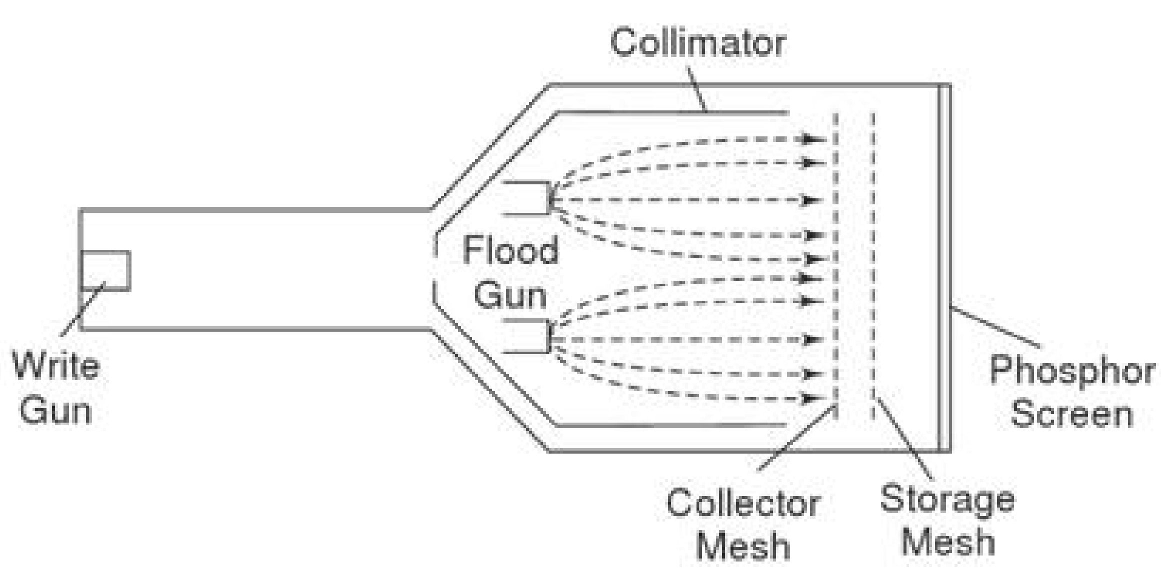


Fig. 7.27 Storage mesh CRT

Since the storage mesh makes use of secondary emission, between the first and second crossover more electrons are emitted than are absorbed by the material, and hence a net positive charge results.

Below the first crossover a net negative charge results, since the impinging electrons do not have sufficient energy to force an equal number to be emitted. In order to store a trace, assume that the storage surface is uniformly charged and write gun (beam emission gun) will hit the storage target. Those areas of the storage surface hit by the deflecting beam lose electrons, which are collected by the collector mesh. Hence, the write beam deflection pattern is traced on the storage surface as a positive charge pattern. Since the insulation of the dielectric material is high enough to prevent any loss of charge for a considerable length of time, the pattern is stored. To view, the stored trace, a flood gun is used when the write gun is turned off. The flood gun, biased very near the storage mesh potential, emits a flood of electrons which move towards the collector mesh, since it is biased slightly more positive than the deflection region. The collimator, a conductive coating on the CRT envelope with an applied potential, helps to align the flood electrons so that they approach the storage target perpendicularly. When the electrons penetrate beyond the collector mesh, they encounter either a positively charged region on the storage surface or a negatively charged region where no trace has been stored. The positively charged areas allow the electrons to pass through to the post accelerator region and the display target phosphor. The negatively charged region repels the flood electrons back to the collector mesh. Thus the charge pattern on the storage surface appears reproduced on the CRT display phosphor just as though it were being traced with a deflected beam.

Figure 7.28 shows a display of the stored charge pattern on a mesh storage.

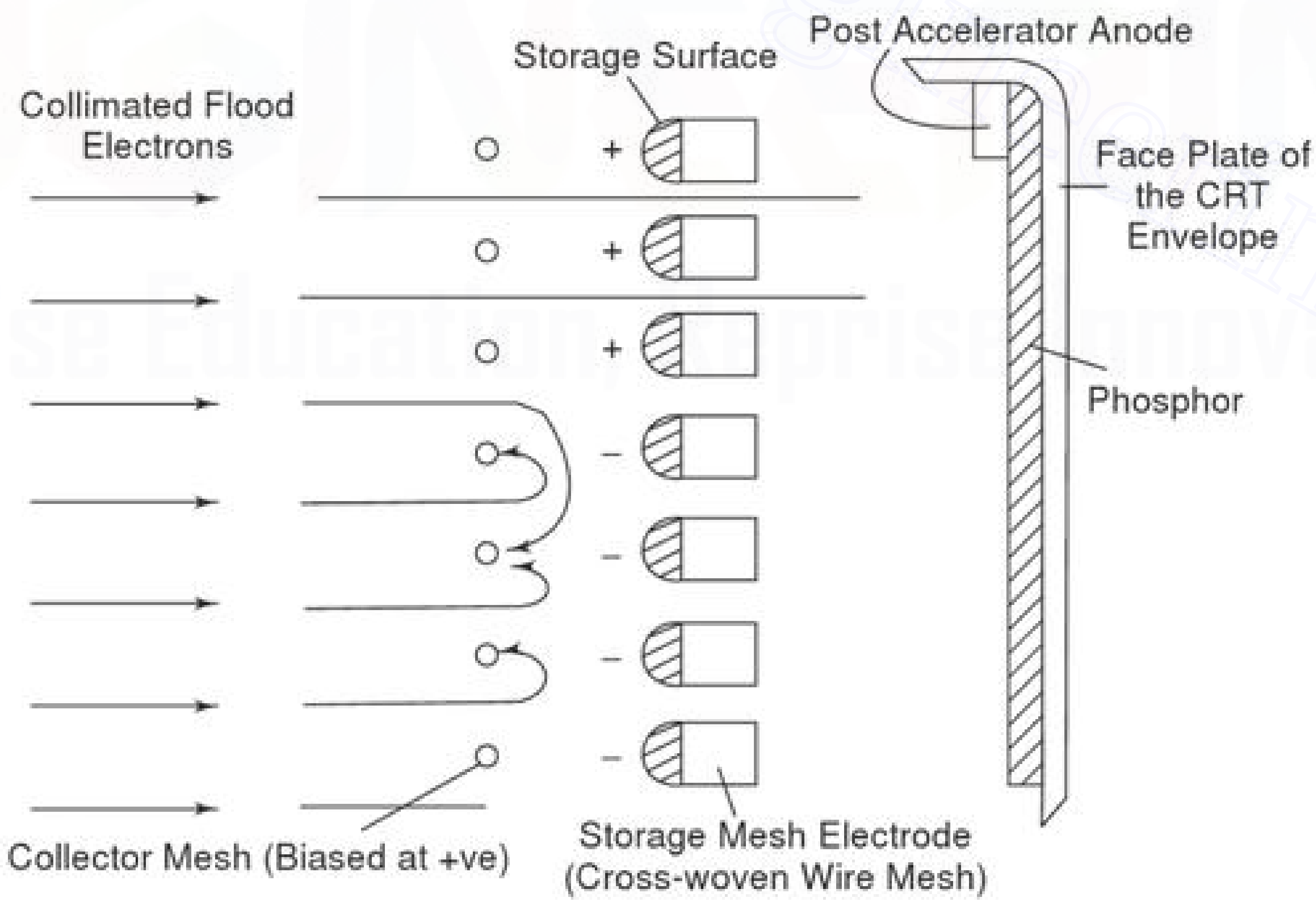


Fig. 7.28 Display of stored charged pattern on a mesh-storage

DIGITAL READOUT OSCILLOSCOPE 7.19

The digital read out oscilloscope instrument has a CRT display and a counter display. The diagram shown is of an instrument where the counter measures the time (Fig. 7.29).

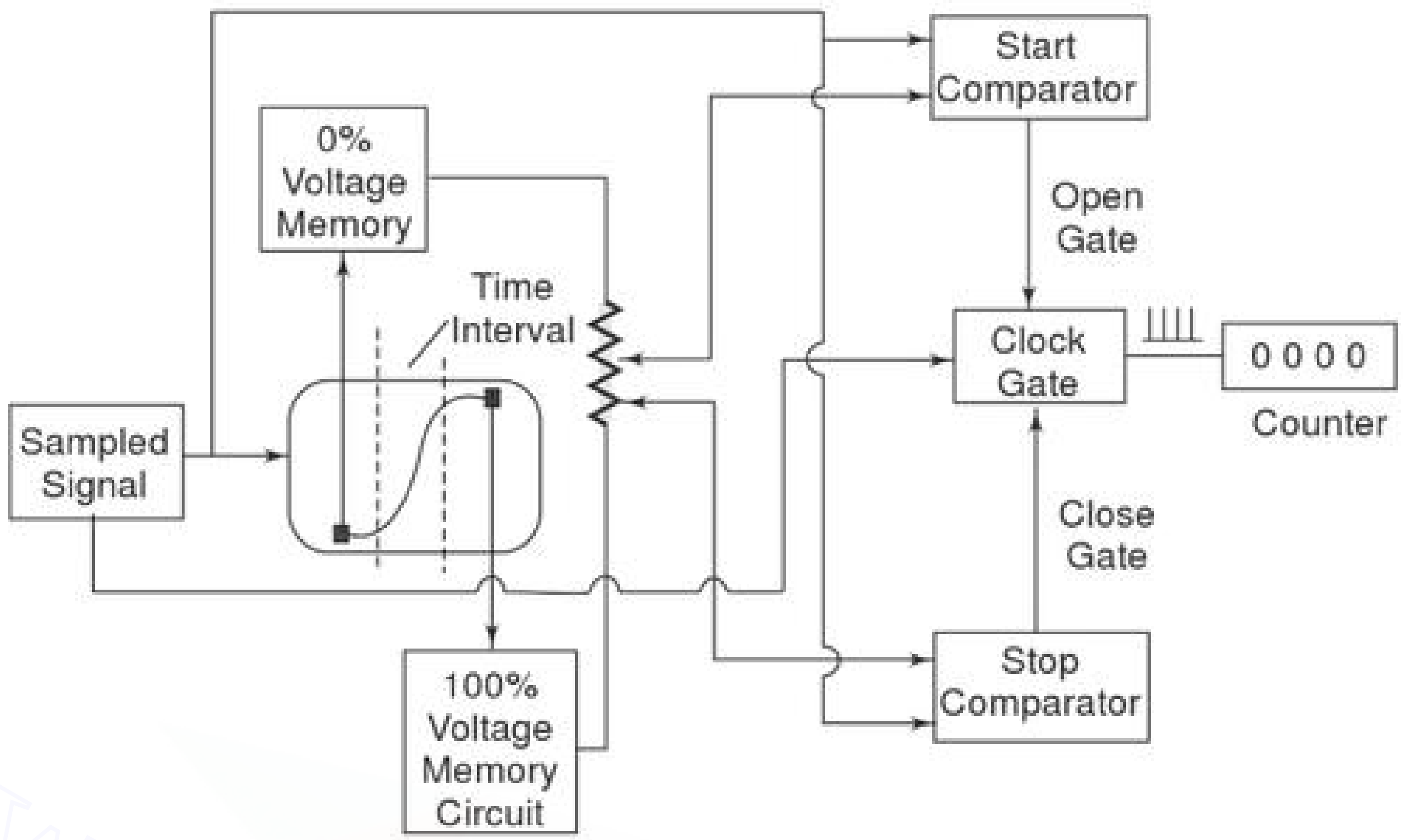


Fig. 7.29 Block diagram of a digital readout oscilloscope when measuring voltage

The input waveform is sampled and the sampling circuit advances the sampling position in fixed increments, a process called strobing. The equivalent time between each sample depends on the numbers of sample taken per cm and on the sweep time/cm, e.g. a sweep rate of 1 nano-sec/cm and a sampling rate of 100 samples/cm gives a time of 10 pico-sec/sample.

Figure 7.29 shows a block diagram of a digital read out oscilloscope when measuring voltage.

Two intensified portions of the CRT trace identify 0% and 100% zones position. Each zone can be shifted to any part of the display. The voltage divider taps between the 0% and 100% memory voltage are set for start and stop timing. The coincidence of any of the input waveforms with the selected percentage point is sensed by this voltage comparator. The numbers of the clock pulse which correspond to the actual sample taken are read out digitally in a Nixie display tube in ns, μs, ms or seconds.

Figure 7.30 shows a block diagram of a digital readout CRO when used for voltage to time conversion.

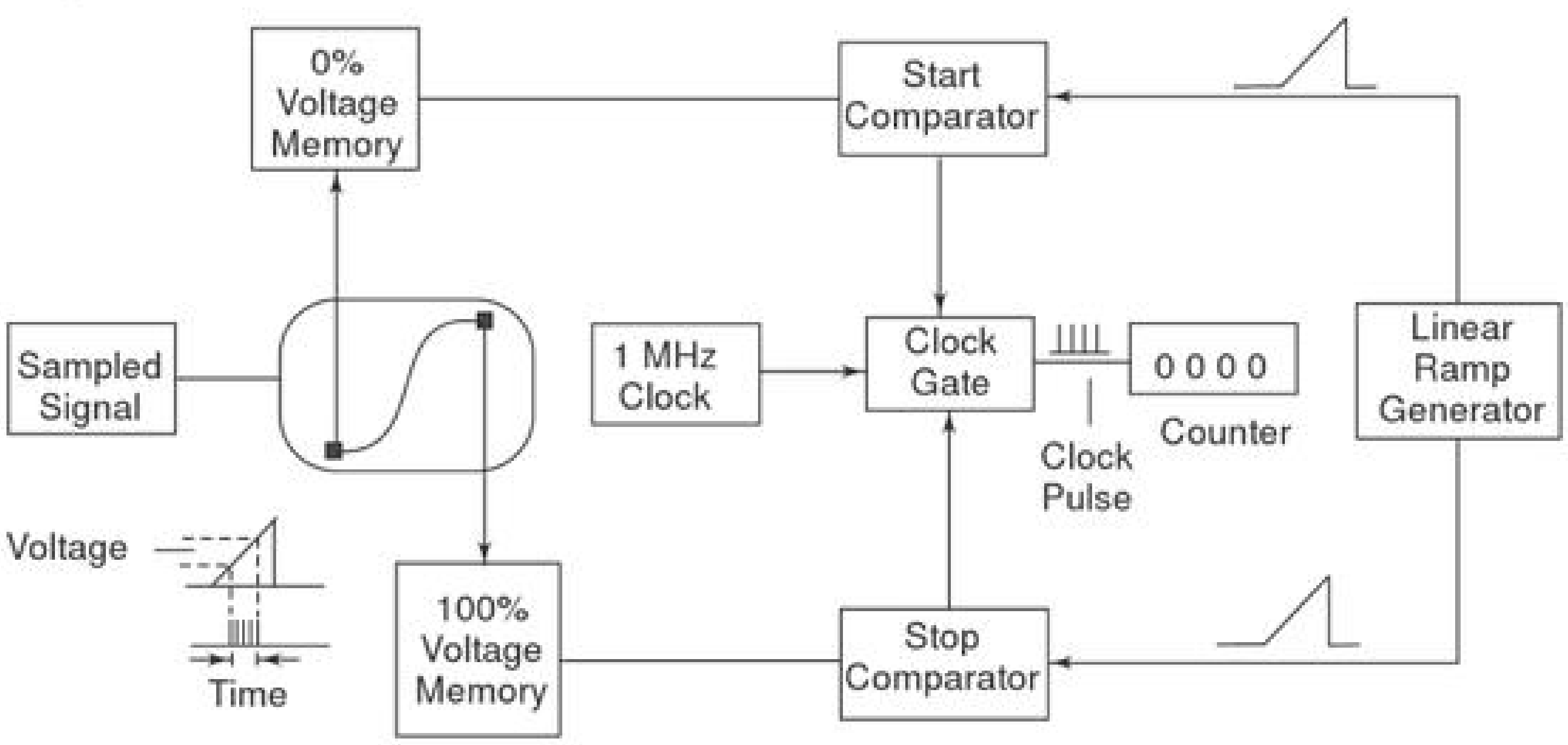


Fig. 7.30 Voltage to time conversion

The CRT display is obtained by sampling the 0% reference voltage as chosen by the memory circuit. A linear ramp generator produces a voltage; when the ramp voltage equals the 0% reference the gate opens. When the ramp equals 100% reference the gate closes. The number of clock pulses that activate the counter is directly proportional to the voltage between the selected reference and is read out in mV or volts by the Nixie tube display.

MEASUREMENT OF FREQUENCY BY LISSAJOUS METHOD 7.20

The oscilloscope is a sensitive indicator for frequency and phase measurements. The techniques used are simple and dependable, and measurement may be made at any frequency in the response range of the oscilloscope.

One of the quickest methods of determining frequency is by using Lissajous patterns produced on a screen. This particular pattern results when sine waves are applied simultaneously to both pairs of the deflection plates. If one frequency is an integral multiple (harmonic) of the other, the pattern will be stationary, and is called a Lissajous figure.

In this method of measurement a standard frequency is applied to one set of deflection plates of the CRT tube while the unknown frequency (of approximately the same amplitude) is simultaneously applied to the other set of plates. However, the unknown frequency is presented to the vertical plates and the known frequency (standard) to the horizontal plates. The resulting patterns depend on the integral and phase relationship between the two frequencies. (The horizontal signal is designated as f_h and the vertical signal as f_v.)

Typical Lissajous figures are shown in Figs 7.31 and 7.32 for sinusoidal frequencies which are equal, integral and in ratio.

7.20.1 Measurement Procedure

Set up the oscilloscope and switch off the internal sweep (change to Ext). Switch off sync control. Connect the signal source as given in Fig. 7.33. Set the horizontal and vertical gain control for the desired width and height of the pattern. Keep frequency f_v constant and vary frequency f_h, noting that the pattern spins in alternate directions and changes shape. The pattern stands still whenever f_v and f_h are in an integral ratio (either even or odd). The $f_v = f_h$ pattern stands still and is a single circle or ellipse. When $f_v = 2f_h$, a two loop horizontal pattern is obtained as shown in Fig. 7.31.

To determine the frequency from any Lissajous figure, count the number of horizontal loops in the pattern, divide it by the number of vertical loops and multiply this quantity by f_h (known or standard frequency).

In Fig. 7.31 (g), there is one horizontal loop and 3 vertical loops, giving a fraction of 1/3. The unknown frequency f_v is therefore 1/3 f_h. An accurately calibrated, variable frequency oscillator will supply the horizontal search frequency for frequency measurement. For the case where the two frequencies are equal and in phase, the pattern appears as a straight line at an angle of 45° with the horizontal. As the phase between the two alternating signals changes, the pattern changes

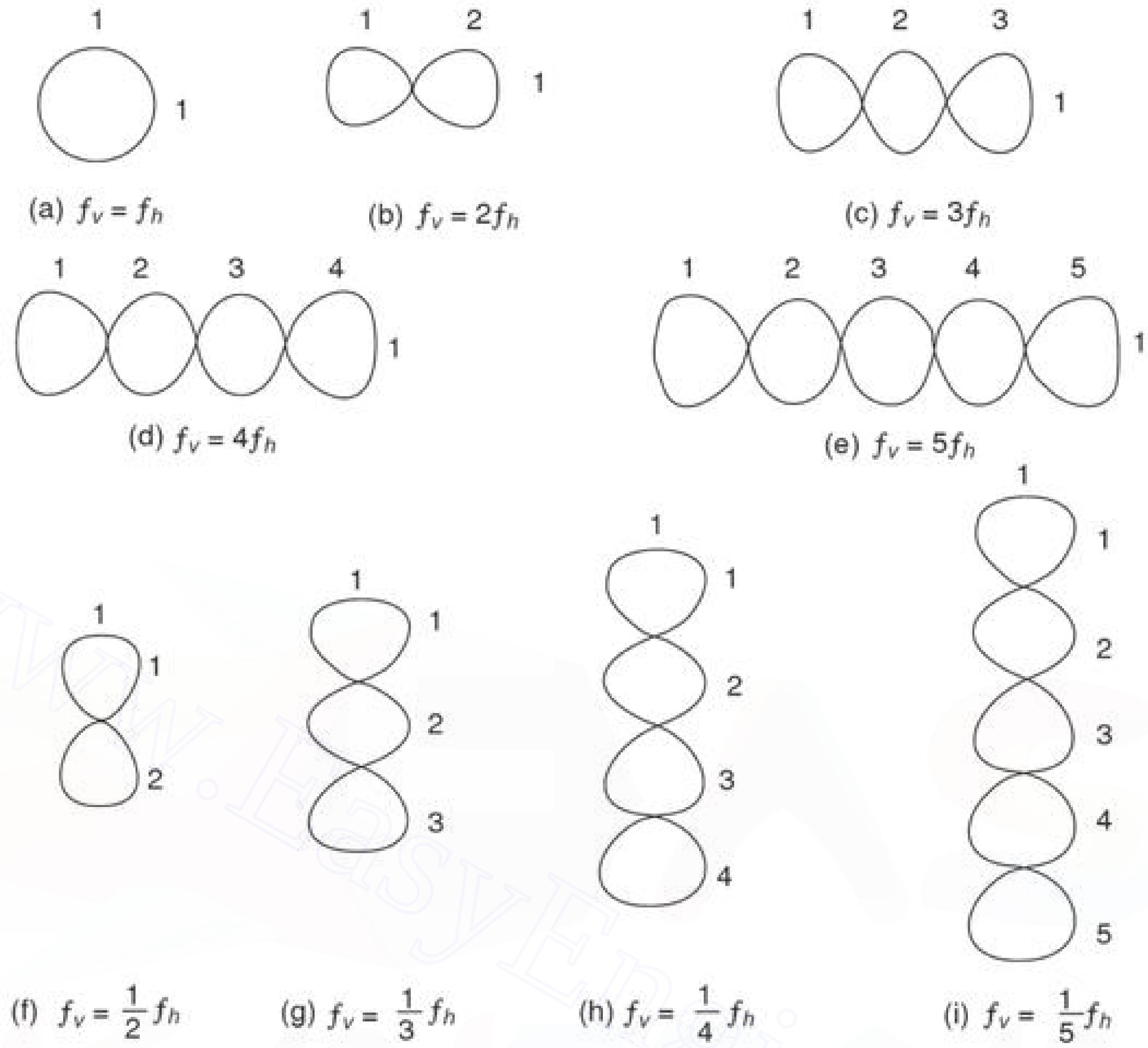


Fig. 7.31 Lissajous patterns for integral frequencies

cyclically, i.e. an ellipse (at 45° with the horizontal) when the phase difference is $\pi/4$, a circle when the phase difference is $\pi/2$ and an ellipse (at 135° with horizontal) when the phase difference is $3\pi/4$, and a straight line pattern (at 135° with the horizontal) when the phase difference is π radians.

As the phase angle between the two signals changes from π to 2π radians, the pattern changes correspondingly through the ellipse-circle-ellipse cycle to a straight line. Hence the two frequencies, as well as the phase displacement can be compared using Lissajous figures techniques.

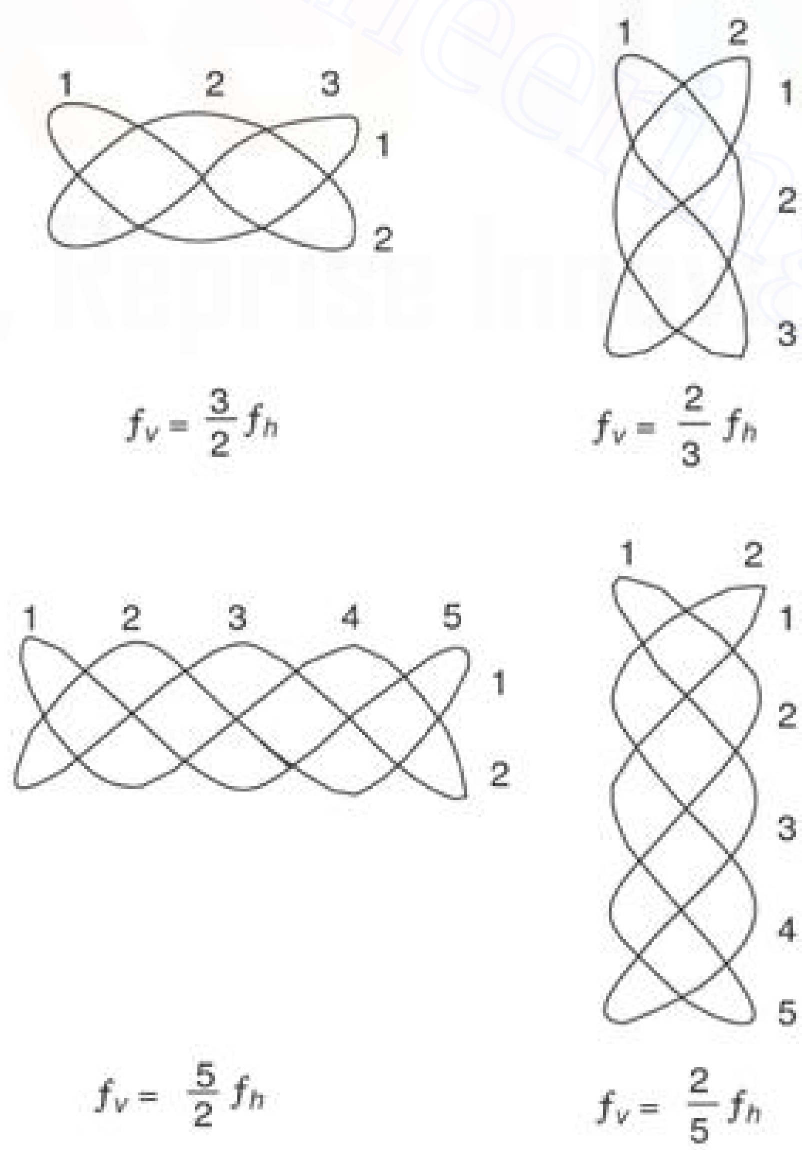


Fig. 7.32 Lissajous patterns for non-integral frequencies

When the two frequencies being compared are not equal, but are fractionally related, a more complex stationary pattern results, whose form is dependent on the frequency ratio and the relative phase between the two signals, as in Fig. 7.32.

The fractional relationship between the two frequencies is determined by counting the number of cycles in the vertical and horizontal.

$$f_v = (\text{fraction}) \times f_h$$

or

$$\frac{f_v}{f_h} = \frac{\text{number of horizontal tangencies}}{\text{number of vertical tangencies}}$$

Figure 7.33 illustrates the basic circuit for comparing two frequencies by the Lissajous method.

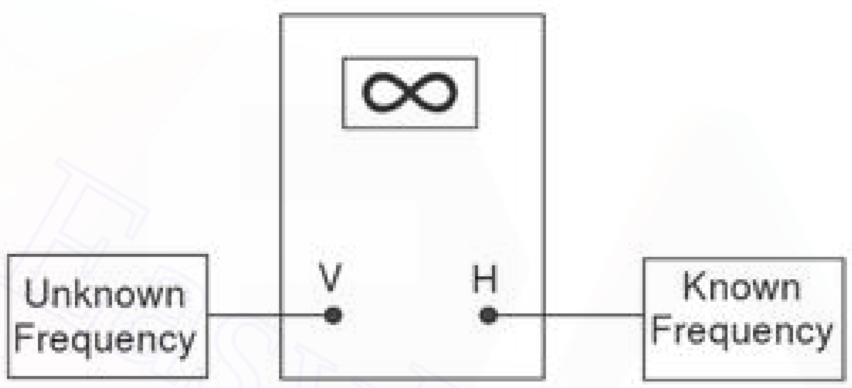


Fig. 7.33 Basic circuit for frequency measurements with lissajous figures

SPOT WHEEL METHOD 7.21

As the ratio of the two frequencies being compared increases, the Lissajous pattern becomes more complicated and hence more difficult to interpret. In such cases, it is advantageous to use the spot-wheel method of display as shown in Fig. 7.34 (a) whereby an intensity modulated circular or elliptical is produced on the face of the CRT. The lesser of the two frequencies being compared is applied to the deflecting plates of the CRT through the resistance-capacitance phase shifter as illustrated, thereby producing the circular (or elliptical) sweep. The higher frequency is applied to the control grid of the CRT (biased slightly below cut off), as shown in Fig. 7.34 (b), thus modulating the intensity of the beam. As a consequence, the pattern appears as a series of alternate bright and dark spots, as shown in Fig. 7.34 (c), where the ratio of the high to low frequencies is given by the number of bright spots.

The application of two sine wave signals, equal in amplitude but 90° out of phase, to the vertical and horizontal deflecting plates results in the formation of a circle. If a single sine wave is applied to a phase shifting circuit, it is possible to obtain two outputs, equal in amplitude and 90° out of phase.

If the voltages across R and C are equal, the pattern is a circle. If they are unequal, the pattern is elliptical.

($R = 1/\omega C$ where $\omega = 2\pi f$. The voltage across C lags the voltage across R by 90°.)

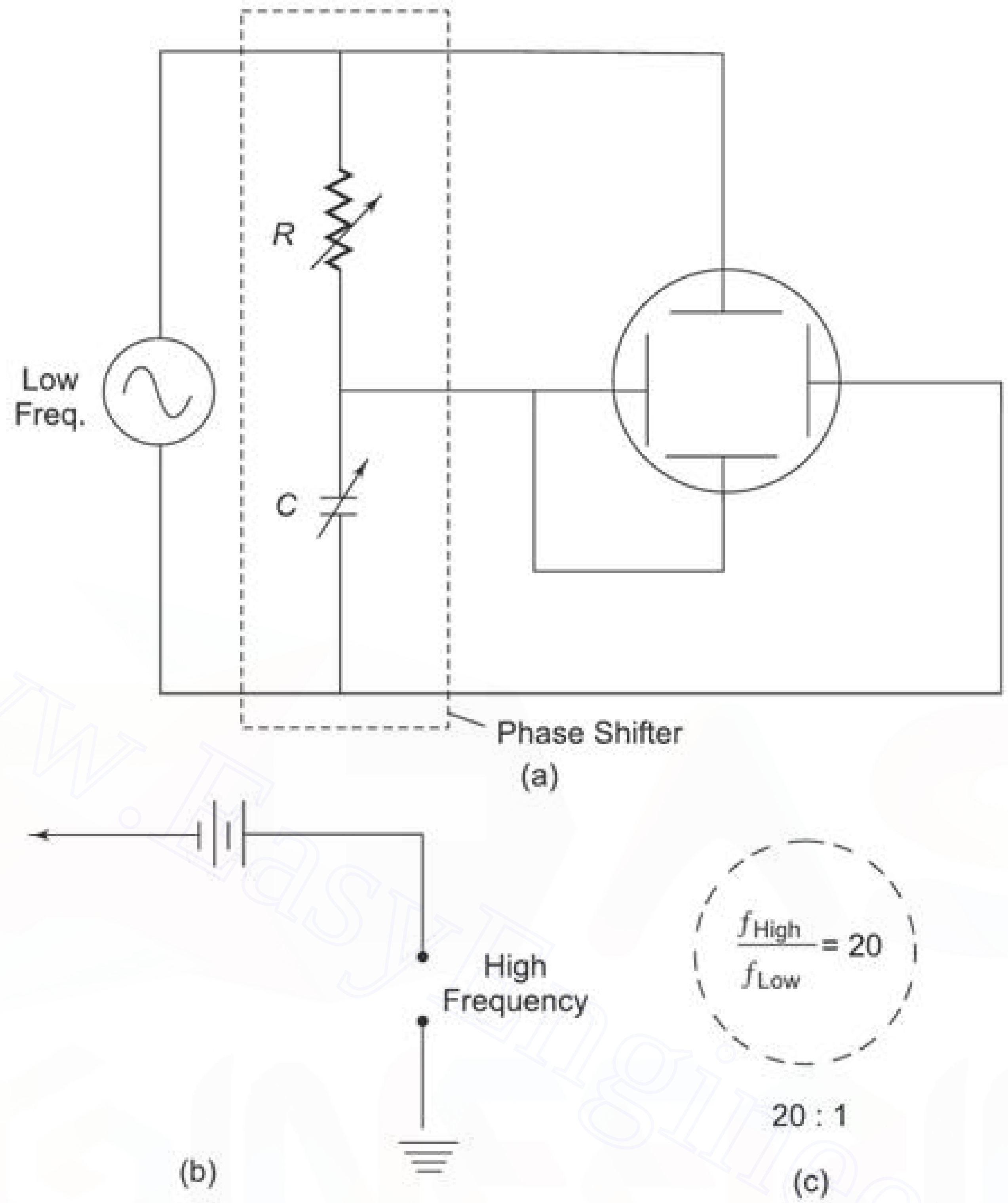


Fig. 7.34 (a) Basic circuit of a spot wheel method for frequency measurement (b) Input circuit to the control grid (c) Spot wheel pattern

Varying the grid-cathode potential changes the density of the electron stream within the CRT and determines the intensity. When the grid bias of the CRT reaches cut off potential, there is no electron stream and fluorescence at the screen cannot occur. This property is used for the comparison of two frequencies, provided their ratio is an integer.

The high frequency signal is applied to the grid. Sufficient grid bias must be present so that the negative peaks of the sine wave cuts off the electron beam. The high frequency signal does not have to be a pure sine wave, it can be a square wave.

In Fig. 7.34 (c), the frequency is 20 : 1 and there are 20 blanks in the pattern.

GEAR WHEEL METHOD 7.22

When a Lissajous figure contains a large number of loops, accurate counting becomes difficult. Figure 7.35 shows a test method that uses a modulated ring pattern in place of the looped figure and permits a higher count. This pattern is also called a Gear wheel or toothed wheel, because of its shape. The unknown frequency is determined by multiplying the known frequency by the number of teeth in the pattern. Figure. 7.36 shows the test set up. Here, a phase shift network (*RC*) introduces a 90° phase shift between the horizontal and vertical channels of the oscilloscope, which is needed to produce a ring or circle pattern with the known frequency f_v.

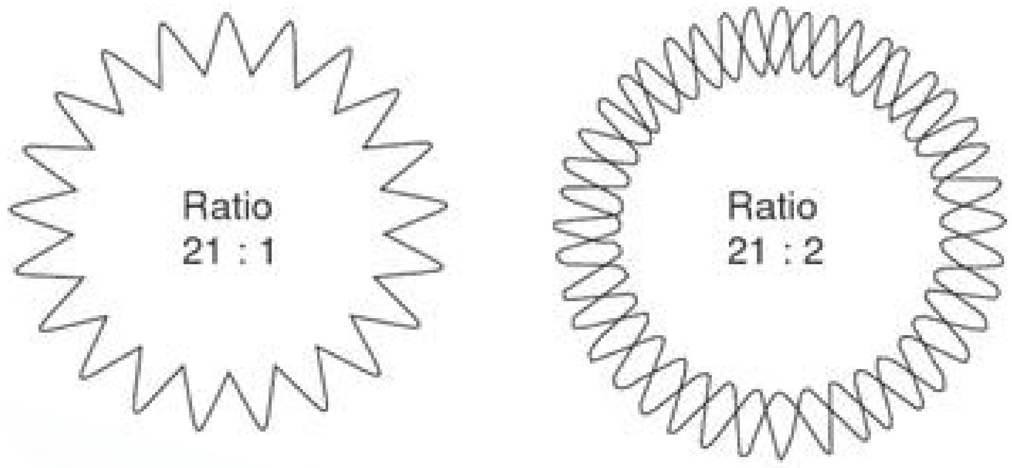


Fig. 7.35 Gear wheel pattern

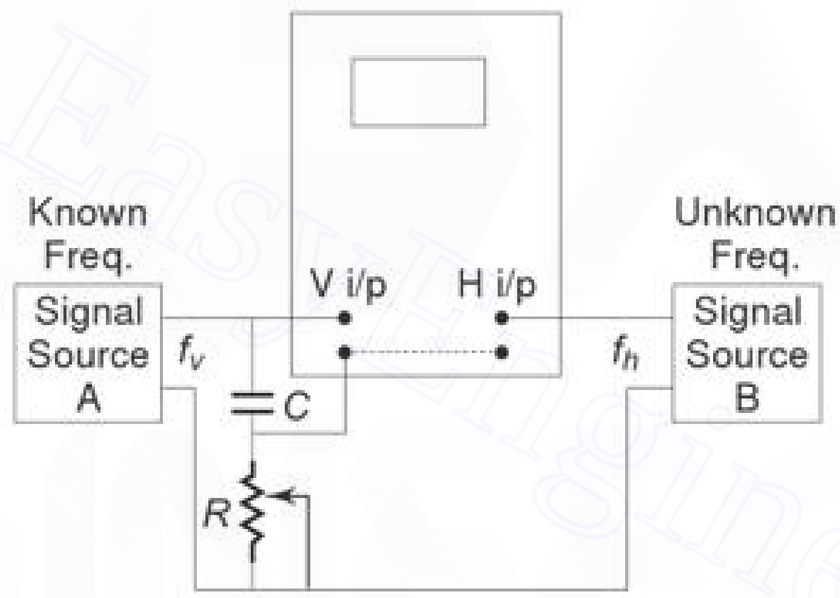


Fig. 7.36 Setup for gear wheel method for frequency measurement

A voltage from the unknown frequency source modulates this ring. When the voltages across *R* and *C* are unequal, the pattern is elliptical. If they are equal, the pattern is a circle. The unknown frequency must be higher than the known frequency and the amplitude of the unknown must be below that of the known to prevent distortion.

7.22.1 Measurement Procedure

Set up the oscilloscope. Switch off the Internal and Sync control. Connect the circuit as in Fig. 7.36, and temporarily switch off signal *B*.

Switch on signal source *A* and adjust *R* to obtain a ring pattern on the screen. Adjust the horizontal and vertical gain controls to spread the ring over the screen as much as possible.

Switch on signal source *B*, noting that the ring becomes toothed by the signal. Adjust the known frequency f_v to stop the ring from rotating. Adjust the amplitude of f_h to obtain a distinct teeth pattern. The unknown frequency is then given by $f_h = nf_v$, where f_h is an integral multiple (odd or even) of f_v. The wheel rotates or spins if f_h is not an exact multiple of f_v. Therefore, adjust the known frequency to stop the wheel from rotating.

CHECKING OF DIODES 7.23

The voltage-current characteristics curve of a crystal diode may be observed using the circuit given in Fig. 7.37 (a).

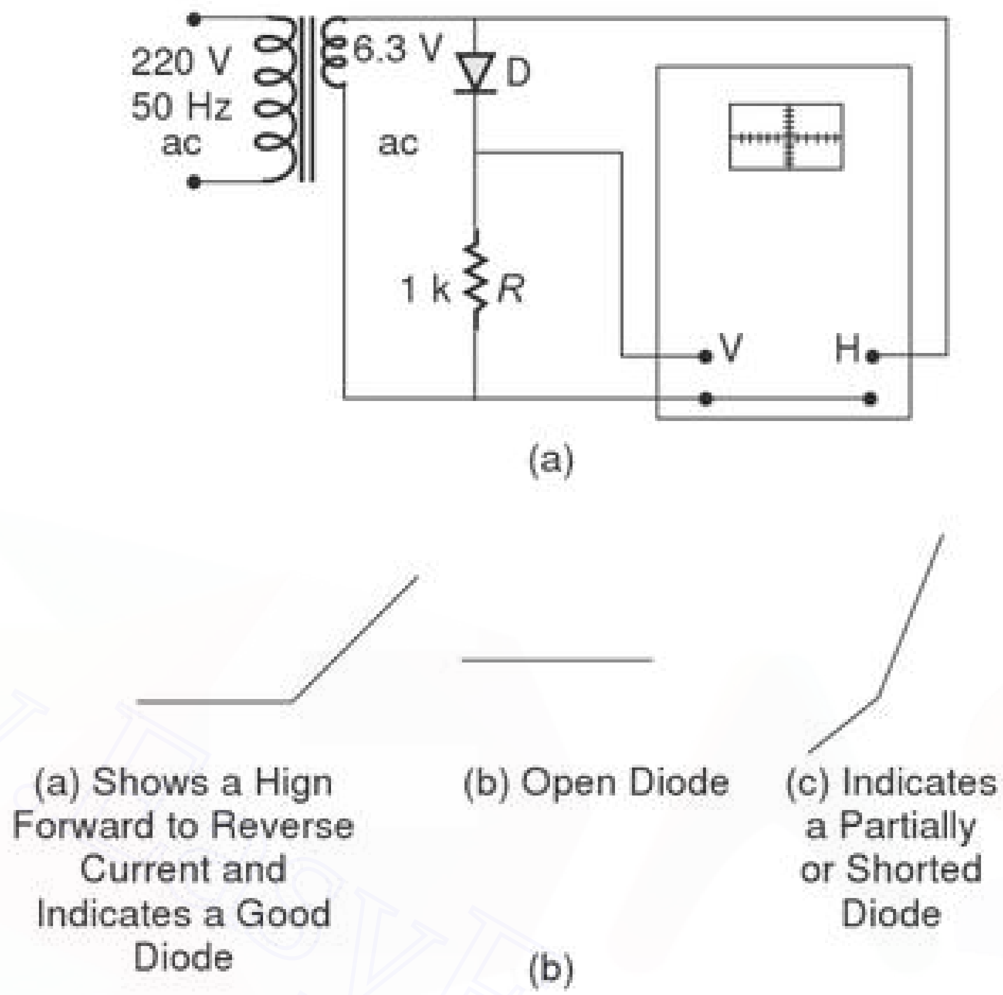


Fig. 7.37 (a) Setup for diode testing (b) Display pattern for diode testing

In this case the internal sweep is not used. Horizonal deflection is obtained by connecting the 6.3 V source directly to the horizontal input and switching the sweep control to horizontal amplifier. This provides an horizontal trace that is proportional to the applied voltage and represents the input signal.

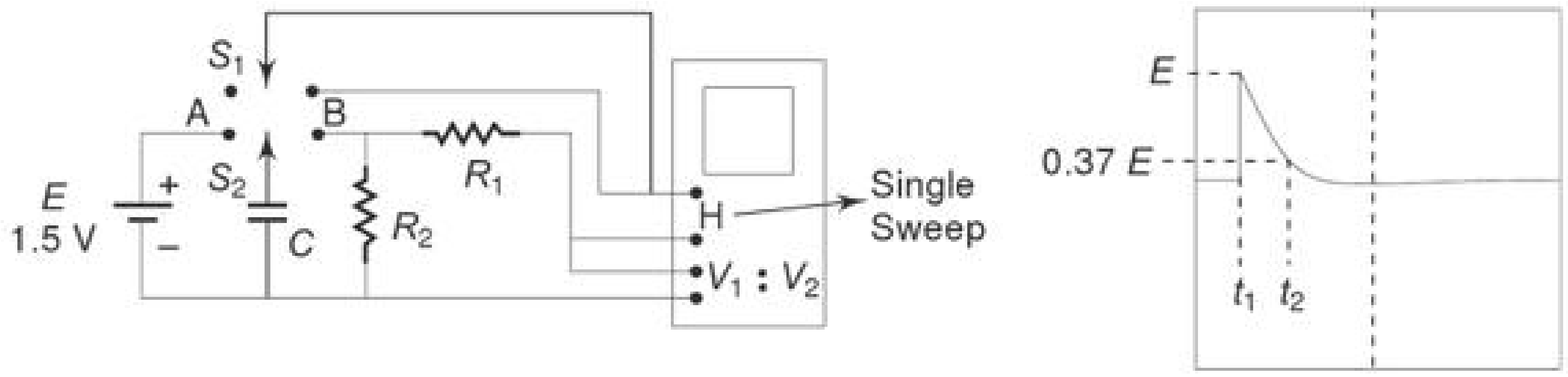
The diode current flowing through the 1 kΩ resistance will develop a voltage across the resistance, which is applied to the vertical input terminals. This represents the rectified signal current, since the voltage drop across R is proportional to the diode current.

If the diode being tested is good, the current through it will be unidirectional, causing the curve to rise vertically from its flat portion. The flat portion represents little or no current in the reverse direction. If the active portion of the curve points downwards, the diode connections should be reversed. The angle between the active and the flat portions of the curve represents the condition of the diode as shown in Fig. 7.37 (b).

BASIC MEASUREMENT OF CAPACITANCE AND INDUCTANCE 7.24

Capacitance may be measured from a capacitor discharge curve. This requires a dc oscilloscope with a triggered single sweep that is of the storage type.

Figure 7.38 (a) shows the test setup. C is the capacitor under test, and E is 1.5 V battery for charging the capacitor. R_1 is the precision 1 W non-inductive resistor. (R_1 should be 100 K for testing capacitances from 10 pf – 0.1 μf, 10 K for 0.1 – 10 µf, 1 K for 10 – 100 µf and 100 Ω for 100 – 1000 µf) R_2 is a 1 MΩ resistor to isolate R_1 from the oscilloscope input resistance.



(a) (b)

Fig. 7.38 (a) Basic setup for measurement of capacitance (b) Discharge curve

When the DPDT switch ($S_1 - S_2$) is connected to position A, capacitor C is charged by the battery; when this switch is connected to position B, the capacitor discharges through R_1. At this time, section S_1 of the switch triggers a single sweep of the oscilloscope. The shape of the discharge curve which is displayed on the screen is shown in Fig. 7.38 (b). When the ($S_1 - S_2$) switch is connected to position B, the voltage across R_1 rises suddenly to the fully charged value E at time t_1. The capacitor immediately begins to discharge through R_1. At time t_2 the voltage has fallen to 37% of the maximum. The unknown capacitor (in µf) is determined from the time interval between t_1 and t_2 (in ms) and the resistance R_1 in ohms.

Therefore
$$C = 1000\left(\frac{t_2 - t_1}{R_1}\right)$$

If a single trace oscilloscope is used, the time interval t_2–t_1 may be measured from (i) the calibrated sweep, and (ii) the calibrated horizontal axis.

Inductances may be measured by means of a time constant method similar to that used in the capacitance case. Figure 7.39 (a) shows the test setup. L is the inductor under test and E is a battery or filtered dc power supply. R_1 is the rheostat for adjusting the current level. A dc ammeter or mA can be temporarily inserted in series with the battery for indicating the maximum safe operating current of the L. The resistance of the rheostat at this setting must be noted.

When the DPST switch is open, no current flows through the inductor and the oscilloscope receives no signal voltage. When the switch is closed, S_1 closes the dc circuit, and current flows through L and R_1 in series. This produces a voltage drop across R_1, which is the signal voltage applied to the oscilloscope. At the same time, S_2 closes the trigger circuit and initiates a single sweep of the oscilloscope. Because of the counter emf generated by the inductor, the current increases exponentially, as shown in Fig. 7.39 (b). At time t_1, the voltage has risen to 63% of its final or maximum value, E. The unknown inductance (in Henries) is determined from the time interval between t_0 and t_1 (t_0 = 0) and resistance $R_1 \cdot t_1$ and t_0 may be measured (i) from the calibrated sweep and (ii) from the time calibrated horizontal axis.

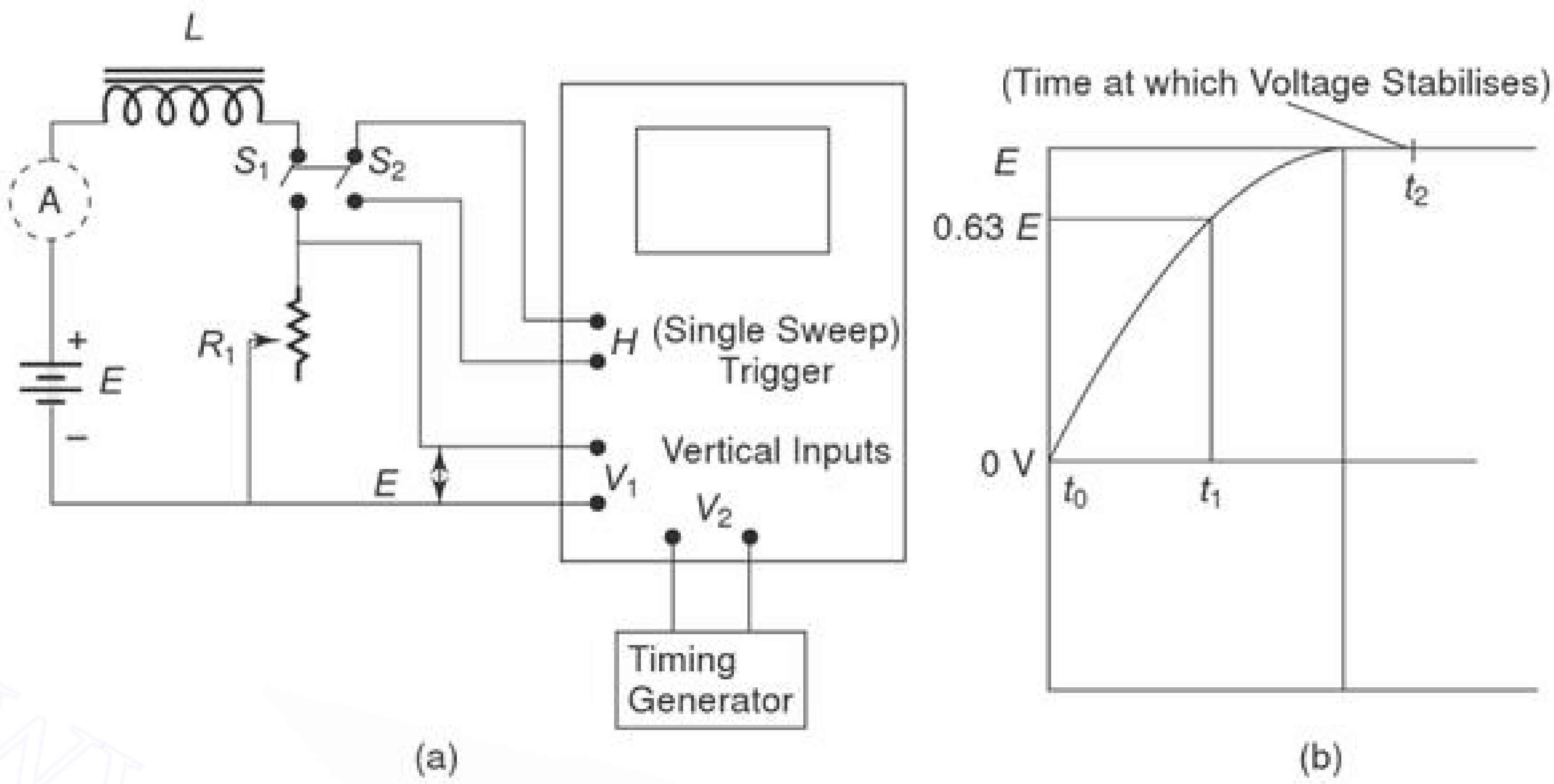


Fig. 7.39 (a) Setup for inductance measurement (b) Display curve

OSCILLOSCOPE AS A BRIDGE NULL DETECTOR 7.25

As a null detector for an ac bridge, the oscilloscope, unlike a meter used for the purpose, gives separate indications for reactive and resistive balances of the bridge.

Figure 7.40 shows how an oscilloscope is connected to the bridge. Here T is the shielded transformer and *C–R* form an adjustable phase shift network. The generator voltage is applied to the horizontal input through a phase shifter, and simultaneously to the bridge input. The bridge output signal is applied to the oscilloscope vertical input. Figure 7.41 shows the type of pattern obtained.

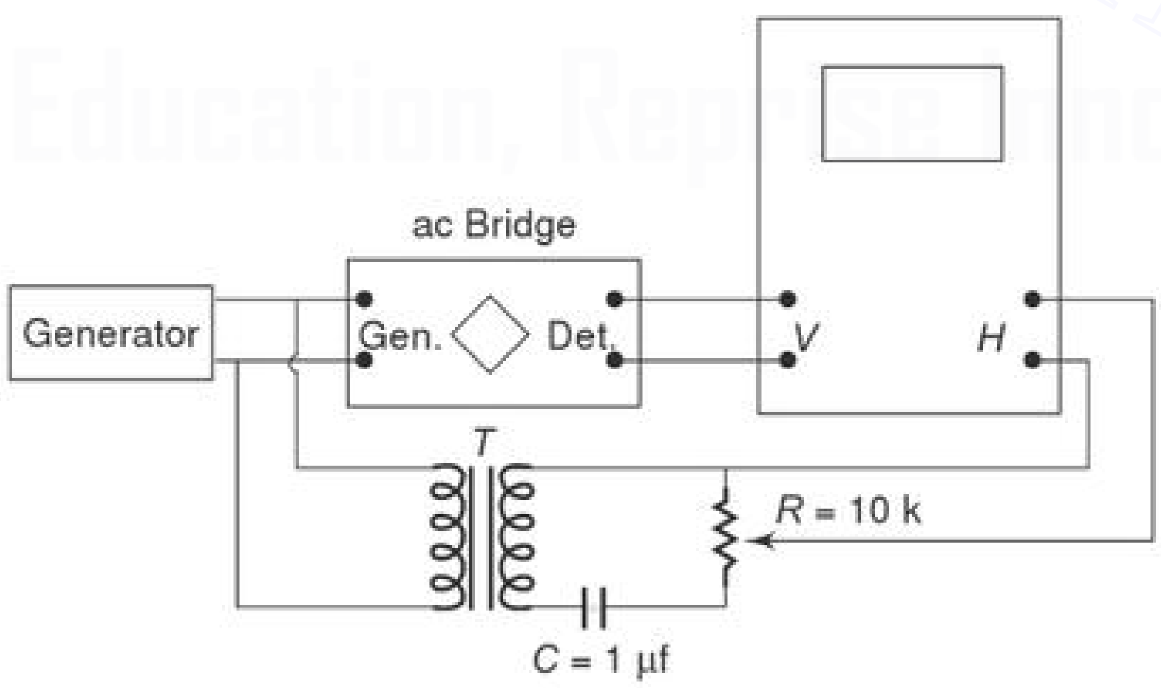


Fig. 7.40 Setup of oscilloscope as a bridge null-detector

7.25.1 Measurement Procedure

Connect the circuit as shown in Fig. 7.40. With the bridge unbalanced, but with test components (*R*, *C*, *L*) connected to the unknown arm of the bridge, adjust *R* in the phase shifter to give an elliptical pattern on the screen. Adjust the vertical and horizontal gain controls to obtain an ellipse of suitable height. Adjust the reactance control of the bridge, noting whether the ellipse tilts to the right or the left. When reactance balance is complete, i.e. reactance = 0, the ellipse will be horizontal.

Adjust the resistance (power factor, dissipation factor, or Q) control of the bridge, noting that the ellipse closes. At complete null (reactance and resistance, both balanced), a straight horizontal line is obtained. If the resistance is balanced while the reactance is not, tilted ellipse collapses, giving a single line trace tilted to the right or left.

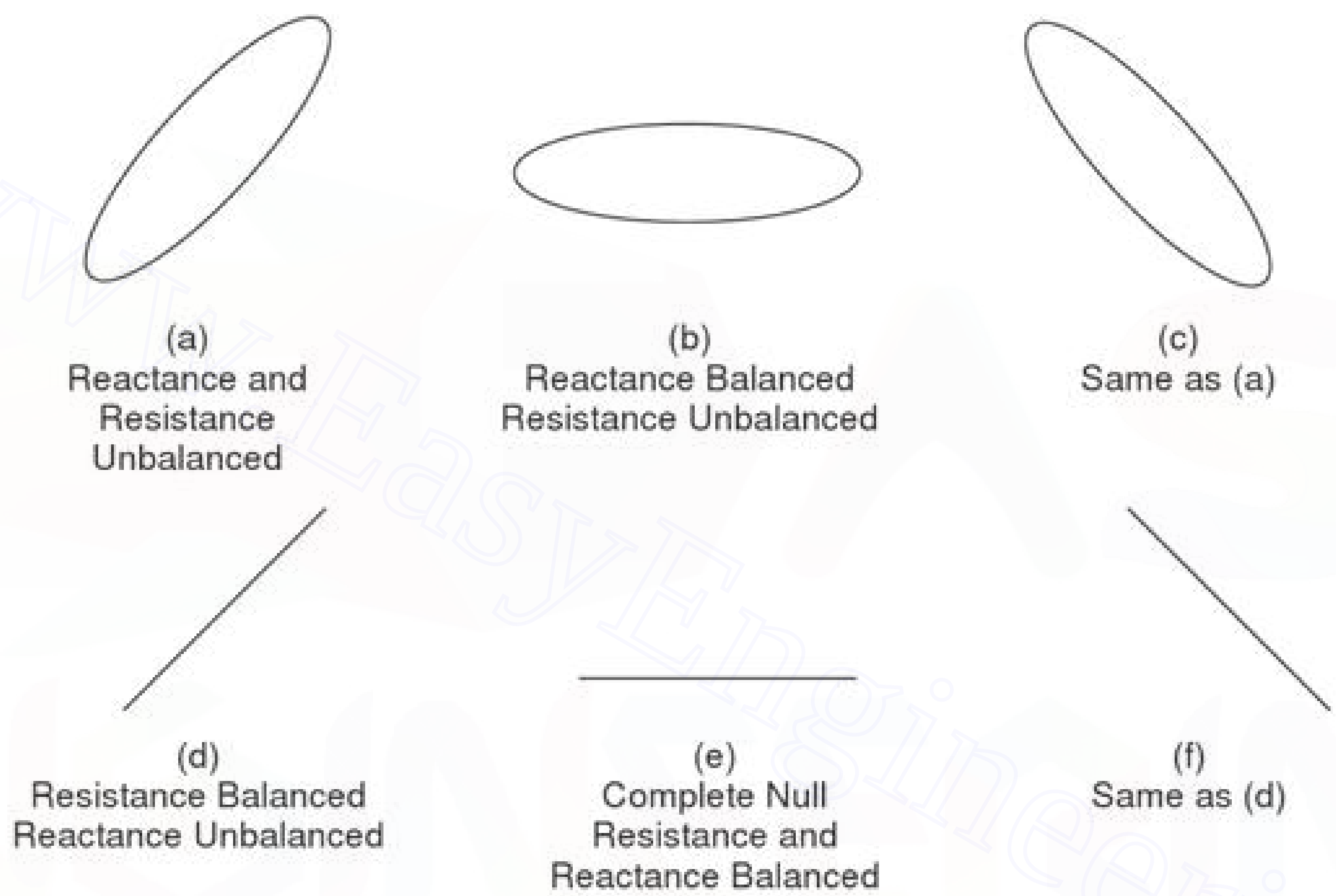


Fig. 7.41 Oscilloscope patterns

A simpler but less effective way of using an oscilloscope as a null detector is to connect the bridge output to the vertical terminals and use the oscilloscope as a voltmeter to give its lowest reading at null.

USE OF LISSAJOUS FIGURES FOR PHASE MEASUREMENT 7.26

When two signals are applied simultaneously to an oscilloscope without internal sweep, one to the horizontal channel and the other to the vertical channel, the resulting pattern is a Lissajous figure that shows a phase difference between the two signals. Such patterns result from the sweeping of one signal by the other.

Figure 7.42 shows the test setup for phase measurement by means of Lissajous figures. Figure 7.43 shows patterns corresponding to

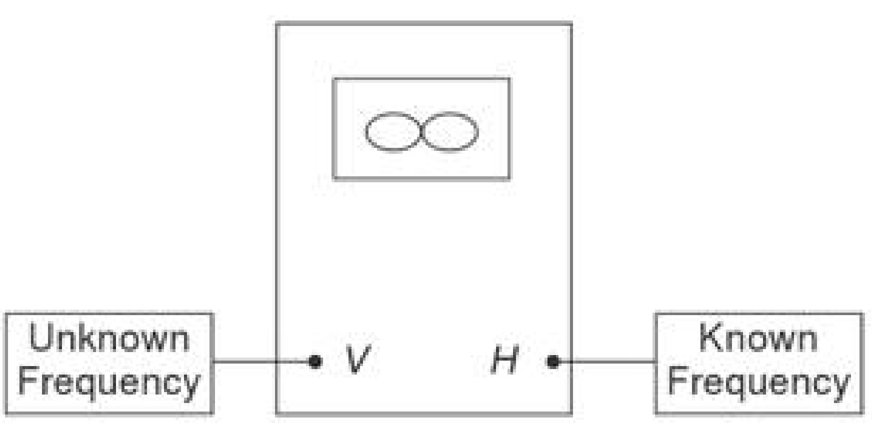


Fig. 7.42 Setup for phase measurement

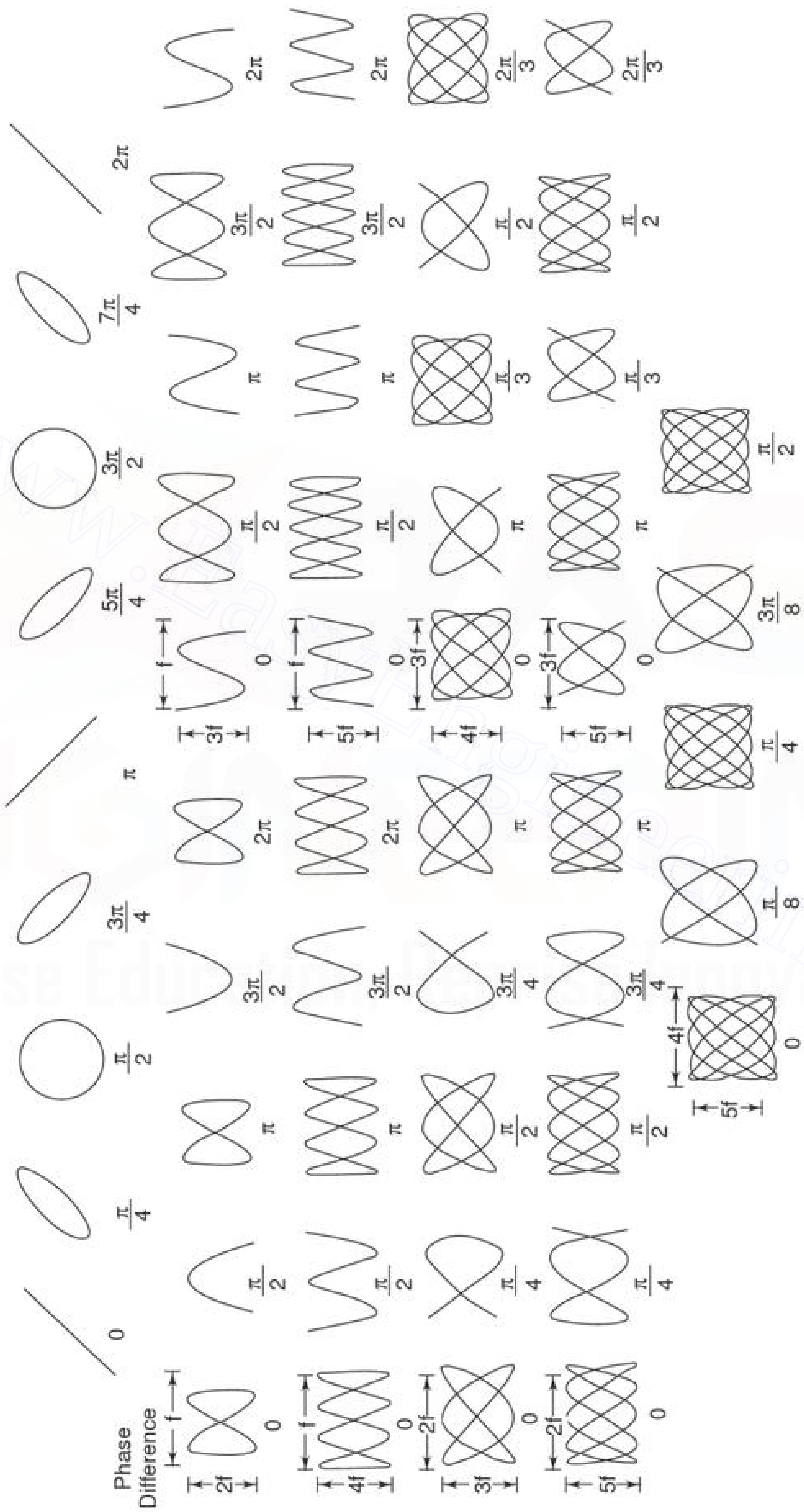


Fig. 7.43 Lissajous pattern

certain phase difference angles, when the two signal voltages are sinusoidal, equal in amplitude and frequency.

A simple way to find the correct phase angle (whether leading or lagging) is to introduce a small, known phase shift to one of the inputs. The proper angle may be then deduced by noting the direction in which the pattern changes.

STANDARD SPECIFICATIONS OF A SINGLE BEAM CRO 7.27

Vertical Amplifier		
Sensitivity	:	5 mV/Div. to 20 V/Div. in 12 calibrated steps in a 1, 2, 5 sequence. Continuous control (uncalibrated) between steps, reduces the sensitivity by a minimum of 2.5 times.
Accuracy	:	± 3%
Bandwidth	:	dc to 20 MHz (– 3 db), dc coupling
	:	0.5 Hz to 20 MHz (– 3 db) ac coupling
Rise time	:	Better than 18 ns
Input Impedance	:	1 MΩ/40 pf
Maximum input voltage	:	400 V (dc + ac peak)
Signal delay	:	Built in delay line sufficient to display leading edge of the waveform
Time Base		
Sweep ranges	:	0.1 μs/Div. to 0.5 s/Div. in 21 calibrated steps in a 1, 2, 5 sequence. Continuous uncalibrated control between steps extending slowest speed to 1.5 s/Div.
Accuracy	:	± 5%
Magnification	:	5 times. Takes the highest speed to 20 ns/Div.
Triggering		
Auto mode	:	Free running in the absence of a trigger signal. Triggers to the input signal automatically.
Level	:	Continuously adjustable on the + ve and – ve going slopes to trigger signal. Level adjustable over 8 Divs.
Source	:	Internal-External-Line
Polarity	:	Positive or negative
Maximum trigger input	:	250 V (dc + ac peak) short term
Input impedance	:	1 MΩ/30 pf
Internal trigger level	:	3 Div from 2 Hz to 20 MHz (1 Div, 30 Hz to 20 MHz in Auto mode)
External trigger level	:	3 V peak to peak, 2 Hz to 20 MHz (1 V, 30 Hz to 20 MHz in Auto mode)
Horizontal Amplifier		
Bandwidth	:	dc – 2 MHz (– 3 db)
Sensitivity	:	100 mV and 0.5 V/Div

Input impedance	:	1 MΩ/50 pf
Maximum input voltage	:	250 V (dc + ac peak)
Calibration	:	200 mV peak to peak square wave at 1 kHz
Cathode ray tube	:	Flat faced medium persistance
Accelerating Potential	:	4.5 kV
Graticule	:	8 × 10 Div of 8 mm each
Power requirements	:	230 V ac, 50 Hz, 50 W
Dimensions	:	220 × 275 × 430 mm
Weight	:	10kg approximately
Optional accessories	:	(i) × 1 probe
		(ii) Oscilloscope trolley
		(iii) × 10 probe (10 MΩ/12 pf)

PROBES FOR CRO 7.28

7.28.1 Direct Probes (1 : 1)

The simplest types of probe (one can hardly call it a probe) is the test lead. Test leads are simply convenient lengths of wire for connecting the CRO input to the point of observation. At the CRO end, they usually terminate with lugs, banana tips or other tips to fit the input jacks of the scope, and at the other end have a crocodile clip or any other convenient means for connection to the electronic circuit.

Since a CRO has high input impedance and high sensitivity, the test leads should be shielded to avoid hum pickup, unless the scope is connected to low impedance high level circuits.

Although the input impedances of most CROs are relatively very high compared to the circuits where they are connected, it is often desirable to increase their impedance to avoid loading of the circuits or causing unstable effects.

The input capacitance of the scope, plus the stray capacitance of the test leads, may be just enough to cause a sensitive circuit to break into oscillation when the CRO is connected. This effect can be prevented by an isolation probe made by placing a carbon resistor in series with the test lead, as shown in Fig. 7.44.

Fig. 7.44 Isolation probe

A slight reduction in the amplitude of the waveform and a slight change in the waveshape occurs with this probe. To avoid this possibility, a high impedance compensated probe, called a low capacitance probe or a 10 : 1 probe, is used.

7.28.2 Passive Voltage (High Z) Probe

Figure 7.45 (a) shows a 10 : 1 probe. Figure 7.45 (b) shows the equivalent circuit. Referring to Fig. 7.45 (b). The capacitor is adjusted so that the elements of the bridge are balanced. Under conditions of balance we have

$$R_1 X_{(C_2+C_{in})} = R_{in} X(C_1)$$

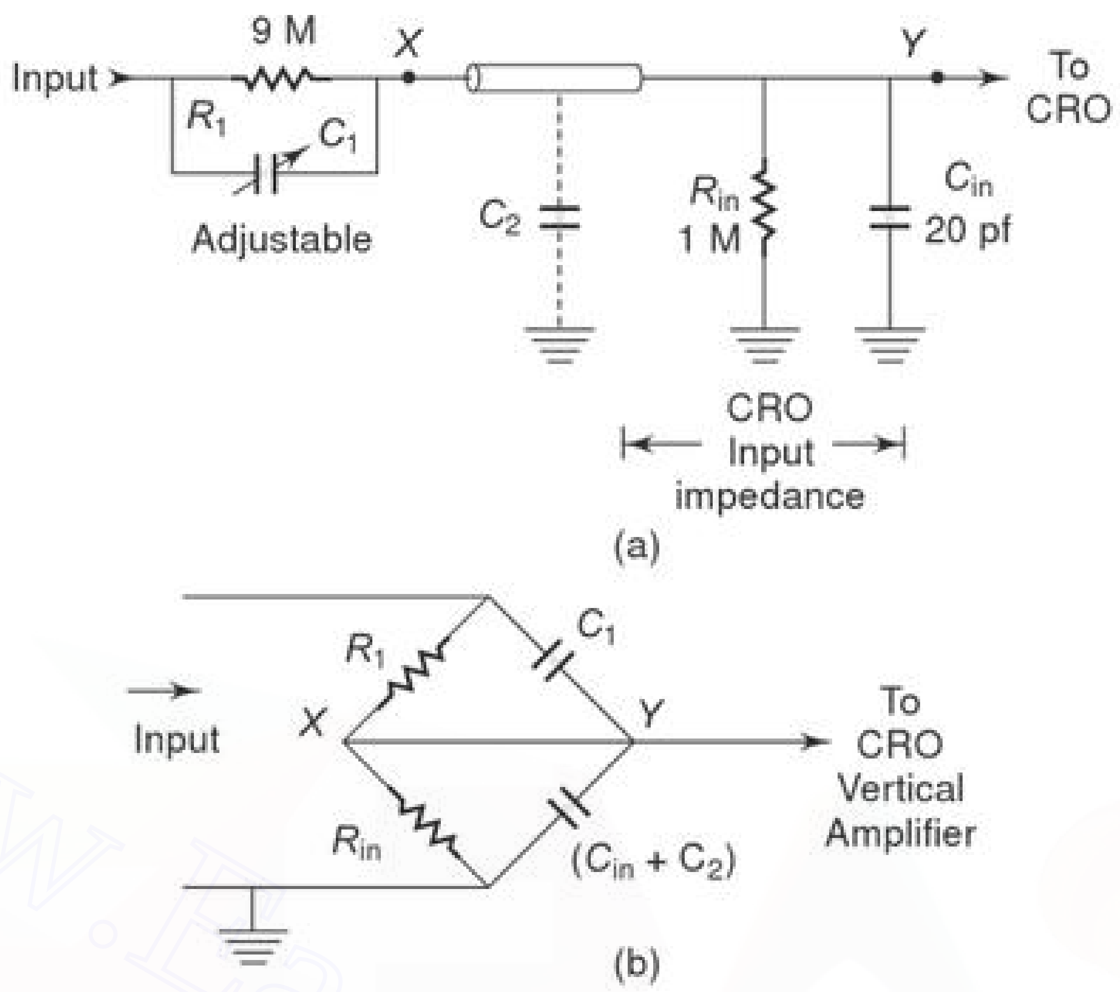


Fig. 7.45 (a) 10 : 1 Probe (b) Equivalent Circuit of 10 : 1 Probe

$$\therefore \qquad \frac{R_1}{\omega(C_2+C_{in})} = \frac{R_{in}}{\omega C_1}$$

$$R_1 C_1 = R_{in}(C_2 + C_{in})$$

Therefore, X and Y are equipotential and the effect of the probe is equivalent to placing a potential divider consisting of R_1 and R_{in} across the input circuit. The attenuation of the signal is 10 : 1, i.e. $(R_1 + R_{in})/R_1 = 10 : 1$ over a wide frequency range. Therefore, it is called a compensated 10×1 probe. As far as dc voltage inputs are concerned, the coaxial capacitance equals 30 pf per foot. (Assuming a coaxial length of 3.5 ft, the total coaxial length capacitance is 105 pf). Substituting this value in the balance bridge equation, we have

$$C_1 = \frac{R_{in}(C_{in}+C_2)}{R_1} = \frac{1\,\text{M}\,(105+20)\,\text{pf}}{9\,\text{M}} = 13.88\ \text{pf}$$

Therefore, the input capacitance of a CRO can range from 15–50 pf. C_1 should be adjusted from 13–47 pf. It must be adjusted to obtain optimum frequency response from the probe-CRO combination. The C_1 adjustment is done by connecting the probe tip to a square wave of 1 kHz and observing the CRT display. When the CRT display has optimum response, the C_1 value is deemed to be appropriate.

Therefore $$V_{out} = (0.1)\,V_{in} = \frac{V_{in} \times R_{in}}{R_1 + R_{in}}$$

7.28.3 Active Probes

Active probes are designed to provide an efficient method of coupling high frequency, fast rise time signals to the CRO input. Usually active probes have very high input impedance, with less attenuation than passive probes. Active devices may be diodes, FETs, BJTs, etc.

Active probes are more expensive and bulky than passive probes, but they are useful for small signal measurements, because their attenuation is less.

Active Probes Using FETs Figure 7.46 shows a basic circuit of an active probe using a FET.

The FET is used as the active element to amplify the input signal. Although the voltage gain of the FET follower circuit shown is unity, the follower circuit provides a power gain so that the input impedance can be increased. To be effective the FET must be mounted directly in the voltage probe tip, so that the capacitance of the interconnecting cable can be eliminated. This requires that the power for the FET be supplied from the oscilloscope to the FET in the probe tip. The FET voltage follower drives a coaxial cable, but instead of the cable connecting directly to the high input impedance of the oscilloscope, it is terminated in its characteristic impedance.

There is no signal attenuation between the FET Amplifier and the probe tip. The range of the signals that can be handled by the FET probe is limited to the dynamic range of the FET amplifier and is typically less than a few volts. To handle a larger dynamic range, external attenuators are added at the probe tip. Active probes have limited use because the FET probe effectively becomes an FET attenuator. Therefore, oscilloscopes are typically used with a 10 to 1 attenuator probe.

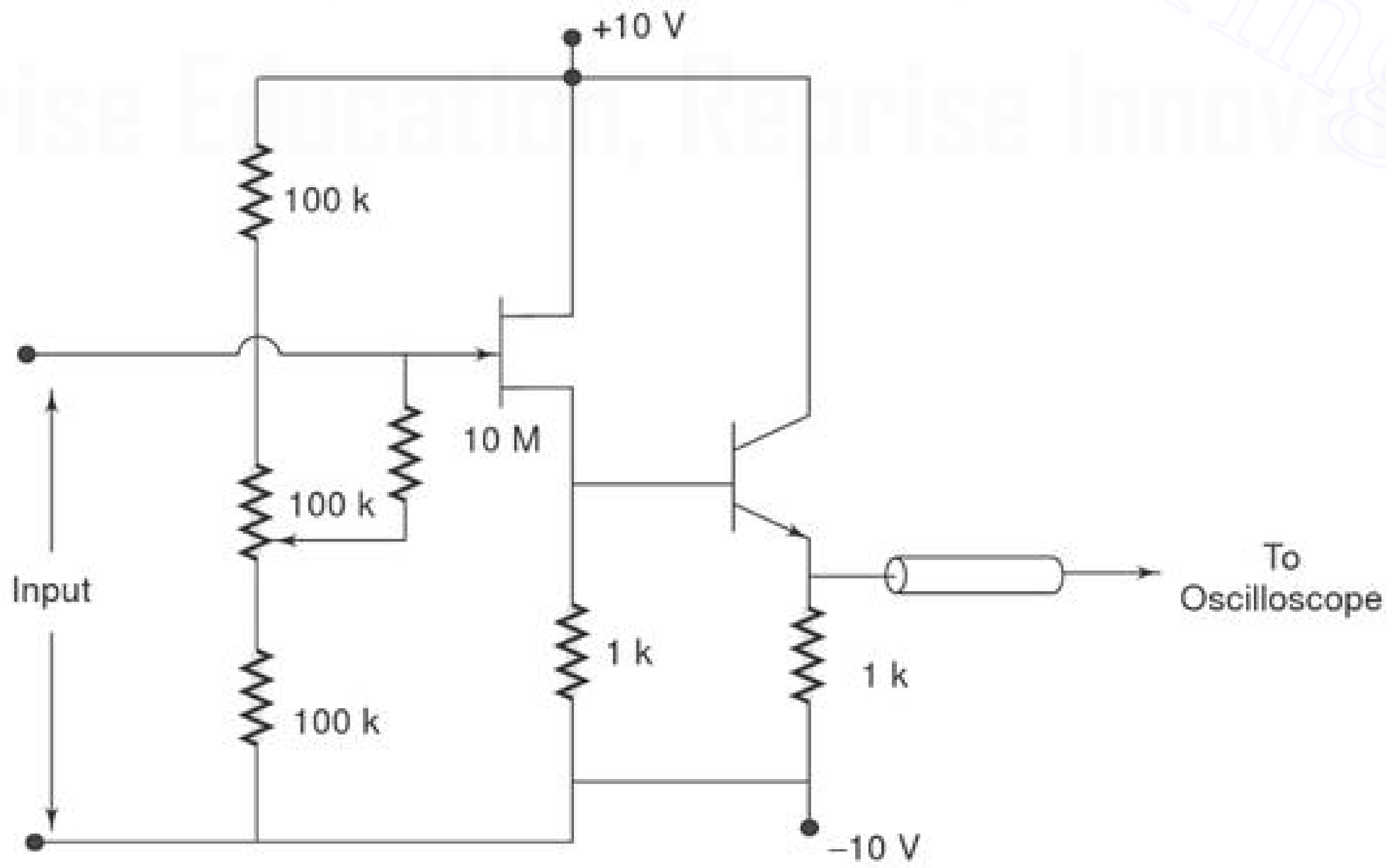


Fig. 7.46 FET probe

ATTENUATORS 7.29

Attenuators are designed to change the magnitude of the input signal seen at the input stage, while presenting a constant impedance on all ranges at the attenuator input.

A compensated RC attenuator is required to attenuate all frequencies equally. Without this compensation, HF signal measurements would always have to take the input circuit RC time constant into account.

The input attenuator must provide the correct 1-2-5 sequence while maintaining a constant input impedance, as well as maintain both the input impedance and attenuation over the frequency range for which the oscilloscope is designed.

7.29.1 Uncompensated Attenuators

The circuit diagram shown in Fig. 7.47 gives a resistive divider attenuator connected to an amplifier with a 10 pf input capacitance. If the input impedance of the amplifier is high, the input impedance of the attenuator is relatively constant, immaterial of the switch setting of the attenuator.

The input impedance, as seen by the amplifier, changes greatly depending on the setting of the attenuator. Because of this, the RC time constant and frequency response of the amplifier are dependent on the setting of the attenuator, which is an undesirable feature.

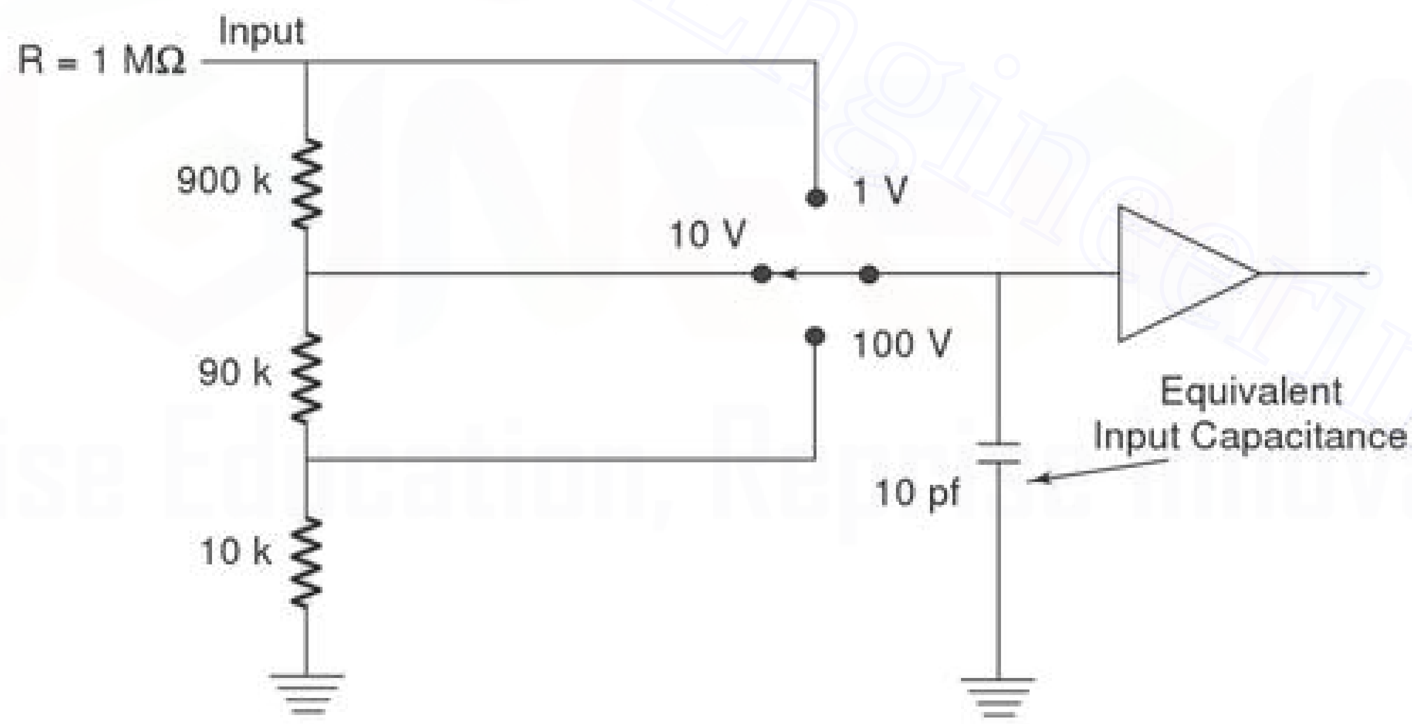


Fig. 7.47 Uncompensated attenuator

7.29.2 Simple Compensated Attenuator

The diagram in Fig. 7.48 shows an attenuator with both resistive and capacitive voltage dividers. The capacitive voltage dividers improve the HF response of the attenuator. This combination of capacitive and resistive voltage dividers is known as a compensated attenuator. For oscilloscopes where the frequency range extends to 100 MHz and beyond, more complex dividers are used.

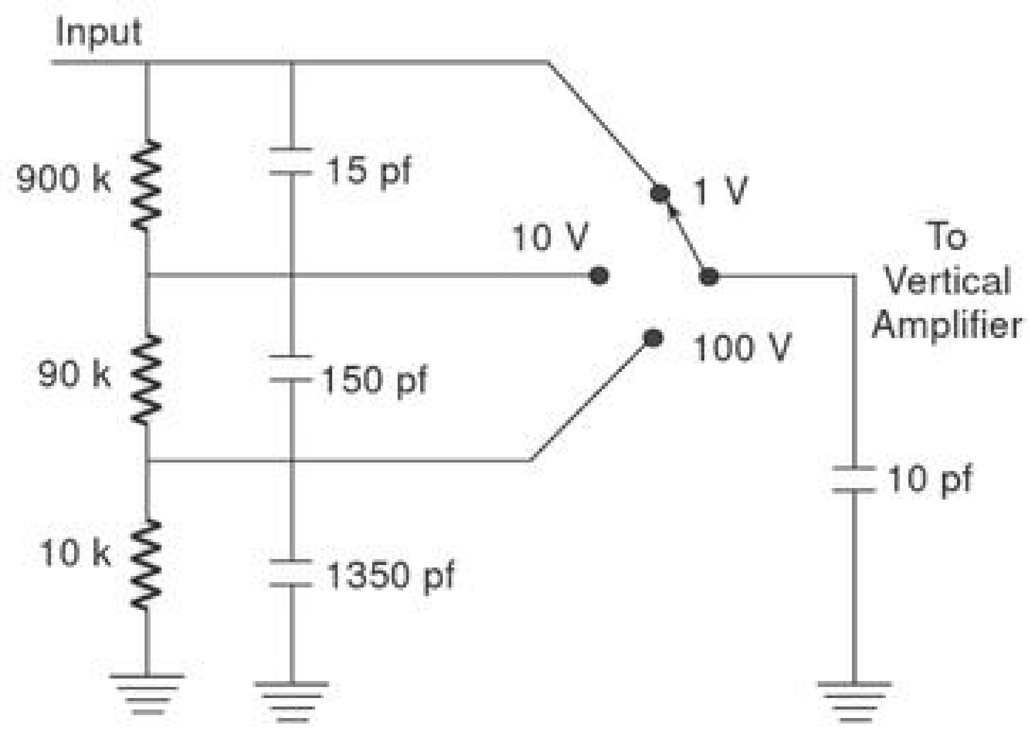


Fig. 7.48 Simple Compensated Attenuator

Figure 7.49 shows an attenuator divider between the input and output of the vertical deflection pre-amplifier. The input attenuator provides switching powers of 10, while attenuators at the output of the vertical preamplifier provides 1–2–5 attenuation.

Practically all oscilloscopes provide a switchable input coupling capacitor, as shown in Fig. 7.49.

The input impedance of an oscilloscope is 1 MΩ which is shunted with an input capacitance of 10–30 pf. If a probe were connected to the oscilloscope, the input impedance at the probe tip would have a greater capacitance because of the added capacitance of the probe assembly and of the connecting shielded cable. If it is desired for HF oscilloscopes to have an input capacitance of much less than 20–30 pf, an attenuator probe is used. Figure 7.48 shows a 10 to 1 attenuator probe connected to the input of the oscilloscope.

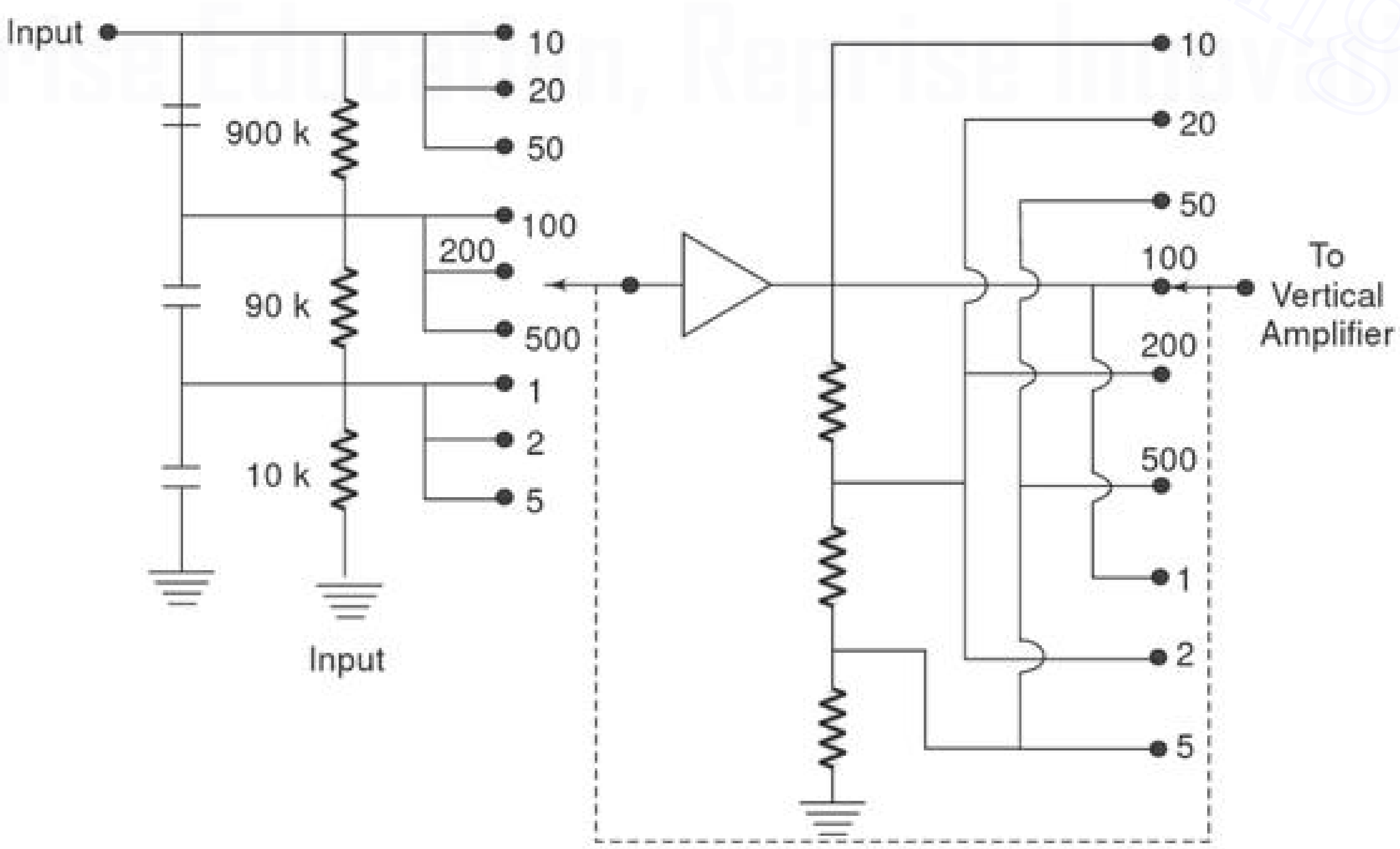


Fig. 7.49 Switchable Input Attenuator

Within the probe tip is a 9 MΩ resistor and shunted across this resistor is a capacitor. This capacitor is adjusted so that the ratio of the shunt capacitance to the series capacitance is exactly 10 to 1.

The attenuator probe, often called a 10 to 1 probe, provides an approximately 10 to 1 reduction in the input capacitance. However, it also gives a 10 to 1 reduction in overall oscilloscope sensitivity.

The input capacitance is not constant from one oscilloscope to another hence the probe is provided with an adjustable compensating capacitor. If the ratio of the series to shunt is not adjusted precisely to 10 to 1, the frequency response of the oscilloscope will be flat.

APPLICATIONS OF OSCILLOSCOPE 7.30

The range of applications of an oscilloscope varies from basic voltage measurements and waveform observation to highly specialised applications in all areas of science, engineering and technology.

7.30.1 Voltage Measurements

The most direct voltage measurement made with the help of an oscilloscope is the peak to peak (p–p) value. The rms value of the voltage can then be easily calculated from the p–p value.

To measure the voltage from the CRT display, one must observe the setting of the vertical attenuator expressed in V/div and the peak to peak deflection of the beam, i.e. the number of divisions. The peak to peak value of voltage is then computed as follows.

$$V_{p-p} = \left(\frac{\text{volts}}{\text{div}}\right) \times \left(\frac{\text{no. of div}}{1}\right)$$

Example 7.1 *The waveform shown in Fig. 7.50 is observed on the screen of an oscilloscope. If the vertical attenuation is set to 0.5 V/div, determine the peak to peak amplitude of the signal.*

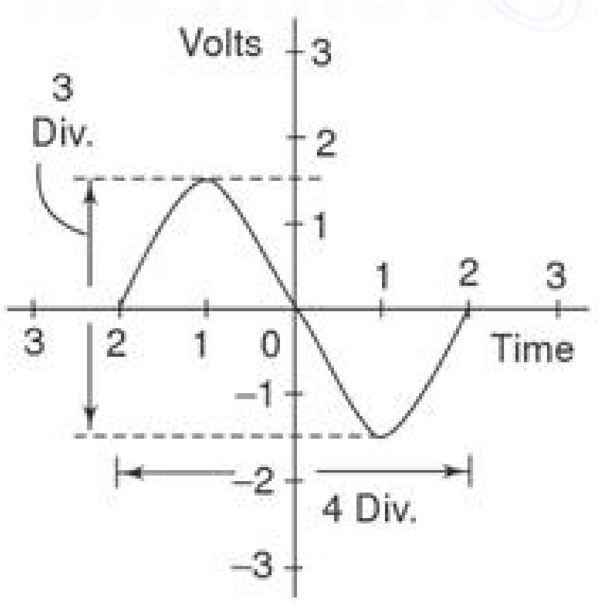


Fig.7.50

Solution Using the equation,

$$V_{p-p} = \left(\frac{\text{volts}}{\text{div}}\right) \times \left(\frac{\text{no. of div}}{1}\right)$$

$$V_{p-p} = 0.5\ V \times 3 = 1.5\ V_{p-p}$$

7.30.2 Period and Frequency Measurements

The period and frequency of periodic signals are easily measured with an oscilloscope. The waveform must be displayed such that a complete cycle is displayed on the CRT screen. Accuracy is generally improved if a single cycle displayed fills as much of the horizontal distance across the screen as possible.

The period is calculated as follows.

$$T = \left(\frac{\text{time}}{\text{div}}\right) \times \left(\frac{\text{No. of div}}{\text{cycle}}\right)$$

The frequency is then calculated as $f = 1/T$.

Example 7.2 *If the time/div control is set to 2μs/div when the waveform in Fig. Ex. 7.1 is displayed on the CRT screen, determine the frequency of the signal.*

Solution The period of the signal is calculated using the equation

$$T = \left(\frac{\text{time}}{\text{div}}\right) \times \left(\frac{\text{No. of div}}{\text{cycle}}\right)$$

$$T = 2\ \mu\text{s} \times 4 = 8\ \mu\text{s}$$

Hence frequency is calculated as

$$f = 1/T = 1/8\ \mu\text{s} = 125\ \text{kHz}$$

DELAYED SWEEP 7.31

Many oscilloscopes of laboratory quality include a delayed sweep feature. This feature increases the versatility of the instrument by making it possible to magnify a selected portion of an undelayed sweep, measure waveform jitter or rise time, and check pulse time modulation, as well as many other applications.

Delayed sweep is a technique that adds a precise amount of time between the trigger point and the beginning of the scope sweep. When the scope is being used in the sweep mode, the start of the horizontal sweep can be delayed, typically from a few μs to perhaps 10 seconds or more. Delayed sweep operation allows the user to view a small segment of the waveform, e.g. an oscillation or ringing that occurs during a small portion of a low frequency waveform.

The most common approaches used by oscilloscpe manufacturers for delayed sweep operations are, the following.

1. Normal triggering sweep after the desired time delay, which is set from the panel controls.
2. A Delay Plus Trigger mode, where a visual indication, such as light, indicates that the delay time has elapsed and the sweep is ready to be triggered.
3. Intensified sweep, where the delayed sweep acts as a positional magnifier.

DIGITAL STORAGE OSCILLOSCOPE (DSO) 7.32

Digital storage oscilloscope are available in processing and non-processing types. Processing types include built in computing power, which takes advantage of the fact that all data is already in digital form.

The inclusion of interfacing and a microprocessor provides a complete system for information acquisition, analysis and output. Processing capability ranges from simple functions (such as average, area, rms, etc.) to complete Fast Fourier Transform (FFT) spectrum analysis capability.

(Units with built in hard copy plotters are particularly useful, since they can serve as digital scope high speed recorders, tabular printers and X–Y plotters, all in one unit, with computing power and an $8\frac{1}{2}'' \times 11''$ paper/ink printout.)

Non-processing digital scopes are designed as replacements for analog instruments for both storage and non-storage types. Their many desirable features may lead to replace analog scopes entirely (within the Bandwidth range where digitization in feasible).

The basic principle of a digital scope is given in Fig. 7.51. The scope operating controls are designed such that all confusing details are placed on the back side and one appears to be using a conventional scope. However, some digital scope panels are simpler also, most digital scopes provide the facility of switching selectable to analog operation as one of the operating modes.

The basic advantage of digital operation is the storage capability, the stored waveform can be repetitively read out, thus making transients appear repetitively and allowing their convenient display on the scope screen. (The CRT used in digital storage is an ordinary CRT, not a storage type CRT.)

Furthermore, the voltage and time scales of display are easily changed after the waveform has been recorded, which allows expansion (typically to 64 times) of selected portions, to observe greater details.

A cross-hair cursor can be positioned at any desired point on the waveform and the voltage/time values displayed digitally on the screen, and/or readout electrically.

Some scopes use 12 bit converters, giving 0.025% resolution and 0.1% accuracy on voltage and time readings, which are better than the 2–5% of analog scopes.

Split screen capabilities (simultaneously displaying live analog traces and replayed stored ones) enable easy comparison of the two signals.

Pretrigger capability is also a significant advantage. The display of stored data is possible in both amplitude versus time and X-Y modes. In addition to the fast memory readout used for CRT display, a slow readout is possible for producing hard copy with external plotters.

When more memory than the basic amount (typically 4096 points/words) is needed, a magnetic disk accessory allows expansion to 32,000 points.

All digital storage scopes are limited in bandwidth by the speed of their A/D converters. However, 20 MHz digitizing rates available on some scopes yield a 5 MHz bandwidth, which is adequate for most applications.

Consider a single channnel of Fig. 7.51. The analog voltage input signal is digitised in a 10 bit A/D converter with a resolution of 0.1% (1 part in 1024) and frequency response of 25 kHz. The total digital memory storage capacity is 4096 for a single channel, 2048 for two channels each and 1024 for four channels each.

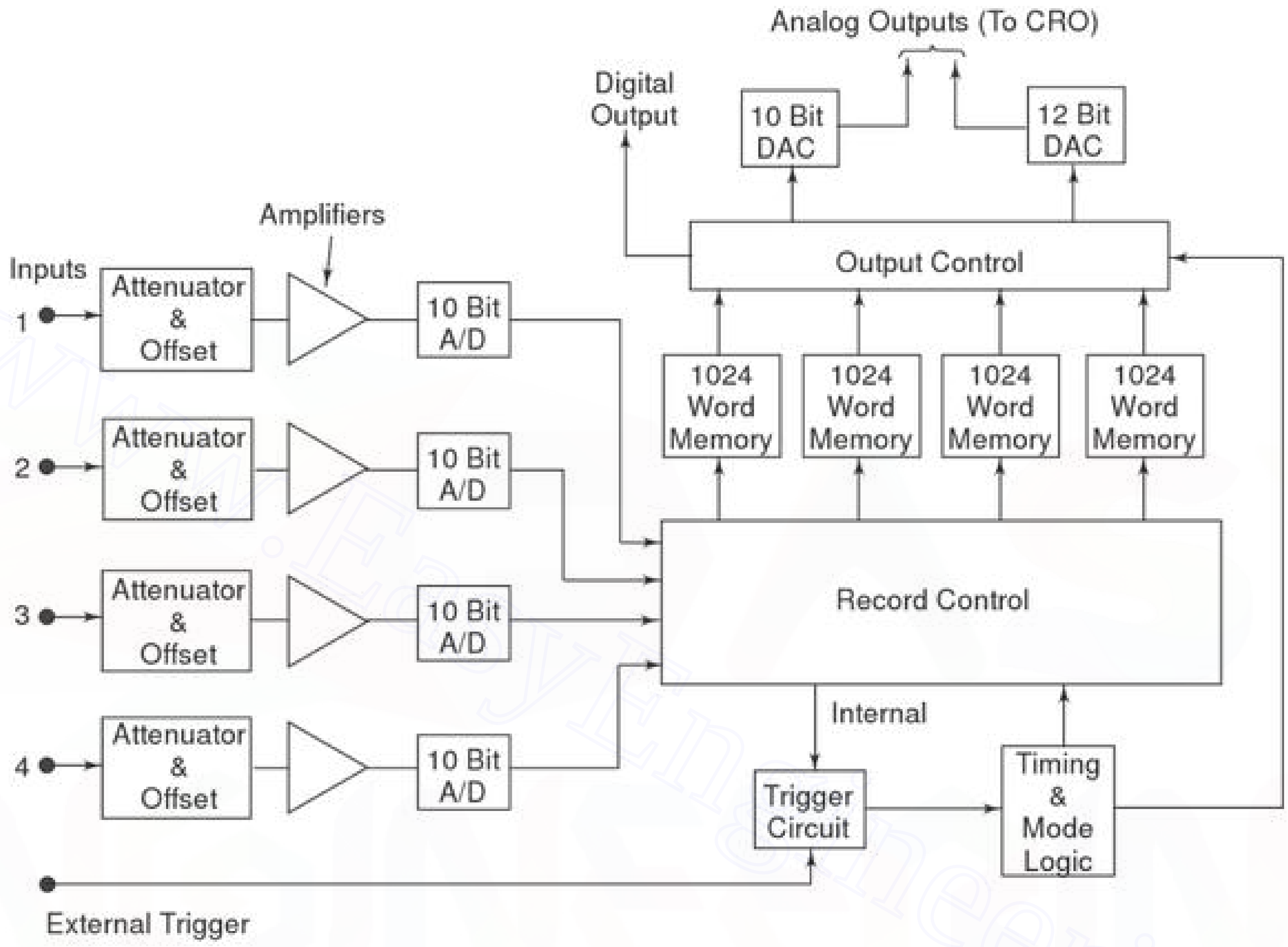


Fig. 7.51 Digital storage CRO

The analog input voltage is sampled at adjustable rates (up to 100,000 samples per second) and data points are read onto the memory. A maximum of 4096 points are storable in this particular instrument. (Sampling rate and memory size are selected to suit the duration and waveform of the physical event being recorded.)

Once the sampled record of the event is captured in memory, many useful manipulations are possible, since memory can be read out without being erased.

If the memory is read out rapidly and repetitively, an input event which was a single shot transient becomes a repetitive or continuous waveform that can be observed easily on an ordinary scope (not a storage scope). The digital memory also may be read directly (without going through DAC) to, say, a computer where a stored program can manipulate the data in almost any way desired.

Pre-triggering recording allows the input signal preceding the trigger points to be recorded. In ordinary triggering the recording process is started by the rise of the input (or some external triggering) above some preset threshold value.

As in digital recorder, DSO can be set to record continuously (new data coming into the memory pushes out old data, once memory is full), until the trigger signal is received; then the recording is stopped, thus freezing data received prior to the trigger signal in the memory.

An adjustable trigger delay allows operator control of the stop point, so that the trigger may occur near the beginning, middle or end of the stored information.

7.32.1 Commercial DSO

IE-522 shown in illustration Fig. 7.52, is a 25 MHz analog digital storage dual trace four display oscilloscope with computer interface.

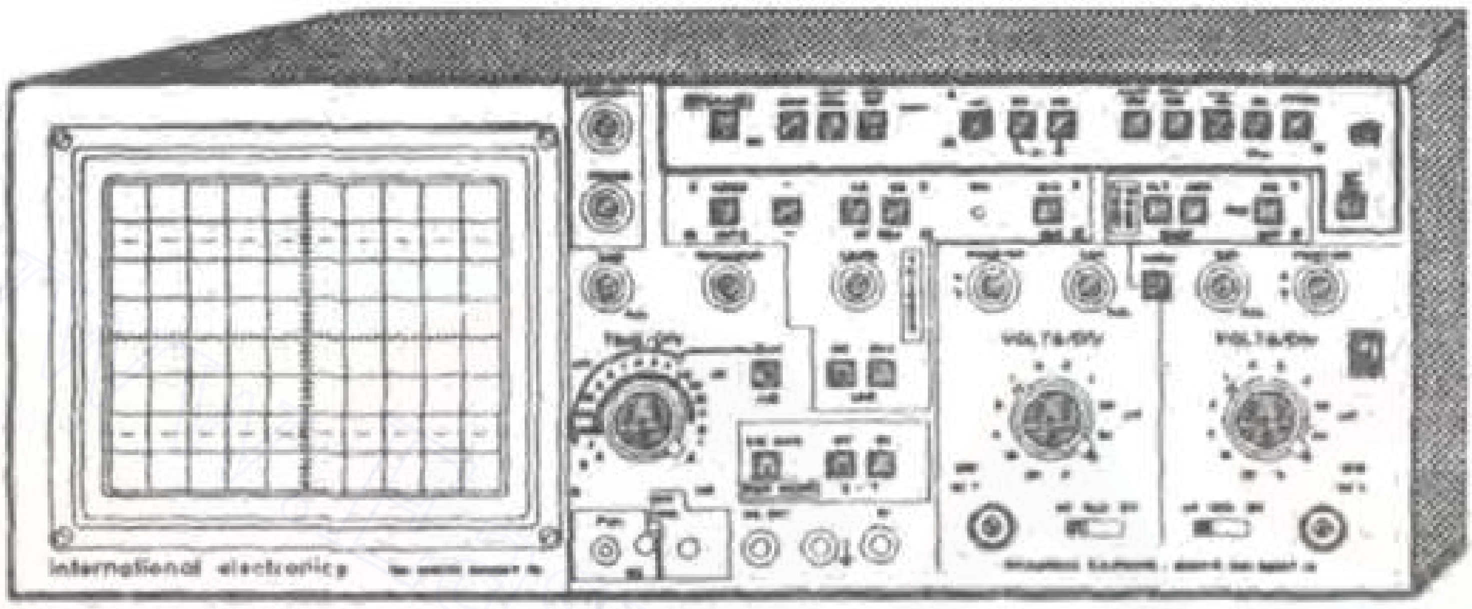


Fig. 7.52 25 MHz digital storage oscilloscope (IE-522) with computer interfacing [*Courtesy:* Inernational Electronics Ltd; Marketed: Signetics Electronics Ltd. Bombay]

The IE-522 Digital Storage Oscilloscopes (DSO) has the following features.

1. Sampling rate 20 Mega-samples per second per channel. Max. (simultaneous) capture of both channels.
2. Pre-trigger: 25%, 50%, 75%, for Single Shot, Roll normal.
3. Roll mode: (Continuous and Single Shot with Pre-trigger of 25%, 50%, 75%)
4. Single Shot (0.5 μs Single shot @ 10 pts./div resolution with pre-trigger 25%, 50%, 75%)
5. Digital Sweep rate: 0.5 μs/cm to 50 sec/cm, (event as long as 8.33 minutes can be captured)
6. Computer built in Interface: (RS 232 Serial port and Centronics Parallel interface).

FIBRE OPTIC CRT RECORDING OSCILLOSCOPE 7.33

The familiar CRT oscilloscope has an extremely HF response, but permanent records, normally photography of the screen, cannot be taken, since they are time limited to one sweep.

By combining a special fibre optic CRT with an oscillograph type paper drive (which passes the paper over the CRT face, where it is exposed by light from the CRT phosphor), a recording oscilloscope with uniquely useful characteristics is obtained. If the paper is held still, conventional CRO operation allows single sweep, i.e. amplitude versus time and X-Y recording of signals from dc to 1

MHz, much like the use of standard camera recording techniques, except that ordinary direct print oscillograph paper is used.

By employing a CRT sweep and simultaneous paper drive (speeds up to about 100 in/s can be selected), the 1 MHz frequency response is retained. Additionally, we can now get as many records as we wish, because they are simply stacked one above the other on the recording paper. This technique gives an equivalent paper speed of 40,000 in/s.

Time skew, resulting from paper motion during a single CRT sweep, is corrected electronically, but there will be small gaps in the data between sweep because of the CRT sweep retrace time.

Since the CRT allows beam intensity (z-axis) modulation, the instrument can produce grey-scale pictures, such as video images.

A multichannel version utilises sampling techniques to obtain direct current to 5 kHz response for up to 18 channels of data.

Digitest Lab The Digitest Lab (IE-549) shown in Fig. 7.53 has the following features,

1. 25 MHz Dual Trace Oscilloscope with rectangular CRT
2. Digital Storage Oscilloscope-5 Mega-samples/second Sampling Rate
3. Frequency Counter-70 MHz : will read internal, external and function generator frequency
4. 100 kHz Function Generator—Sine, Square, Triangular
5. Power Supply : + 12, – 12 V/0.2 A and 5 V/1 A
6. Component Tester: Test capacitors, Resistors, Diodes, etc.
7. Continuity Tester:
   Test for breaks/shorts in PCB tracks and cable harnesses.
8. Curve Tracer:

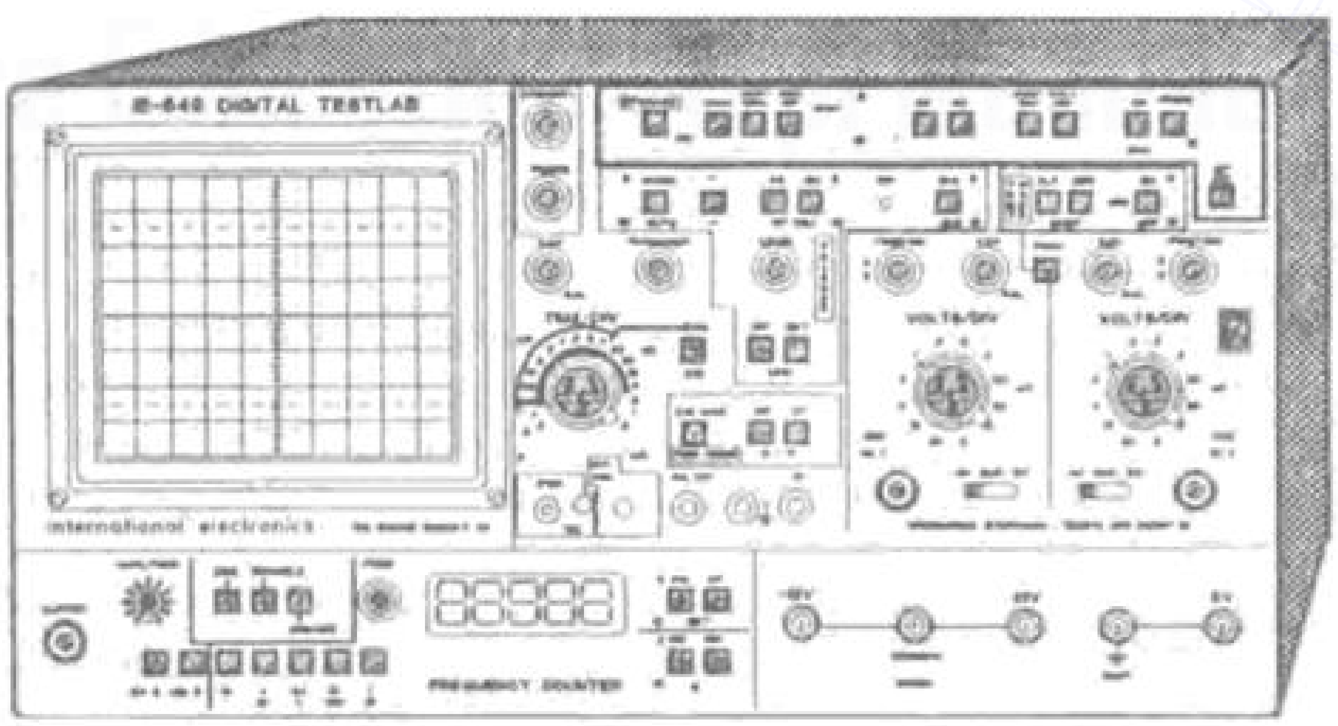


Fig. 7.53 8 in 1 digitest lab [IE-549]
[*Courtesy:* International Electronics Ltd.] [Marketed: Signetics Electronics Ltd.]

Test semiconductors like Transistors, FET's, Diodes, etc. You can check for selected parameters and obtain matched pairs of devices for production and service.

OSCILLOSCOPE OPERATING PRECAUTIONS 7.34

In addition to the general safety precautions, the following specific precautions should be observed when operating any type of oscilloscope. Most of the precautions also apply to recorders.

1. Always study the instruction manual of any oscilloscope with which you are not familiar even if you have had considerable experience with oscilloscopes.
2. Use the procedure of Section 7.35 to place the oscilloscope in operation. It is a good practice to go through the procedures each time the oscilloscope is used. This is especially true when the oscilloscope is used by other persons. The operator cannot be certain that position, focus and (especially) intensity control are at safe positions and the oscilloscope CRT could be damaged by switching on immediately.
3. As for any cathode ray tube device (such as a TV receiver), the CRT spot should be kept moving on the screen. If the spot must remain in one position, keep the intensity control as low as possible.
4. Always keep the minimum intensity necessary for good viewing.
5. If possible, avoid using the oscilloscope in direct sunlight or in a brightly lighted room. This will permit a low intensity setting. If the oscilloscope must be used in bright light, use the viewing hood.
6. Make all measurements in the centre area of the screen; even if the CRT is flat, there is a chance of reading errors caused by distortion at the edges.
7. Use only shielded probes. Never allow your fingers to slip down to the metal probe tip when the probe is in contact with a hot circuit.
8. Avoid operating an oscilloscope in a strong magnetic field. Such fields can causes distortion of the display. Most quality oscilloscopes are well shielded against magnetic interference. However, the face of the CRT is exposed and is subjected to magnetic interference.
9. Most oscilloscopes and their probes have some maximum input voltage specified in the instruction manual. Do not exceed this maximum value. Also, do not exceed the maximum line voltage or use a different power frequency.
10. Avoid operating the oscilloscope with the shield or case removed. Besides the danger of exposing high voltage circuits (several thousand volts are used on the CRT), there is the hazard of the CRTs imploding and scattering glass at high velocity.
11. Avoid vibration and mechanical shock. Like most electronic equipment, an oscilloscope is a delicate instrument.
12. If an internal fan or blower is used, make sure that it is operating. Keep ventilation air filters clean.
13. Do not attempt repair of an oscilloscope unless you are a qualified instrument technician. If you must adjust any internal circuits, follow the instruction manual.

14. Study the circuit under test before making any test connections. Try to match the capability of the oscilloscope to the circuit under test. For example, if the circuit has a range of measurements to be made (ac, dc, RF, pulse), you must use a wide-band DC oscilloscope, with a low capacitance probe and possibly a demodulator probe. Do not try to measure 3 MHz signals with a 100 kHz bandwidth oscilloscope. On the other hand, it is wasteful to use a dual trace 50 MHz laboratory oscilloscope to check out the audio sections of transistor radios.

PLACING AN OSCILLOSCOPE IN OPERATION 7.35

After the setup instruction of the oscilloscope manual have been digested, they can be compared with the following general or typical procedures.

1. Set the power switch to Off
2. Set the internal recurrent sweep to OFF
3. Set the focus, gain, intensity and sync controls to their lowest position (usually fully counterclockwise)
4. Set the sweep selector to External
5. Set the vertical and horizontal position controls to their approximate midpoint
6. Set the power switch to ON. It is assumed that the power cord has been connected.
7. After a suitable warmup period (as recommended by the manual) adjust the intensity control until the trace spot appears on the screen. If a spot is not visible at any setting of the intensity control, the spot is probably off screen (unless the oscillsocope is defective). If necessary, use the vertical and horizontal position controls to bring the spot into view. Always use the longest setting of the intensity control needed to see the spot, so as to prevent burning of the oscilloscope screen.

   It should be noted that dc oscilloscopes need longer warmup times than ac oscilloscopes because of drift problems associated with dc amplifiers.
8. Set the focus control for a sharp fine dot
9. Set the vertical and horizontal position controls to centre the spot on the screen
10. Set the sweep selector to Internal. This should be the linear internal sweep, if more than one internal sweep is available.
11. Set the internal recurrent sweep to ON. Set the sweep frequency to any frequency, or a recurrent rate higher than 100 Hz.
12. Adjust the horizontal gain control and check that the spot is expanded into a horizontal trace or line. The line length should be controllable by adjusting the horizontal gain control.
13. Return the horizontal gain control to zero, set the internal recurrent sweep to OFF.
14. Set the vertical gain control to its approximate midpoint, and touch the vertical input with you finger. The stray signal pickup should cause the

spot to be deflected vertically into a trace of line. Check that the line length is controllable by adjustment of the vertical gain control.

15. Return the vertical gain control to zero (or its lowest setting).
16. Set the internal recurrent sweep to ON. Advance the horizontal gain control to expand the spot into a horizontal line.
17. If required, connect a probe to the vertical input.
18. The oscilloscope should now be ready for immediate use. Depending on the test to be performed the oscilloscope may require calibration.

Review Questions

1. List the major components of a CRT.
2. What does the term phosphorescence mean?
3. Explain the principle of operation of a single beam CRO.
4. Draw the basic block diagram of an oscilloscope and state the functions of each block.
5. How is an electron beam focused onto a fine spot on the face of the CRT.
6. Why are the operating voltages of a CRT arranged so that the deflection plates are at nearly ground potential?
7. How is the vertical axis of an oscilloscope deflected? How does it differ from the horizontal axis?
8. How does the X-shift and Y-shift function.
9. Explain the function of a trigger circuit.
10. State the function of a delay line used in the vertical section of an oscilloscope.
11. List the various controls on the front panel of a CRO. State the function of various controls on the front panel of a CRO.
12. State the need of a time base generator.
13. Describe with a diagram the operation of a continuous sweep generator. List the drawbacks of a continuous sweep generator.
14. Explain with a diagram the operation of a triggered sweep generator.
15. List the advantages of using negative supply in a CRO.
16. Define intensity, focus and astigmatism.
17. Describe with a diagram the operation of a vertical amplifier. State the function of using FET stage in the vertical amplifier.
18. State the advantages of dual trace over dual beam?
19. Describe with diagram the operation of a dual beam CRO.
20. Explain the working principle of a dual trace CRO.
21. Describe with a diagram and waveforms the operation of a dual trace CRO in alternate and Chop mode. State the functions of each block.
22. How does alternate sweep compare with chopped sweep? When would one method be selected over the other?
23. State the function of the electronic switch. Explain with a diagram the working of an electronic switch.
24. Explain with a diagram the operation of a dual trace in X-Y mode.
25. Compare dual beam and dual trace CRO.
26. Explain with diagram the operation of a delayed sweep CRO. State the advantages of using delayed sweep CRO.

27. How does the sampling CRO increase the apparent frequency response of an oscilloscope.
28. Describe with diagram the operation of a sampling CRO. State the function of the staircase generator used in a sampling CRO.
29. Explain with a diagram the principle of analog storage CRO.
30. What is the speciality of a storage CRO.
31. Describe with a diagram the operation of an analog storage CRO.
32. State the advantages and disadvantages of a phosphor storage oscilloscope.
33. Describe with a block diagram the operation of a digital storage CRO. State the functions of each block.
34. Explain how frequency can be measured by a CRO using lissajous figures.
35. Explain with a diagram how frequency can be measured using spot wheel method. Explain with a diagram how frequency can be measured using a gear wheel method.
36. Compare the spot wheel method with that of the gear wheel method.
37. Explain with a diagram how CRO can be used to check diodes, inductors and capacitors.
38. State the standard specifications of a simple CRO.
39. State the function of a probe. State the function and explain with a diagram the operation of a 10:1 probe.
40. Compare passive probes with active probes.
41. State the advantages of using a probe.
42. State the function of attenuators in CRO.
43. What do you understand by compensation in attenuators? Explain with a diagram the operation of a simple compensated attenuator.
44 State the various applications of an oscilloscope.

Multiple Choice Questions

1. Post deflection acceleration is used to
   (a) enhance the intensity of the beam
   (b) focus the beam
   c) repel the electron beam
   (d) increase the velocity of the electron beam
2. Trigger pulses in the CRO are used
   (a) to generate high voltage required for the CRT
   (b) to synchronise the input with the time base generator
   (c) to synchronise the input and the vertical amplifier
   (d) to generate low voltages required for the CRT
3. The function of the sync section in CRO is
   (a) to match the horizontal sweep rate with the frequency of the vertical signal
   (b) to start the horizontal sweep at the same relative point on the vertical signal
   (c) to adjust the intensity control
   (d) to control the gain of the amplifier
4. The amplitude read on CRO set of 1 V/div is 1.5 cm on the vertical axis. The value of amplitude in V is
   (a) 1.5 V (b) 5 V
   (c) 1 V (d) 0.15 V
5. The distance between two peaks measured on the *X*-axis is 2 cm, at 1 ms/div. The frequency of the signal is
   (a) 50 Hz (b) 5 Hz
   (c) 1 kHz (d) 500 Hz

6. A dual beam CRO uses
   (a) electronic switch
   (b) two electron guns
   (c) one electron gun
   (d) two time base generator circuits
7. A dual trace CRO uses
   (a) one electron gun
   (b) two electron guns
   (c) two pairs of VDPs
   (d) two pairs of HDPs
8. An electronic switch is used in a
   (a) single beam CRO
   (b) dual beam CRO
   (c) dual Trace CRO
   (d) sampling CRO
9. A sampling CRO is used for
   (a) HF (b) VLF (c) VHF (d) LF
10. An analog storage CRO is used for displaying waveforms in the frequency range of
   (a) VHF (b) VLF (c) HF (d) LF

Practice Problems

1. A CRO with a sensitivity of 5 V/cm is used. An ac voltage is applied to the y-input. A 10 cm long straight line is observed. Determine the ac voltage.
2. The Lissajous pattern on an CRO is stationary and has five horizontal and two vertical tangencies. The frequency of the horizontal input is 1000 Hz. Determine the frequency of vertical input.
3. A CRO is set to a time base of 0.1 ms/cm with a 10 cm amplitude. Sketch the display of the pulse signal waveform with a pulse repetition rate of 2000 Hz and a duty cycle of 25%.

Further Reading

1. Refuse P. Turner, Practical Oscilloscope Handbook, Vol. 2, D.B. Taraporewala Sons & Co., 1985.
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3. John D. Lenk, Handbook of Electronic Meters (Theory and Applications), D.B. Taraporewala Sons & Co., Prentice-Hall, 1980)
4. Oliver Cage, Electronic Measurements & Instrumentation, McGraw-Hill, 1975.
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Chapter 8

Signal Generators

INTRODUCTION 8.1

A signal generator is a vital component in a test setup, and in electronic troubleshooting and development, whether on a service bench or in a research laboratory. Signal generators have a variety of applications, such as checking the stage gain, frequency response, and alignment in receivers and in a wide range of other electronic equipment.

They provide a variety of waveforms for testing electronic circuits, usually at low powers. The term oscillator is used to describe an instrument that provides only a sinusoidal output signal, and the term generator to describe an instrument that provides several output waveforms, including sine wave, square wave, triangular wave and pulse trains, as well as an amplitude modulated waveform. Hence, when we say that the oscillator generates a signal, it is important to note that no energy is created; it is simply converted from a dc source into ac energy at some specific frequency.

There are various types of signal generator but several requirements are common to all types.

1. The frequency of the signal should be known and stable.
2. The amplitude should be controllable from very small to relatively large values.
3. Finally, the signal should be distortion-free

The above mentioned requirements vary for special generators, such as function generators, pulse, and sweep generators.

Various kinds of signals, at both audio and radio frequencies, are required at various times in an instrumentation system. In most cases a particular signal required by the instrument is internally generated by a self-contained oscillator. The oscillator circuit commonly appears in a fixed frequency form (e.g. when it provides a 1000 c/s excitation source for an ac bridge). In other cases, such as in a *Q*-meter, oscillators in the form of a variable frequency arrangement for covering *Q*-measurements over a wide range of frequencies, from a few 100 kHz to the MHz range, are used.

In contrast with self-contained oscillators that generate only the specific signals required by the instrument, the class of generators that are available as separate instruments to provide signals for general test purposes are usually designated as signal generators. These AF and RF generators are designed to provide extensive and continuous coverage over as wide a range of frequencies as is practical.

In RF signal generators, additional provision is generally made to modulate the continuous wave signal to provide a modulated RF signal. The frequency band limits are listed in Table 8.1.

Table 8.1

Band	*Approximate Range*		
AF	20 Hz	–	20 kHz
RF	above 30 kHz		
VLF – Very Low Frequency	15	–	100 kHz
LF – Low Frequency	100	–	500 kHz
Broadcast	0.5	–	1.5 MHz
Video	DC	–	5 MHz
HF	1.5	–	30 MHz
VHF	30	–	300 MHz
UHF	300	–	3000 MHz
Microwave	beyond 3000 MHz (3 GHz)		

Most of the service type AF generators commonly cover from 20 Hz to 200 kHz, which is far beyond the AF range.

In more advanced laboratory types of AF generators, the frequency range extends quite a bit further e.g. a Hewlett Packard model covers 5 Hz – 600 kHz and a Marconi model generates both sine and square waves and has a very wide range of 10 Hz – 10 MHz.

FIXED FREQUENCY AF OSCILLATOR 8.2

In many cases, a self-contained oscillator circuit is an integral part of the instrument circuitry and is used to generate a signal at some specified audio frequency. Such a fixed frequency might be a 400 Hz signal used for audio testing or a 1000 Hz signal for exciting a bridge circuit.

Oscillations at specified audio frequencies are easily generated by the use of an iron core transformer to obtain positive feedback through inductive coupling between the primary and secondary windings.

VARIABLE AF OSCILLATOR 8.3

A variable AF oscillator for general purpose use in a laboratory should cover atleast the full range of audibility (20 Hz to 20 kHz) and should have a fairly constant pure sinusoidal wave output over the entire frequency range.

Hence, variable frequency AF generators for laboratory use are of the *RC* feedback oscillator type or Beat Frequency Oscillator (BFO) type.

BASIC STANDARD SIGNAL GENERATOR (SINE WAVE) 8.4

The sine wave generator represents the largest single category of signal generator. This instrument covers a frequency range from a few Hertz to many Giga-Hertz. The sine wave generator in its simplest form is given in Fig. 8.1.

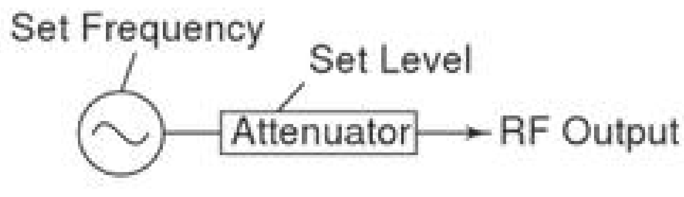


Fig. 8.1 Basic sine wave generator

The simple sine wave generator consists of two basic blocks, an oscillator and an attenuator. The performance of the generator depends on the success of these two main parts. The accuracy of the frequency, stability, and freedom from distortion depend on the design of the oscillator, while the amplitude depends on the design of the attenuator.

STANDARD SIGNAL GENERATOR 8.5

A standard signal generator produces known and controllable voltages. It is used as power source for the measurement of gain, signal to noise ratio (S/N), bandwidth, standing wave ratio and other properties. It is extensively used in the testing of radio receivers and transmitters.

The instrument is provided with a means of modulating the carrier frequency, which is indicated by the dial setting on the front panel. The modulation is indicated by a meter. The output signal can be Amplitude Modulated (AM) or Frequency Modulated (FM). Modulation may be done by a sine wave, square wave, triangular wave or a pulse. The elements of a conventional signal generator are shown in Fig. 8.2 (a).

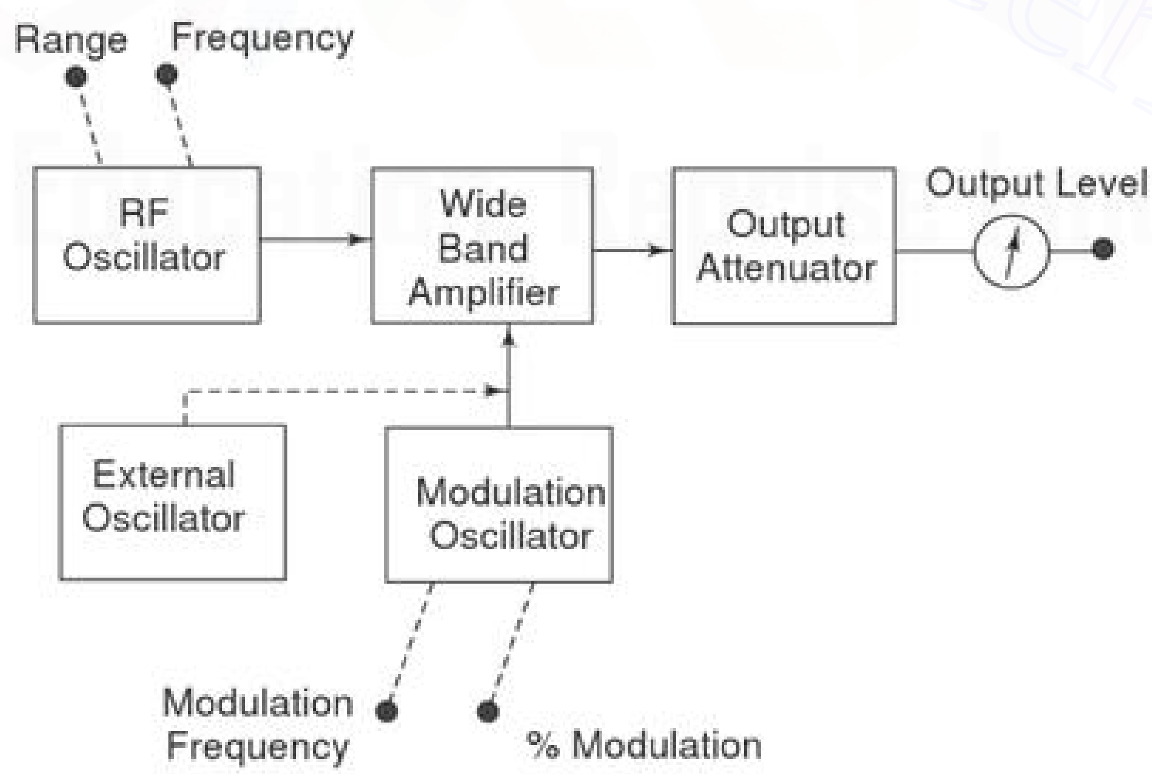


Fig. 8.2 (a) Conventional standard signal generator

The carrier frequency is generated by a very stable RF oscillator using an LC tank circuit, having a constant output over any frequency range. The frequency of oscillations is indicated by the frequency range control and the vernier dial setting. AM is provided by an internal sine wave generator or from an external source.

(Modulation is done in the output amplifier circuit. This amplifier delivers its output, that is, modulation carrier, to an attenuator. The output voltage is read by an output meter and the attenuator output setting.)

Frequency stability is limited by the LC tank circuit design of the master oscillator. Since range switching is usually accomplished by selecting appropriate capacitors, any change in frequency range upsets the circuit design to some extent and the instrument must be given time to stabilise at the new resonant frequency.

In high frequency oscillators, it is essential to isolate the oscillator circuit from the output circuit. This isolation is necessary, so that changes occurring in the output circuit do not affect the oscillator frequency, amplitude and distortion characteristics. Buffer amplifiers are used for this purpose.

Figure 8.2(b) illustrates a commercial AM/FM signal generator (IE900A) having a frequency range from 100 kHz – 110 MHz, along with a frequency counter and TTL output.

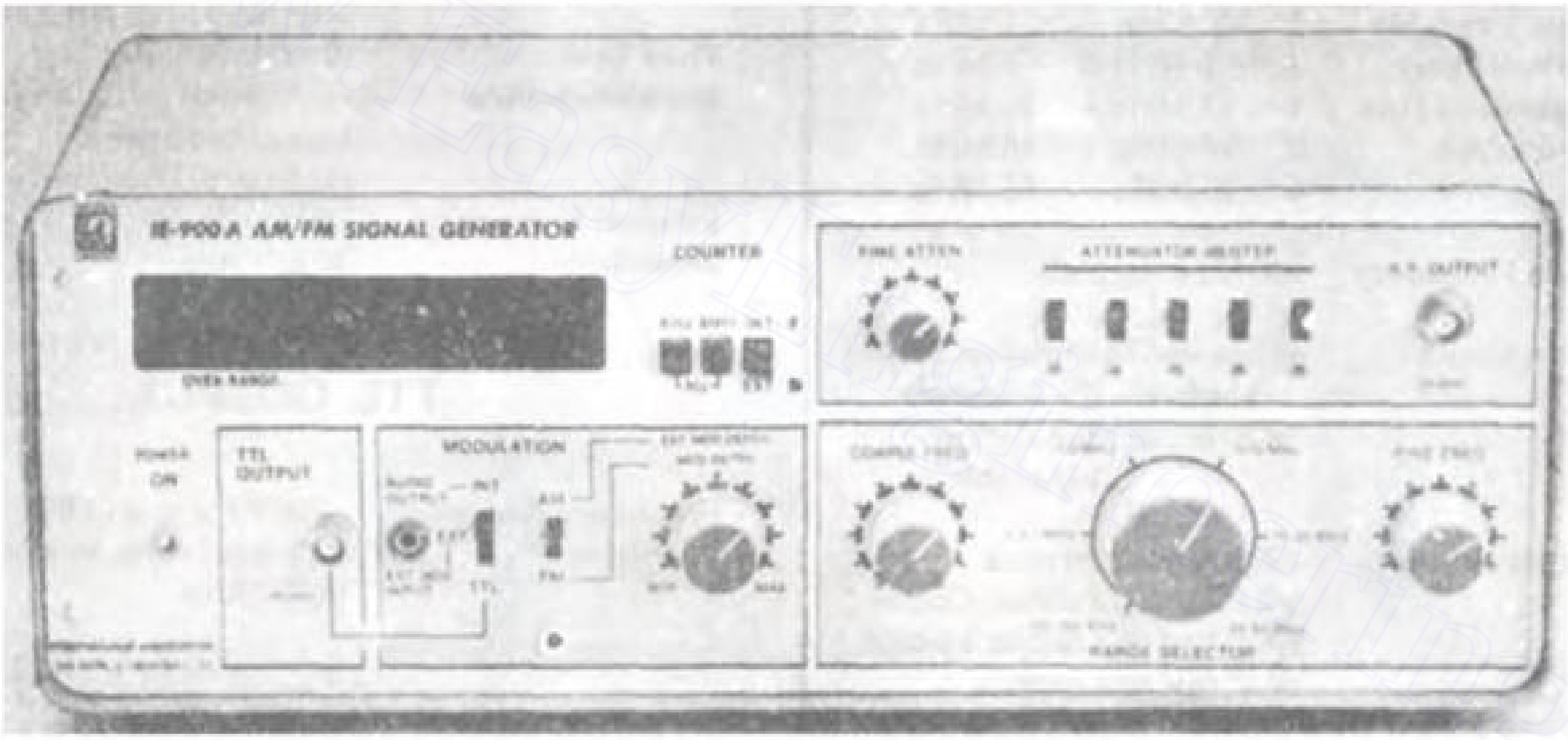


Fig. 8.2 (b) Commercial 110 MHz AM/FM Signal Generator (IE900A) along with a Frequency Counter [Courtesy: International Electronics Ltd., Bombay]

MODERN LABORATORY SIGNAL GENERATOR 8.6

To improve the frequency stability, a single master oscillator is optimally designed for the highest frequency range and frequency dividers are switched in to produce lower ranges. In this manner the stability of the top range is imparted to all the lower ranges.

The master oscillator is made insensitive to temperature variations and also to the influence of the succeeding stages by careful circuit design. Temperature compensation devices are used for any temperature changes. The block diagram of the modern standard signal generator is given in Fig. 8.3.

The highest frequency range of 34 – 80 MHz, is passed through B_1, an untuned buffer amplifier. B_2 and B_3 are additional buffer amplifiers and A is the main amplifier. The lowest frequency range produced by the cascaded frequency divider (9 frequency dividers of 2:1 ratio are used), is the highest frequency range divided by 512, or 2^9, or 67 – 156 kHz. Thus, the frequency stability of the highest range is imparted to the lower frequency ranges.

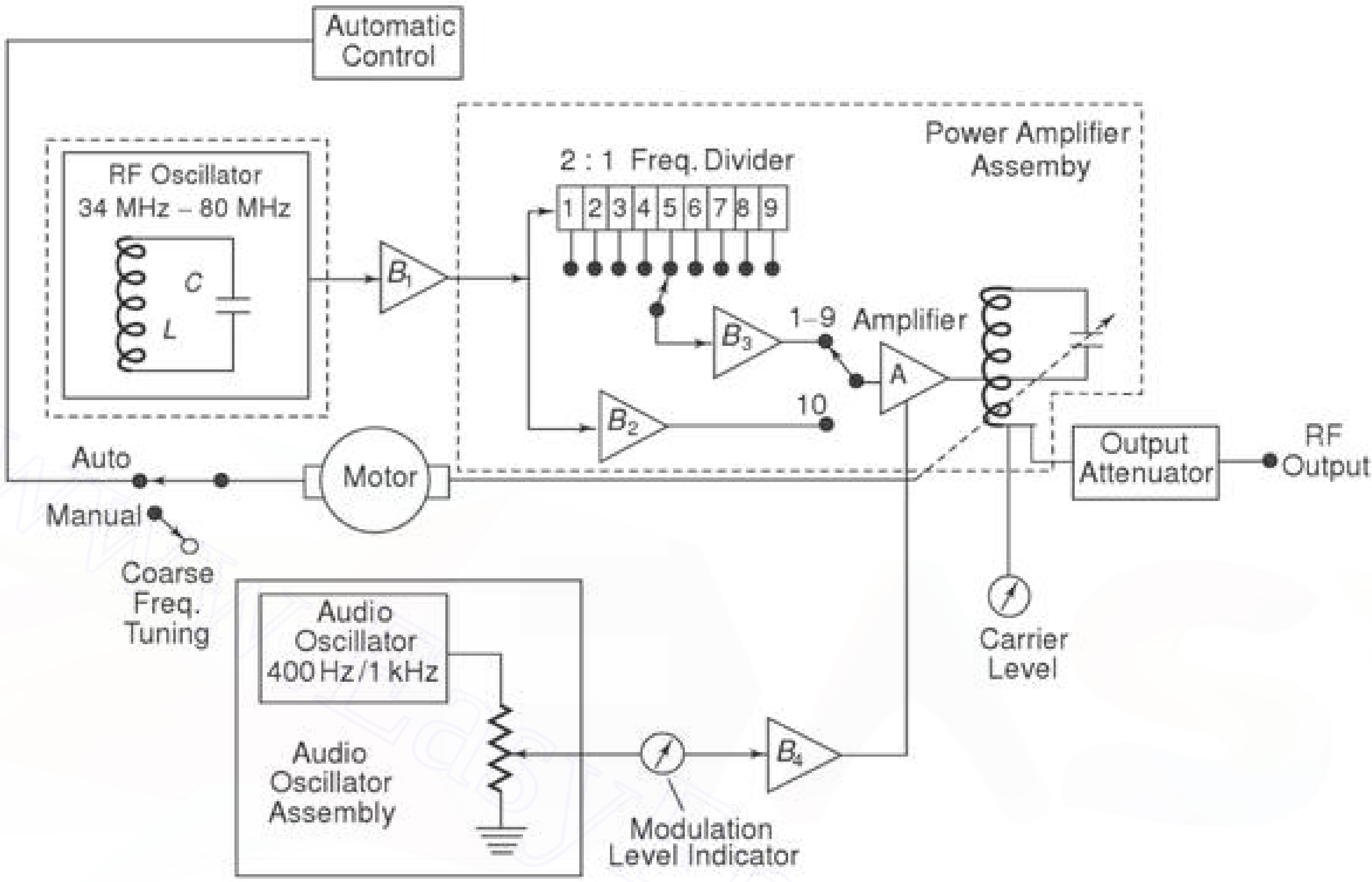


Fig. 8.3 Modern signal generator

The use of buffer amplifiers provides a very high degree of isolation between the master oscillator and the power amplifier, and almost eliminates all the frequency effects (distortion) between the input and output circuits, caused by loading.

Range switching effects are also eliminated, since the same oscillator is used on all bands. The master oscillator is tuned by a motor driven variable capacitor. For fast coarse tuning, a rocker switch is provided, which sends the indicator gliding along the slide rule scale of the main frequency dial at approximately 7% frequency changes per second. The oscillator can then be fine tuned by means of a large rotary switch (control), with each division corresponding to 0.01% of the main dial setting.

The master oscillator has both automatic and manual controllers. The availability of the motor driven frequency control is employed for programmable automatic frequency control devices.

Internal calibration is provided by the 1 MHz crystal oscillator. The small power consumption of the instruments makes it relatively easy to obtain excellent regulation and Q stability with very low ripple. The supply voltage of the master oscillator is regulated by a temperature compensated reference circuit.

The modulation is done at the power amplifier stage. For modulation, two internally generated signals are used, that is, 400 Hz and 1 kHz. The modulation level may be adjusted up to 95% by a control device. Flip-flops can be used as frequency dividers to get a ratio of 2:1.

AF SINE AND SQUARE WAVE GENERATOR 8.7

The block diagram of an AF Sine-Square wave audio oscillator is illustrated in Fig. 8.4.

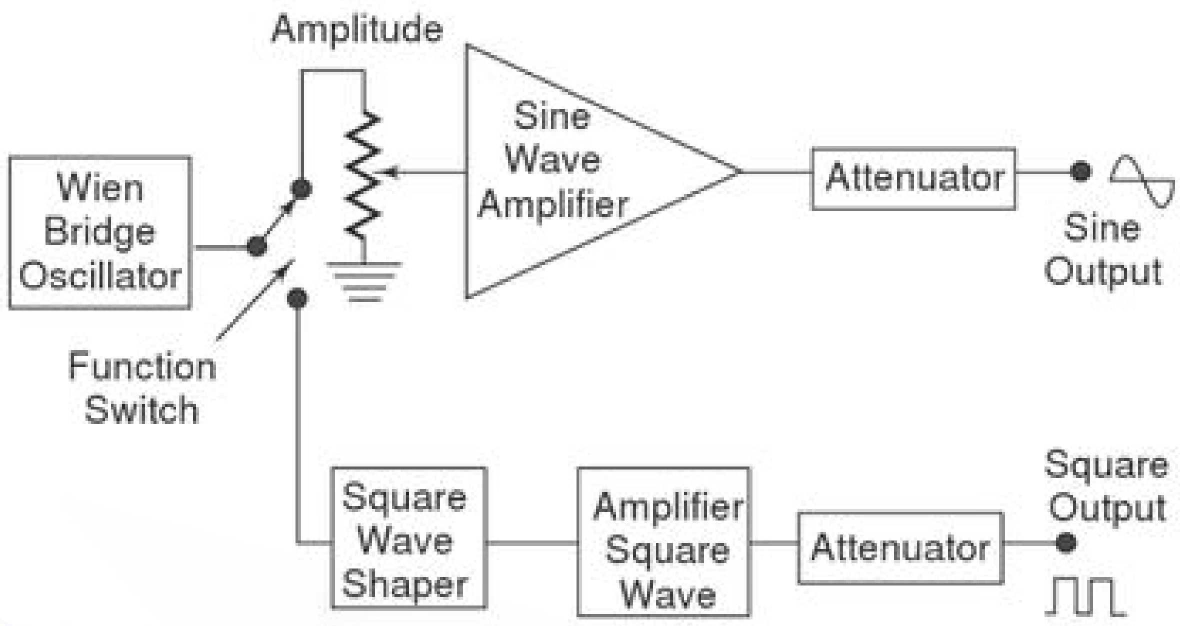


Fig. 8.4 AF sine and square wave generator

The signal generator is called an oscillator. A Wien bridge oscillator is used in this generator. The Wien bridge oscillator is the best for the audio frequency range. The frequency of oscillations can be changed by varying the capacitance in the oscillator. The frequency can also be changed in steps by switching in resistors of different values.

The output of the Wien bridge oscillator goes to the function switch. The function switch directs the oscillator output either to the sine wave amplifier or to the square wave shaper. At the output, we get either a square or sine wave. The output is varied by means of an attenuator.

The instrument generates a frequency ranging from 10 Hz to 1 MHz, continuously variable in 5 decades with overlapping ranges. The output sine wave amplitude can be varied from 5 mV to 5 V (rms).The output is taken through a push-pull amplifier. For low output, the impedance is 600Ω. The square wave amplitudes can be varied from 0 – 20 V (peak). It is possible to adjust the symmetry of the square wave from 30 – 70%. The instrument requires only 7 W of power at 220 V – 50 Hz.

The front panel of a signal generator consists of the following.

1. *Frequency selector* It selects the frequency in different ranges and varies it continuously in a ratio of 1 : 11. The scale is non-linear.
2. *Frequency multiplier* It selects the frequency range over 5 decades, from 10 Hz to 1 MHz.
3. *Amplitude multiplier* It attenuates the sine wave in 3 decades, × 1, × 0.1 and × 0.01.
4. *Variable amplitude* It attenuates the sine wave amplitude continuously.
5. *Symmetry control* It varies the symmetry of the square wave from 30% to 70%.
6. *Amplitude* It attenuates the square wave output continuously.
7. *Function switch* It selects either sine wave or square wave output.

8. *Output available* This provides sine wave or square wave output.
9. *Sync* This terminal is used to provide synchronisation of the internal signal with an external signal.
10. On-Off Switch

FUNCTION GENERATOR 8.8

A function generator produces different waveforms of adjustable frequency. The common output waveforms are the sine, square, triangular and sawtooth waves. The frequency may be adjusted, from a fraction of a Hertz to several hundred kHz.

The various outputs of the generator can be made available at the same time. For example, the generator can provide a square wave to test the linearity of an amplifier and simultaneously provide a sawtooth to drive the horizontal deflection amplifier of the CRO to provide a visual display.

Capability of Phase Lock The function generator can be phase locked to an external source. One function generator can be used to lock a second function generator, and the two output signals can be displaced in phase by adjustable amount.

In addition, the fundamental frequency of one generator can be phase locked to a harmonic of another generator, by adjusting the amplitude and phase of the harmonic, almost any waveform can be generated by addition.

The function generator can also be phase locked to a frequency standard and all its output waveforms will then have the same accuracy and stability as the standard source.

The block diagram of a function generator is illustrated in Fig. 8.5. Usually the frequency is controlled by varying the capacitor in the LC or RC circuit. In this instrument the frequency is controlled by varying the magnitude of current which drives the integrator. The instrument produces sine, triangular and square waves with a frequency range of 0.01 Hz to 100 kHz.

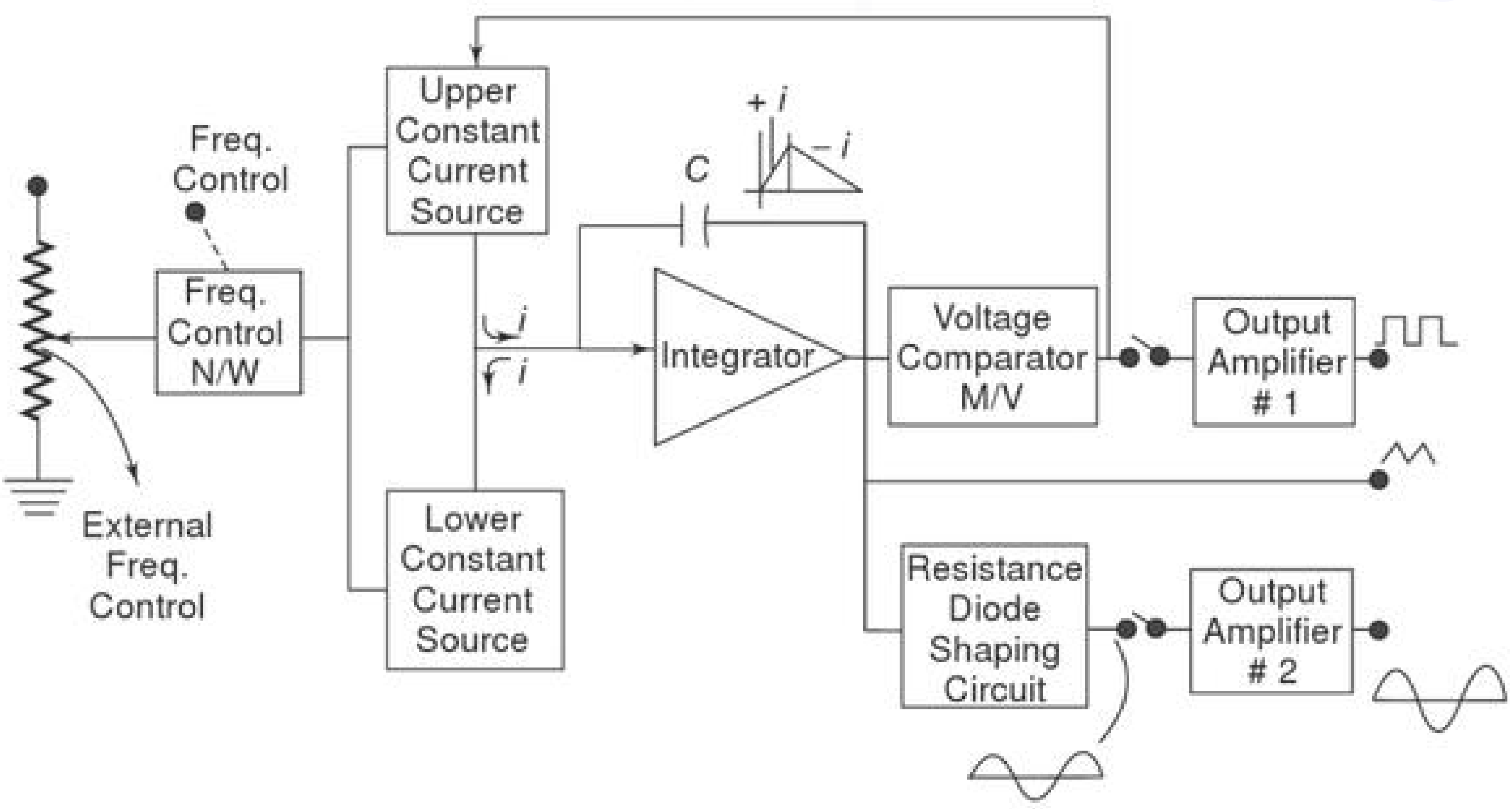


Fig. 8.5 Function generator

The frequency controlled voltage regulates two current sources. The upper current source supplies constant current to the integrator whose output voltage increases linearly with time, according to the equation of the output signal voltage.

$$e_{out} = -\frac{1}{C}\int_0^t i\,dt$$

An increase or decrease in the current increases or decreases the slope of the output voltage and hence controls the frequency.

The voltage comparator multivibrator changes states at a pre-determined maximum level of the integrator output voltage. This change cuts off the upper current supply and switches on the lower current supply.

The lower current source supplies a reverse current to the integrator, so that its output decreases linearly with time. When the output reaches a pre-determined minimum level, the voltage comparator again changes state and switches on the upper current source.

The output of the integrator is a triangular waveform whose frequency is determined by the magnitude of the current supplied by the constant current sources.

The comparator output delivers a square wave voltage of the same frequency. The resistance diode network alters the slope of the triangular wave as its amplitude changes and produces a sine wave with less than 1% distortion.

SQUARE AND PULSE GENERATOR (LABORATORY TYPE) 8.9

These generators are used as measuring devices in combination with a CRO. They provide both quantitative and qualitative information of the system under test. They are made use of in transient response testing of amplifiers. The fundamental difference between a pulse generator and a square wave generator is in the duty cycle.

$$\text{Duty cycle} = \frac{\text{pulse width}}{\text{pulse period}}$$

A square wave generator has a 50% duty cycle.

8.9.1 Requirements of a Pulse

1. The pulse should have minimum distortion, so that any distortion, in the display is solely due to the circuit under test.
2. The basic characteristics of the pulse are rise time, overshoot, ringing, sag, and undershoot.
3. The pulse should have sufficient maximum amplitude, if appreciable output power is required by the test circuit, e.g. for magnetic core memory. At the same time, the attenuation range should be adequate to produce small amplitude pulses to prevent over driving of some test circuit.

4. The range of frequency control of the pulse repetition rate (PRR) should meet the needs of the experiment. For example, a repetition frequency of 100 MHz is required for testing fast circuits. Other generators have a pulse-burst feature which allows a train of pulses rather than a continuous output.
5. Some pulse generators can be triggered by an externally applied trigger signal; conversely, pulse generators can be used to produce trigger signals, when this output is passed through a differentiator circuit.
6. The output impedance of the pulse generator is another important consideration. In a fast pulse system, the generator should be matched to the cable and the cable to the test circuit. A mismatch would cause energy to be reflected back to the generator by the test circuit, and this may be re-reflected by the generator, causing distortion of the pulses.
7. DC coupling of the output circuit is needed, when dc bias level is to be maintained.

The basic circuit for pulse generation is the asymmetrical multi-vibrator. A laboratory type square wave and pulse generator is shown in Fig. 8.6.

The frequency range of the instrument is covered in seven decade steps from 1 Hz to 10 MHz, with a linearly calibrated dial for continuous adjustment on all ranges.

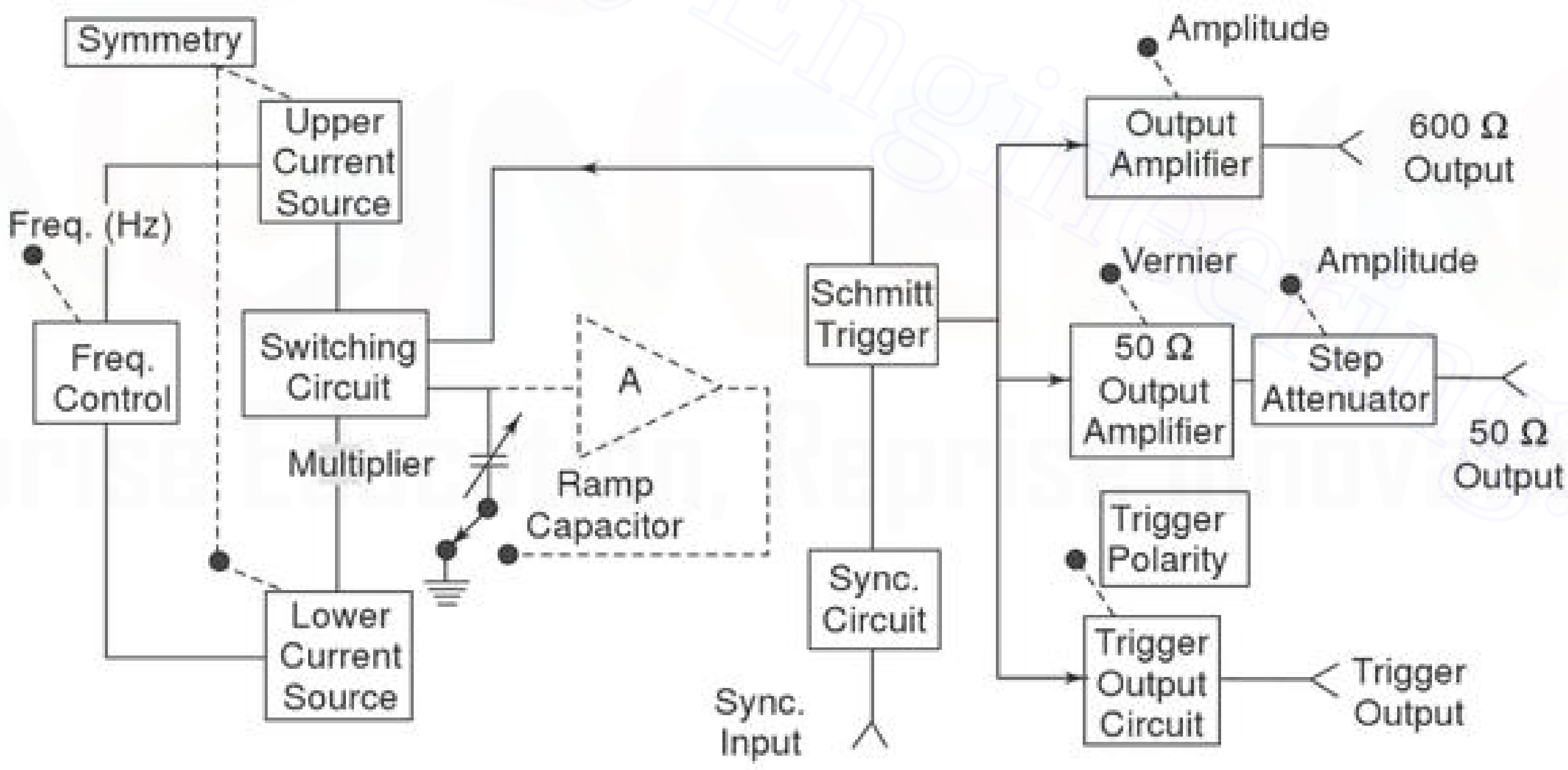


Fig. 8.6 Block diagram of a pulse generator

The duty cycle can be varied from 25 – 75%. Two independent outputs are available, a 50 Ω source that supplies pulses with a rise and fall time of 5 ns at 5 V peak amplitude and a 600 Ω source which supplies pulses with a rise and fall time of 70 ns at 30 V peak amplitude. The instrument can be operated as a free-running generator, or it can be synchronised with external signals.

The basic generating loop consists of the current sources, the ramp capacitor, the Schmitt trigger and the current switching circuit, as shown in Fig. 8.7.

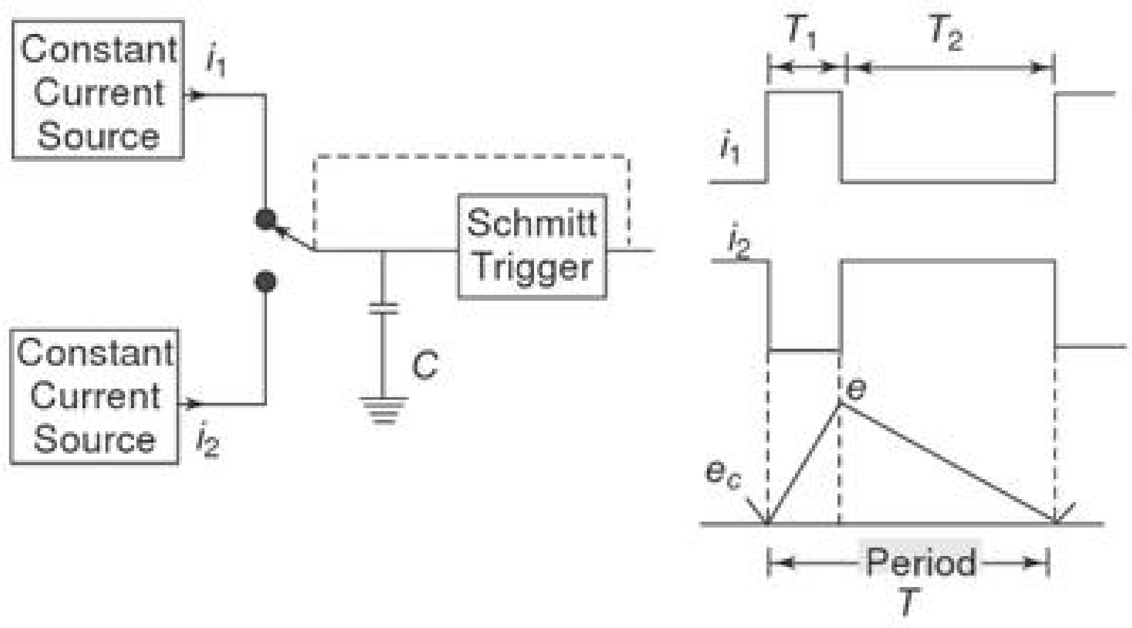


Fig. 8.7 Basic generating loop

The upper current source supplies a constant current to the capacitor and the capacitor voltage increases linearly. When the positive slope of the ramp voltage reaches the upper limit set by the internal circuit components, the Schmitt trigger changes state. The trigger circuit output becomes negative and reverses the condition of the current switch. The capacitor discharges linearly, controlled by the lower current source. When the negative ramp reaches a predetermined lower level, the Schmitt trigger switches back to its original state. The entire process is then repeated. The ratio i_1/i_2 determines the duty cycle, and is controlled by symmetry control. The sum of i_1 and i_2 determines the frequency. The size of the capacitor is selected by the multiplier switch.

The unit is powered by an internal supply that provides regulated voltages for all stages of the instrument.

RANDOM NOISE GENERATOR 8.10

A simplified block diagram used in the audio frequency range is shown in Fig. 8.8.

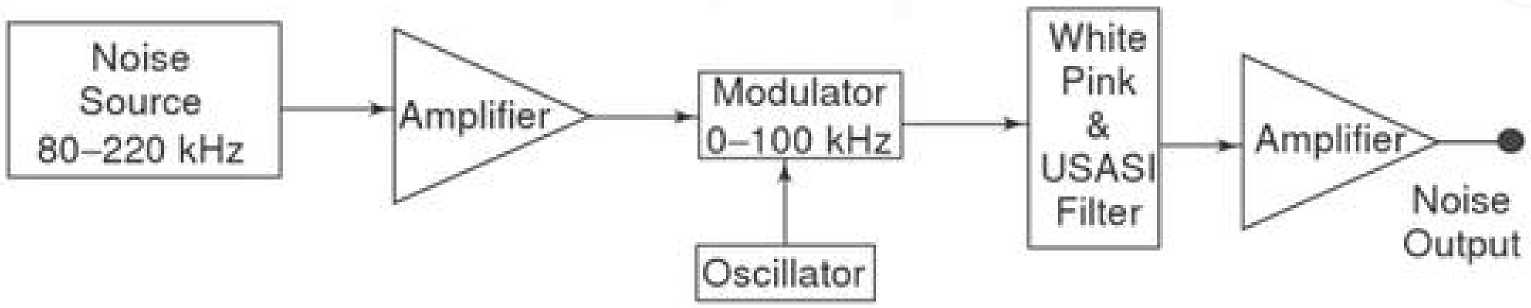


Fig. 8.8 Random noise generator

The instrument offers the possibility of using a single measurement to indicate performance over a wide frequency band, instead of many measurements at one frequency at a time. The spectrum of random noise covers all frequencies and is referred to as White noise, i.e. noise having equal power density at all frequencies (an analogy is white light). The power density spectrum tells us how the energy of a signal is distributed in frequency, but it does not specify the signal uniquely, nor does it tell us very much about how the amplitude of the signal varies with time. The spectrum does not specify the signal uniquely because it contains no phase information.

The method of generating noise is usually to use a semi conductor noise diode, which delivers frequencies in a band roughly extending from 80 – 220 kHz. The output from the noise diode is amplified and heterodyned down to the audio frequency band by means of a balanced symmetrical modulator. The filter arrangement controls the bandwidth and supplies an output signal in three spectrum choices, white noise, pink noise and Usasi noise.

From Fig. 8.9, it is seen that white noise is flat from 20 Hz to 25 kHz and has an upper cutoff frequency of 50 kHz with a cutoff slope of –12 dbs/octave.

Pink noise is so called because the lower frequencies have a larger amplitude, similar to red light. Pink noise has a voltage spectrum which is inversely proportional to the square root of frequency and is used in bandwidth analysis.

Usasi noise ranging simulates the energy distribution of speech and music frequencies and is used for testing audio amplifiers and loud speakers.

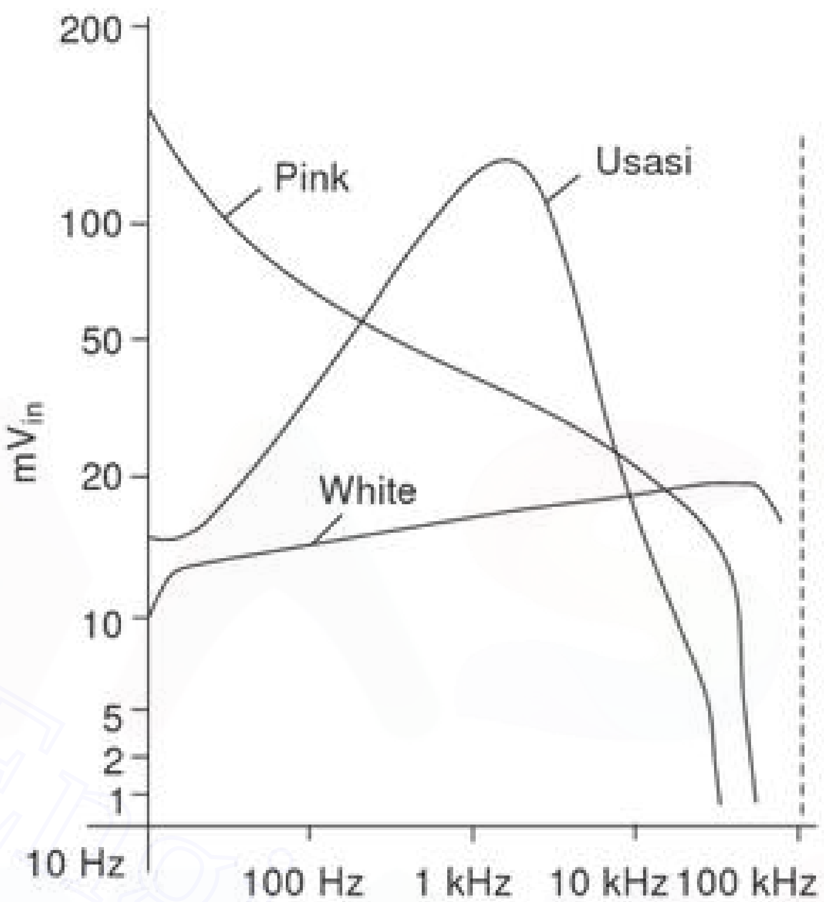


Fig. 8.9 Random noise generator

SWEEP GENERATOR 8.11

It provides a sinusoidal output voltage whose frequency varies smoothly and continuously over an entire frequency band, usually at an audio rate. The process of frequency modulation may be accomplished electronically or mechanically.

It is done electronically by using the modulating voltage to vary the reactance of the oscillator tank circuit component, and mechanically by means of a motor driven capacitor, as provided for in a modern laboratory type signal generator. Figure 8.10 shows a basic block diagram of a sweep generator.

The frequency sweeper provides a variable modulating voltage which causes the capacitance of the master oscillator to vary. A representative sweep rate could be of the order of 20 sweeps/second. A manual control allows independent adjustment of the oscillator resonant frequency.

The frequency sweeper provides a varying sweep voltage for synchronisation to drive the horizontal deflection plates of the CRO. Thus the amplitude of the response of a test device will be locked and displayed on the screen.

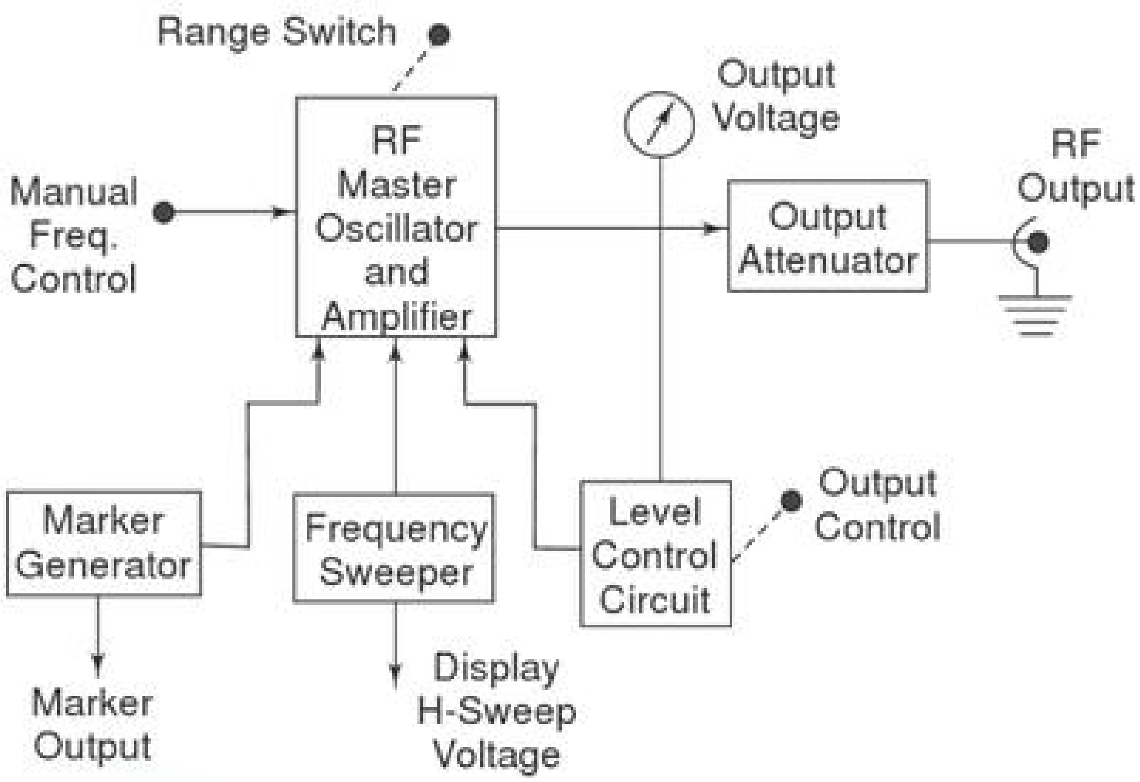


Fig. 8.10 Sweep generator

To identify a frequency interval, a marker generator provides half sinusoidal waveforms at any frequency within the sweep range. The marker voltage can be added to the sweep voltage of the CRO during alternate cycles of the sweep voltage, and appears superimposed on the response curve.

The automatic level control circuit is a closed loop feedback system which monitors the RF level at some point in the measurement system. This circuit holds the power delivered to the load or test circuit constant and independent of frequency and impedance changes. A constant power level prevents any source mismatch and also provides a constant readout calibration with frequency.

TV SWEEP GENERATOR 8.12

An RF generator, when used for alignment and testing of the RF and IF stages of a TV receiver, permits recording of circuit performance at one frequency at a time. Therefore, plotting the total response curve point by point over the entire channel bandwidth becomes a laborious process and takes a long time. To overcome this difficulty, a special RF generator, known as a sweep generator, is used. It delivers RF output voltage at a constant amplitude which sweeps across a range of frequencies and continuously repeats at a predetermined rate.

The sweep generator is designed to cover the entire VHF and UHF range. Any frequency can be selected as the centre frequency by a dial on the front panel of the instrument.

Frequency sweep is obtained by connecting a varactor diode across the HF oscillator circuits. A modified triangular voltage at 50 Hz is used to drive the varactor diode. Thus the frequency sweeps on either side of the oscillator centre frequency, at the rate of driving voltage frequency. The amplitude of the driving voltage applied across the varactor diodes can be varied to control maximum frequency deviation on either side of the carrier frequency. This is known as the sweep width and can be adjusted to the desired value, up to a maximum of about ± 15 MHz. A width control is provided for this procedure.

Alignment Procedure The output of the sweep generator is connected to the input terminals of the tuned circuit under test.

The frequency and sweep width dials are adjusted to a sweep range which lies in the pass-band of the circuit. With an input signal of constant amplitude, the output voltage varies in accordance with the frequency gain characteristics of the circuit. The magnitude of the output voltage varies with time as the oscillator frequency sweeps back and forth through the centre frequency. The RF output is detected either by a video detector in the receiver or by a demodulator probe. The detected output varies at the sweep rate of 50 Hz and its instantaneous amplitude changes in accordance with the circuit characteristics. Thus the output signal is a low frequency signal at 50 Hz and can be displayed on an ordinary scope, provided the low frequency response of the vertical amplifier is flat, down to atleast 50 Hz.

In order to obtain a linear display of the detected signal on the CRO, the scope sweep voltage must vary accordingly and have a frequency of 50 Hz.

The basic circuit configuration used for the alignment of any tuned circuit with a sweep generator and scope is shown in Fig. 8.11.

The time base switch of the CRO is set on External and its horizontal input terminals are connected to the sweep output on the sweep generator. Thus, the application of a 50 Hz triangular voltage to the horizontal deflecting plates results in a linear display on the scope screen, both during trace and retrace periods.

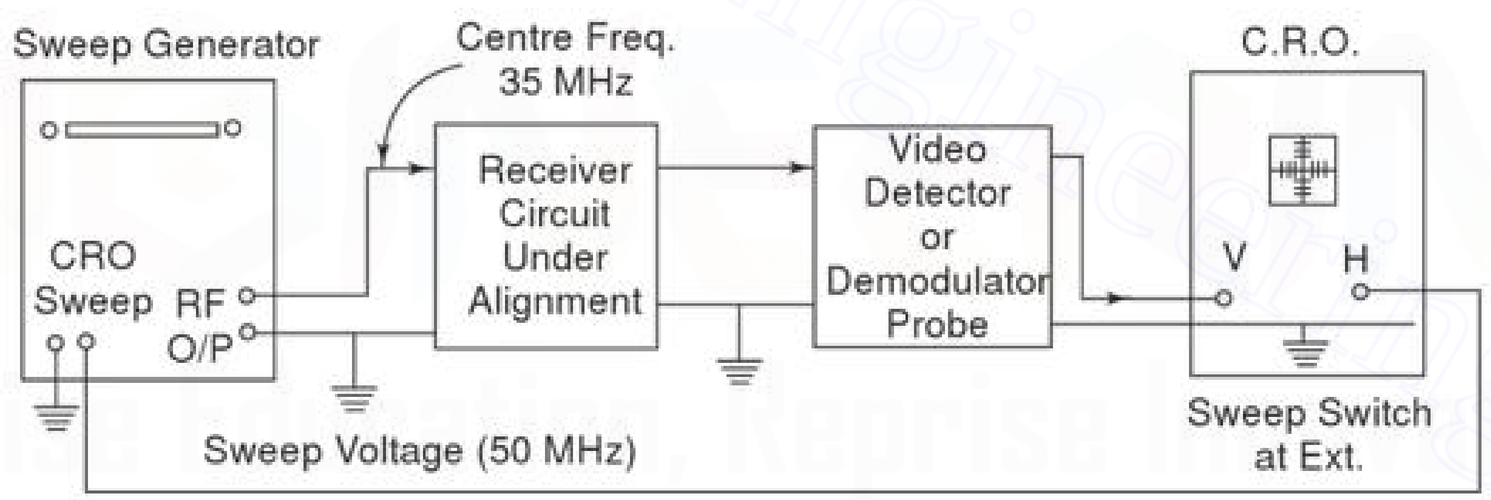


Fig. 8.11 Test Equipment connections for alignment of RF/IF sections of the receiver

MARKER GENERATOR 8.13

The sweep generator provides a visual display of the characteristics of the circuit or amplifier, but this is inadequate because it does not give any precise information of the frequency on the traced curve. For this, a separate RF generator, known as the Marker generator is used. This generator though essentially an RF signal generator in the VHF and UHF bands, is of much higher accuracy than other signal generators.

The output of the Marker generator is set at the desired frequency within the pass-band of the circuit under test.

As given in Fig. 8.12, the outputs from two generators are mixed together before being applied to the input terminals of the circuit under test.

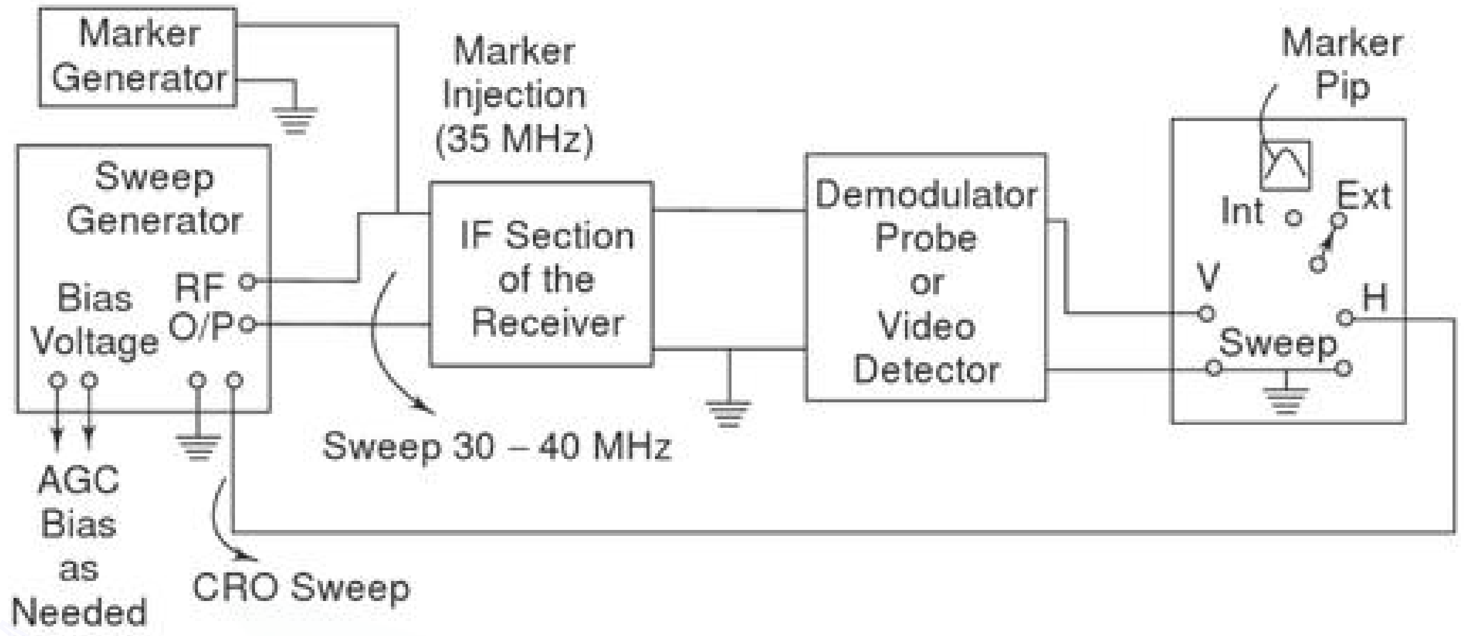


Fig. 8.12 Marker generator

The two signals are heterodyned to produce outputs at the sum and difference of two frequencies. These appear at the detector output and represent the amplitude characteristics of the circuit, because of the limited frequency response of the CRO vertical amplifier, the sum and difference frequency signals are produced when the sweep frequency varies over a wide range. When no difference frequency is produced, no vertical deflection is produced on the screen. However, as the frequency approaches and just crosses the marker frequency, the difference frequency signals which are produced, lie within the pass-band of the vertical amplifier. Thus, they produce a pip on the screen along the trace generated by the low frequency output of the detector. In order to get a sharp pip, a suitable capacitor is shunted across the vertical input terminals of the scope.

Since the pip is produced at the marker frequency, it can be shifted to any point on the response curve by varying the marker generator frequency.

The marker generator, besides providing dial controlled frequency, often has a provision to generate crystal controlled fixed frequency outputs at several important frequencies.

The additional frequency in a generator designed for a CCIR 625 lines system consists of the following.

31.4 MHz (Band-edge)
31.9 MHz (Trap-frequency)
33.4 MHz (Sound IF)
34.47 MHz (Colour IF)
36.15 MHz (Band centre)
38.9 MHz (Picture IF)
40.4 MHz (Trap frequency)
41.4 MHz (Band-edge)

These birdy-type markers can be switched in, either individually or simultaneously by the use of toggle switches on the front panel.

SWEEP-MARKER GENERATOR 8.14

Sweep and Marker generators were earlier manufactured as separate units. Now the two instruments are combined into a single instrument known as a Sweep-Marker generator.

This includes a built-in Marker adder for post-injection of the marker signal. Also provided is a variable dc bias source for feeding a fixed bias to the RF and IF sections of the receiver.

The frequency spectrum covered is in the VHF and UHF band ranges in both manual and auto modes. The RF output is about 0.5 V rms across a 75 Ω with a continuously variable attenuator, up to 50 db or 0 – 60 db in 10 db steps. The marker section provides crystal controlled output at all important frequencies. The output can be internally modulated with a 1 kHz tone when necessary. A demondulator probe, a balun and special cables with matched terminations are the additional accessories.

WOBBLUSCOPE 8.15

This instrument combines a Sweep generator, a Marker generator, and an oscilloscope, as shown in Fig. 8.13. It is a very useful unit for the alignment of RF, IF and video sections of a TV receiver. It may not have all the features of a high quality sweep generator but is an economical and compact piece of equipment specially designed for TV servicing. The oscilloscope usually has a provision for TV-V (vertical) and TV-H (horizontal) sweep modes. An RF output, down to 1 MHz, is available for video amplifier testing.

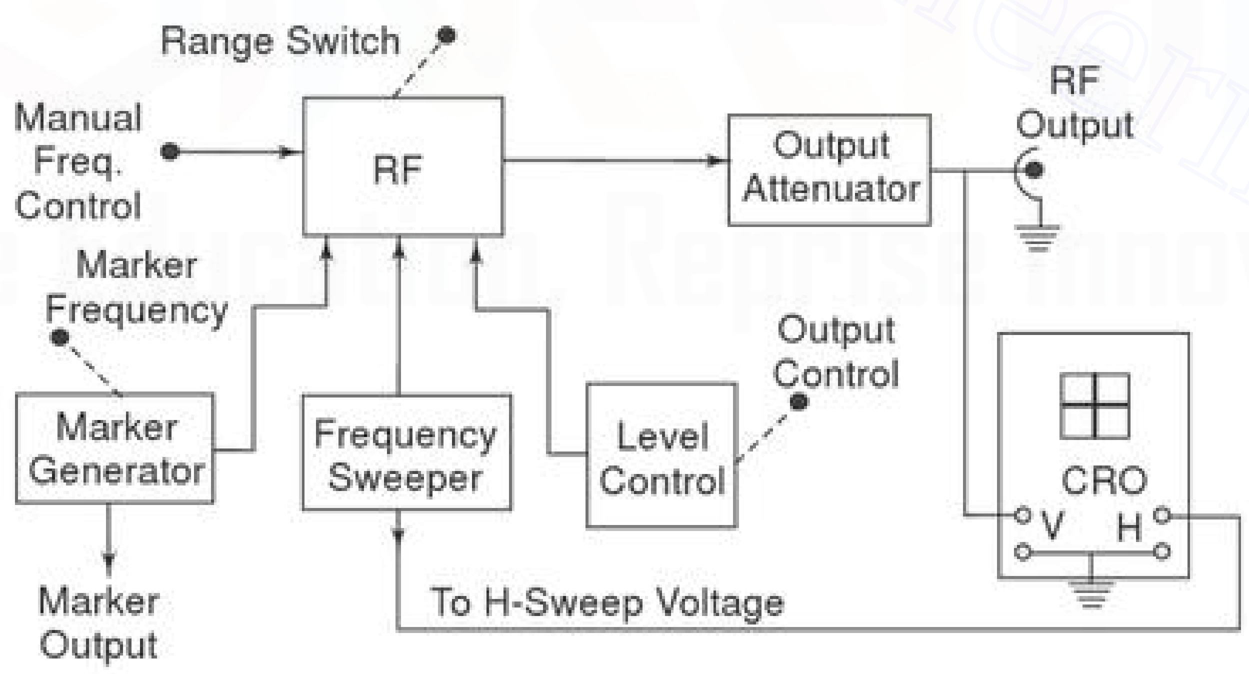


Fig. 8.13 Basic block diagram of a wobbluscope

VIDEO PATTERN GENERATOR 8.16

A pattern generator provides video signals directly, and with RF modulation, on standard TV channels for alignment, testing and servicing of TV receivers. The output signal is designed to produce simple geometric patterns like vertical and horizontal bars, checkerboard, cross-hatch, dots, etc.

These patterns are used for linearity and video amplifier adjustment. In addition to this, an FM sound signal is also provided in pattern generators for aligning sound sections of the receiver.

A simplified functional block diagram of a pattern cum sound signal generator is shown in Fig. 8.14.

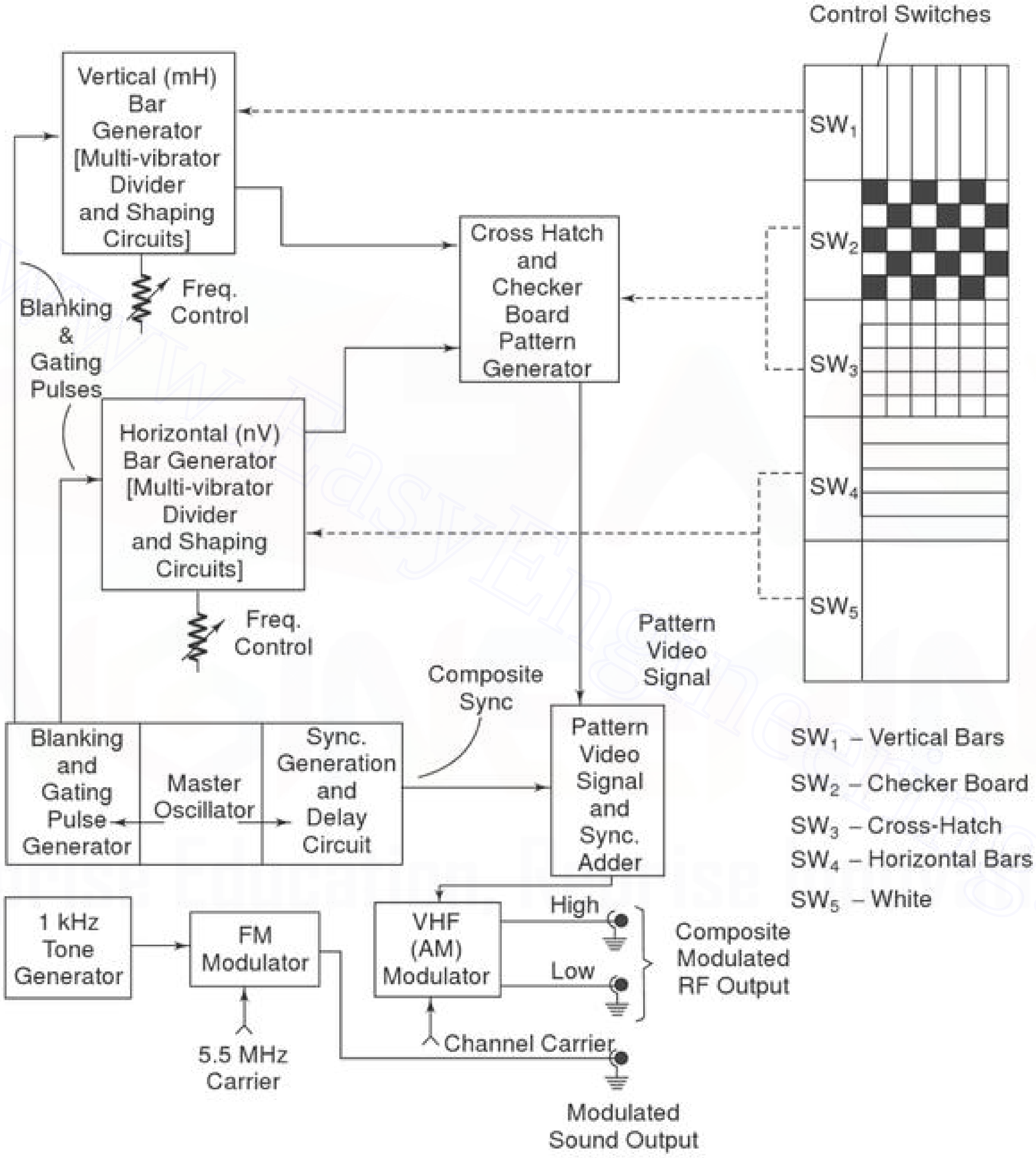


Fig. 8.14 Simplified functional block diagram of a pattern cum sound signal generator

The generator employs two stable chains of multivibrators, dividers and pulse shaping circuits, one below the line frequency to produce a series of horizontal bars, and another above 15625 Hz to produce vertical bars. The signals are modified into short duration pulses, which when fed to the video section of the receiver along with the sync pulse train, produce fine lines on the screen.

Multivibrators produce a square wave video signal at *m* times the horizontal frequency to provide *m* vertical black and white bars. After every *m* cycles, the horizontal blanking pulse triggers the multivibrators for synchronising the bar signal on every line. A control on the front panel of the pattern generator enables variation of multivibrators frequency to change the number of bars.

Similarly, square wave pulses derived either from 50 Hz mains or from the master oscillator are used to trigger another set of multivibrator to generate square wave video signals that are *n* times the vertical frequency. On feeding the video amplifier these produce horizontal black and white bars. The number of horizontal bars can also be varied by a potentiometer that controls the switching rate of the corresponding multivibrator. (The bar pattern signal is combined with the sync and blanking pulses in the video adder to produce composite video signals before being fed to the modulator). The provision of switches in the signal path of the two multivibrators enables the generation of various patterns. If both mH and nV switches are off, a blank white raster is produced. With only the mH switch on, vertical bars are produced, and with only the nV switch on, horizontal bars are generated. With both switches on, a cross-hatch pattern will be produced (Fig. 8.14).

The horizontal bar pattern is used for checking vertical linearity. These bars should be equally spaced throughout the screen for linearity. Similarly, the vertical bar pattern can be used for checking and setting horizontal linearity. With the cross-hatch pattern formed by the vertical and horizontal lines, linearity can be adjusted more precisely, because any unequal spacing of the lines can be discerned.

Picture centering and aspect ratio can also be checked with the cross-hatch pattern by counting the number of squares on the vertical and horizontal sides of the screen.

The pattern generator can also be used for detecting any spurious oscillations in the sweep generation circuits, interaction between the two oscillators, poor interlacing, and barrel and pin cushion effects.

Modulated picture signals are available on limited channels for injecting into the RF section of the receiver.

Similarly, an FM sound signal with a carrier frequency of 5.5 MHz ±100 kHz, modulated by a 1 kHz tone, is provided for aligning sound IF and discriminator circuits. A 75/300 Ω VHF balun is usually available as a standard accessory with the pattern generator.

COLOUR BAR GENERATOR 8.17

The composite video signal at the output of a video detector consists of luminance Y signals, the chrominance signal, the colour burst, sync pulses and blanking pulses.

The amplitude of the video signal varies continuously due to the changing picture content, such a waveform is not useful for adjustment and trouble shooting purposes.

The colour bar generator acts as a substitute transmitter and supplies to the receiver, a known constant amplitude colour pattern signal for alignment and servicing purposes.

8.17.1 The Gated Rainbow Colour Bar Generator

The gated colour bar generator develops a composite video signal that produces a rainbow colour bar pattern on the receiver screen. The pattern consists of 10 colour bars ranging in colour shades from red on the left side through blue in the centre, to green on the far right.

The colour bar pattern, the associated video waveform and the corresponding phase relationship of the gated pattern is given in Figs. 8.15 and 8.16 respectively.

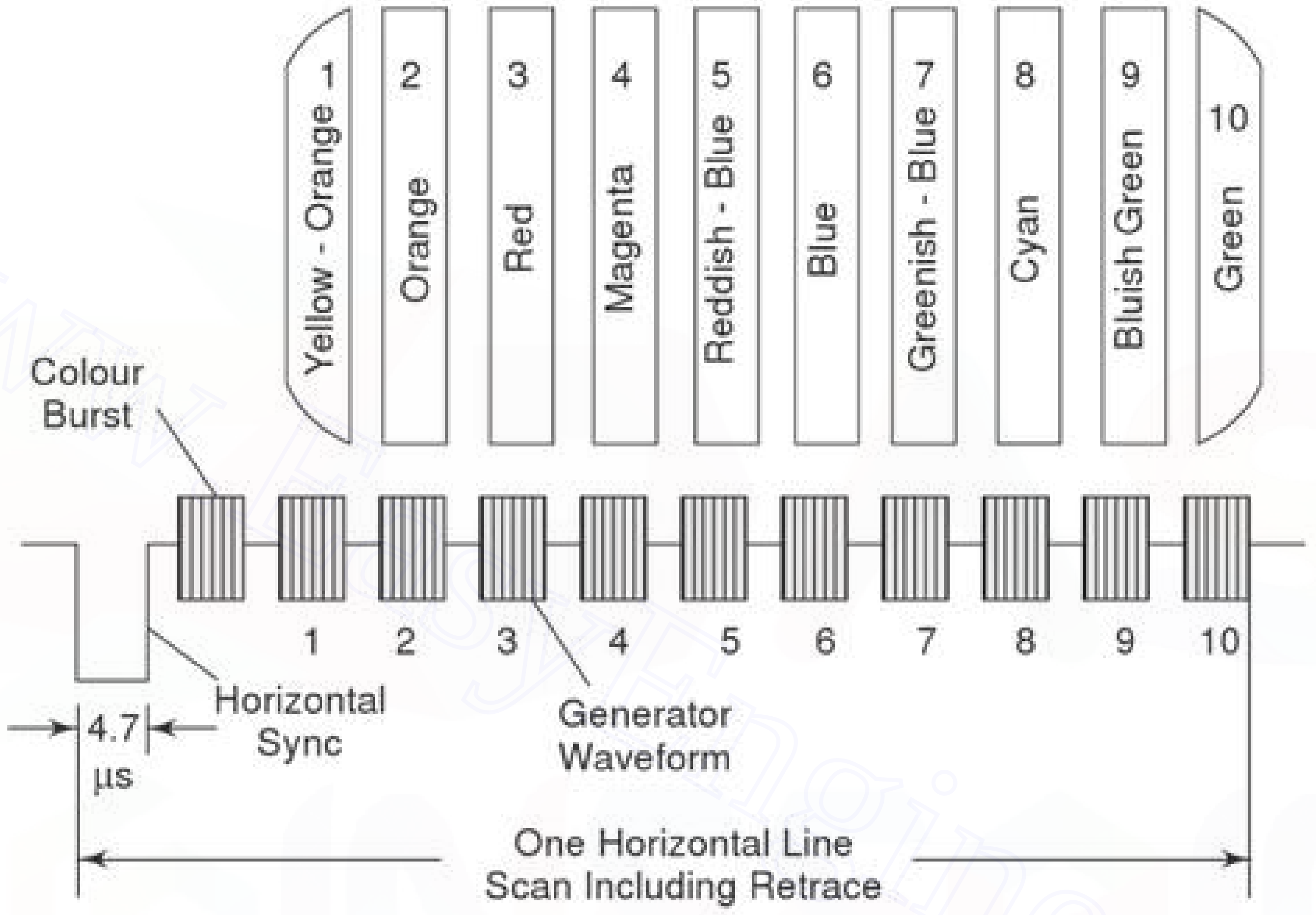


Fig. 8.15 Colour bar pattern on the screen of a colour picture tube

Each colour in the bar pattern has been identified and lined up with the associated modulated voltage.

The composite video signal for the pattern consists of a horizontal sync pulse and 11 equal amplitude bursts of colour sub-carrier frequency. The burst to the right is a colour burst; and other bursts from 1 to 10 differ in phase from one another and correspond to different colours in the bar pattern.

The basic principle of a colour bar generator is quite simple. Any two signals at different frequencies have a phase difference that changes continuously.

As shown in Fig. 8.17, a crystal oscillator is provided to generate a frequency of 4.41799375 MHz. This is 15625 Hz lower than the colour sub-carrier frequency (4.43361875 – 4.41799375 MHz = 15625 Hz). Since the difference in frequency is equal to the horizontal scanning rate, the relative phase between the two carrier frequencies changes by 360° per horizontal line. Thus the effective carrier signal at 4.41799375 MHz will appear as a signal that is continuously changing in phase (360° during each H-line) when compared to the 4.43361875 MHz reference oscillator in the TV receiver. It is the phase of the chrominance signal which determines the colour seen, and therefore has a frequency relationship with the subcarrier frequency that provides the colour bar signal. Since there is a

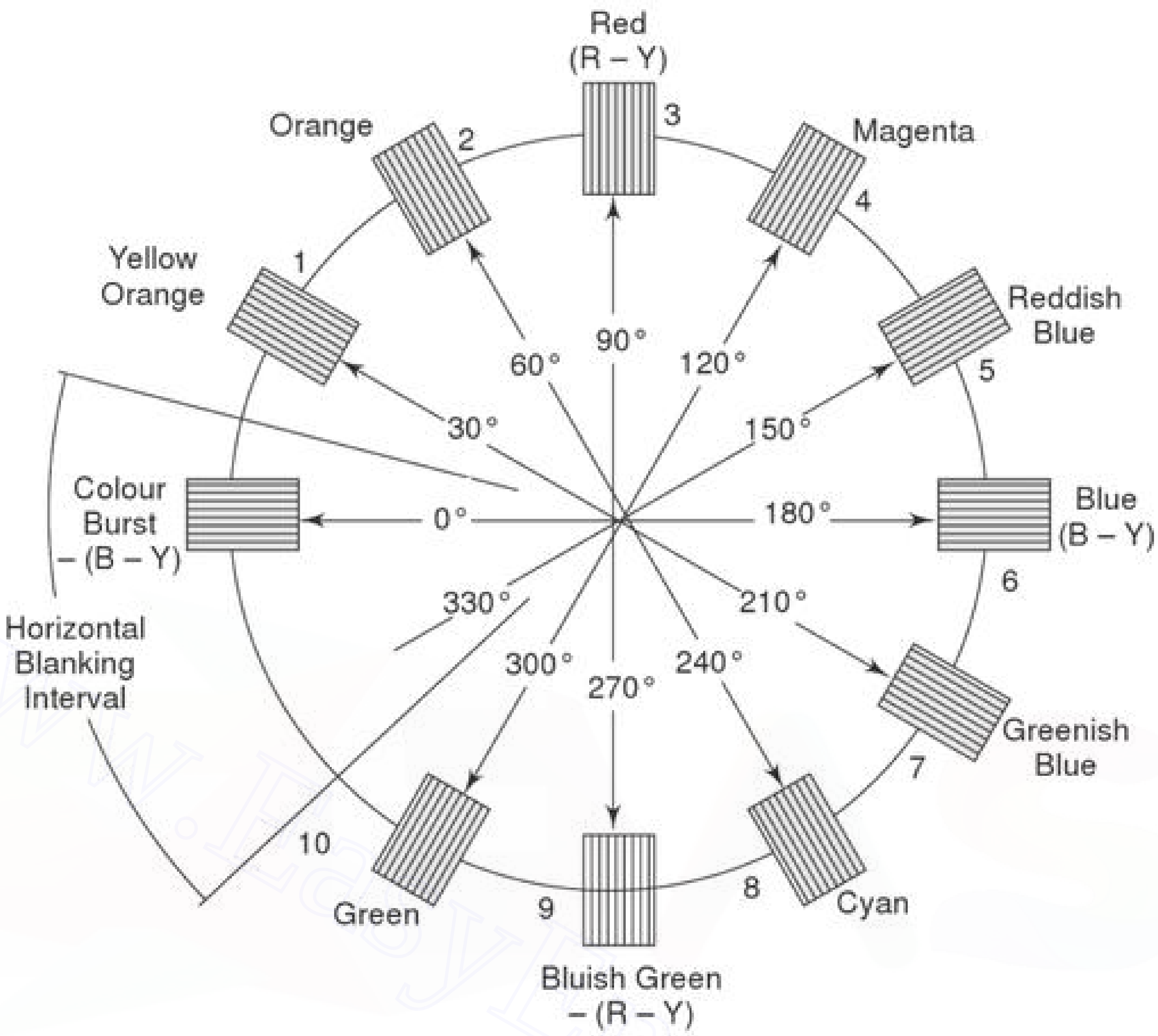


Fig. 8.16 Colour signal phase relationship with respect to colour burst

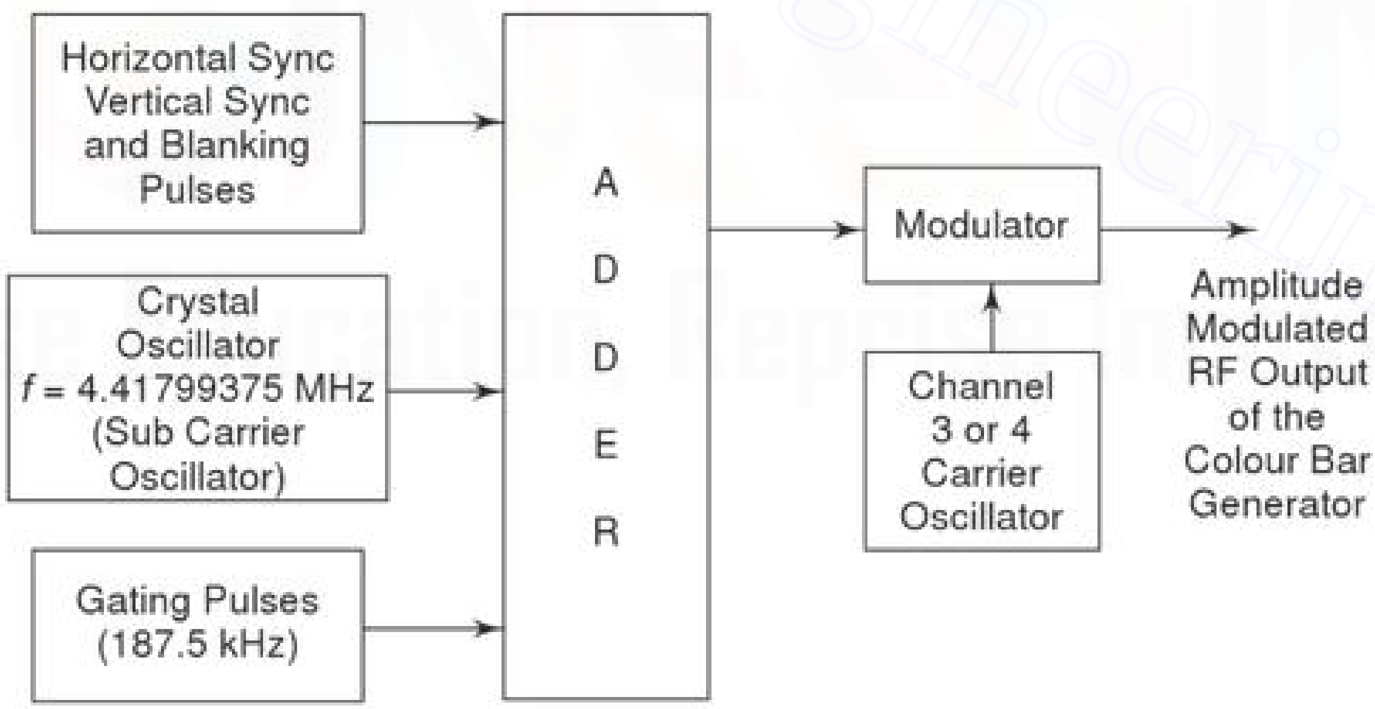


Fig. 8.17 Simplified block diagram of a gated rainbow colour bar generator

complete change of phase of 360° for each H-sweep, a complete range of colours is produced during each H-line. Each line displays all the colours simultaneously, since the phase between the frequency of the crystal oscillator and the horizontal scanning rate frequency is zero at the beginning of each such line and advances to become 360° at the end of each horizontal sweep stroke.

The colour bar pattern is produced by gating On and Off the 4.41799375 MHz oscillator at a rate 12 times higher than the H-sweep frequency (15625 × 12

= 187.5 kHz). The gating at a frequency of 187.5 kHz produces colour bars with blanks between them. The colour bars have a duration corresponding to 15°, and are 30° apart all around the colour spectrum. When viewed on the picture tube screen of a normally operated colour receiver, these bars appear as shown in Fig. 8.15.

Only 10 colour bars are shown in the screen, because one of the bursts occurs at the same time as the H-sync pulse and is thus eliminated. The adder, while gating the crystal oscillator output, also combines H-sync, V-sync and blanking pulses to the oscillator output. The composite colour video signal available at the output of the adder can be fed directly to the chrominance band-pass amplifier in the TV receiver. This signal is usually AM modulated with the carrier of either channel 3 or 4.

The main technical specifications of a colour bar pattern generator are as follows.

Test signals

1. 8 bars, linearised, grey scale
2. Cross-hatch pattern
3. 100% white pattern (with burst)
4. Red pattern (50% saturated)
5. Standard colour bar with white reference. 75% contrast (internally changeable to full bars).

Video carrier

1. VHF B-III (170 MHz - 230 MHz)
2. UHF B-IV (470 MHz - 600 MHz)

RF output

>> 100 mV peak to peak (75 Ω impedance)

Video modulation

Amplitude modulation (negative)

Sound carrier

Frequency	–	5.5 MHz (or 6 MHz by internal adjustment)
Modulation	–	Frequency modulation
Internal signal	–	1 kHz sine wave.

FM Sweep 40 kHz on 5.5 MHz

Chroma-PAL-G and I standards

Power

115 – 230 V; 50 – 60 Hz, 6 W

Dimension

$23 \times 11 \times 21$ cm – $(w \times h \times d)$

Weight

1.25 kg

Figure 8.18 illustrates a commercial VHF colour pattern generator (IE-1044) along with the various test patterns generated.

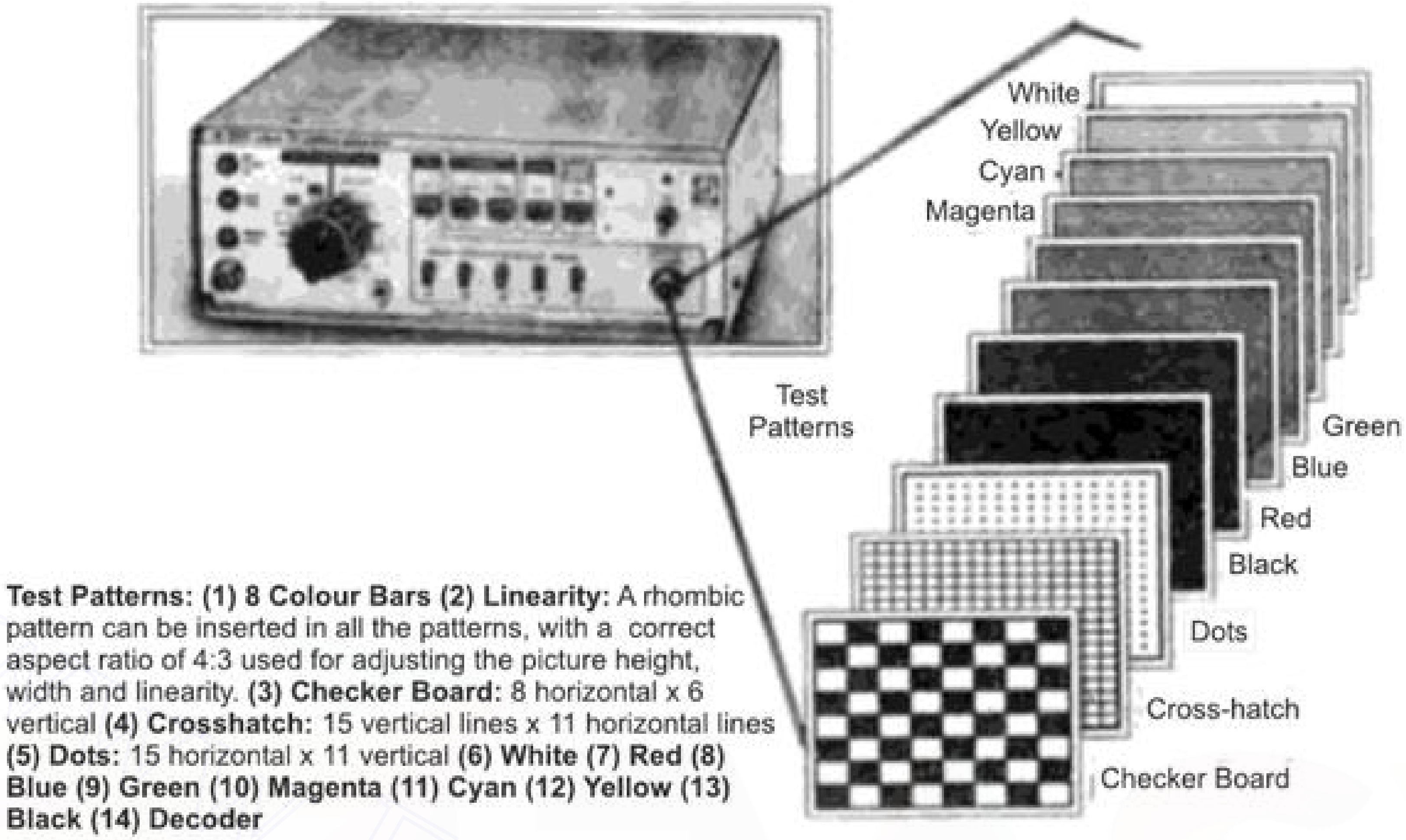


Fig. 8.18 VHF colour pattern generator (IE-1044) along with the test patterns (Courtesy: International Electronics Ltd. Marketed by Signetics Electronics Ltd., Bombay)

VECTROSCOPE 8.18

This test instrument combines a keyed colour bar generator with an oscilloscope and is used for alignment and testing the colour section of a TV receiver. The amplitude and phase of the chrominance signal represents the colour saturation and hue of the scene. This information can also be displayed on the oscilloscope screen in the form of Lissajous patterns. The resultant display is called a vectrogram.

A separate colour bar generator with a conventional CRO can be used to produce a vectrogram. The necessary circuit connections and the resulting pattern are shown in Fig. 8.19.

With the gated colour bar generator connected at the input terminals of the receiver, serrated (R – Y) and (B – Y) video signals become available at corresponding control grids of the colour picture tube. These two outputs are connected to the vertical and horizontal inputs of the CRO. Since both (R – Y) and (B – Y) inputs are interrupted sine waves and have a phase difference of 90° with each other, the resultant Lissajous pattern is in the basic form of a circle which collapses towards the centre during the serrations in the signals.

Assuming ideal input signal waveforms, the formation of a vectrogram is given in Fig. 8.20.

Since there are 10 colour bursts, the pattern displays ten petals. The horizontal sync and colour burst do not appear in the display because these are blanked out during retrace intervals.

The position of each petal represents the phase angle of each colour in the colour bar pattern.

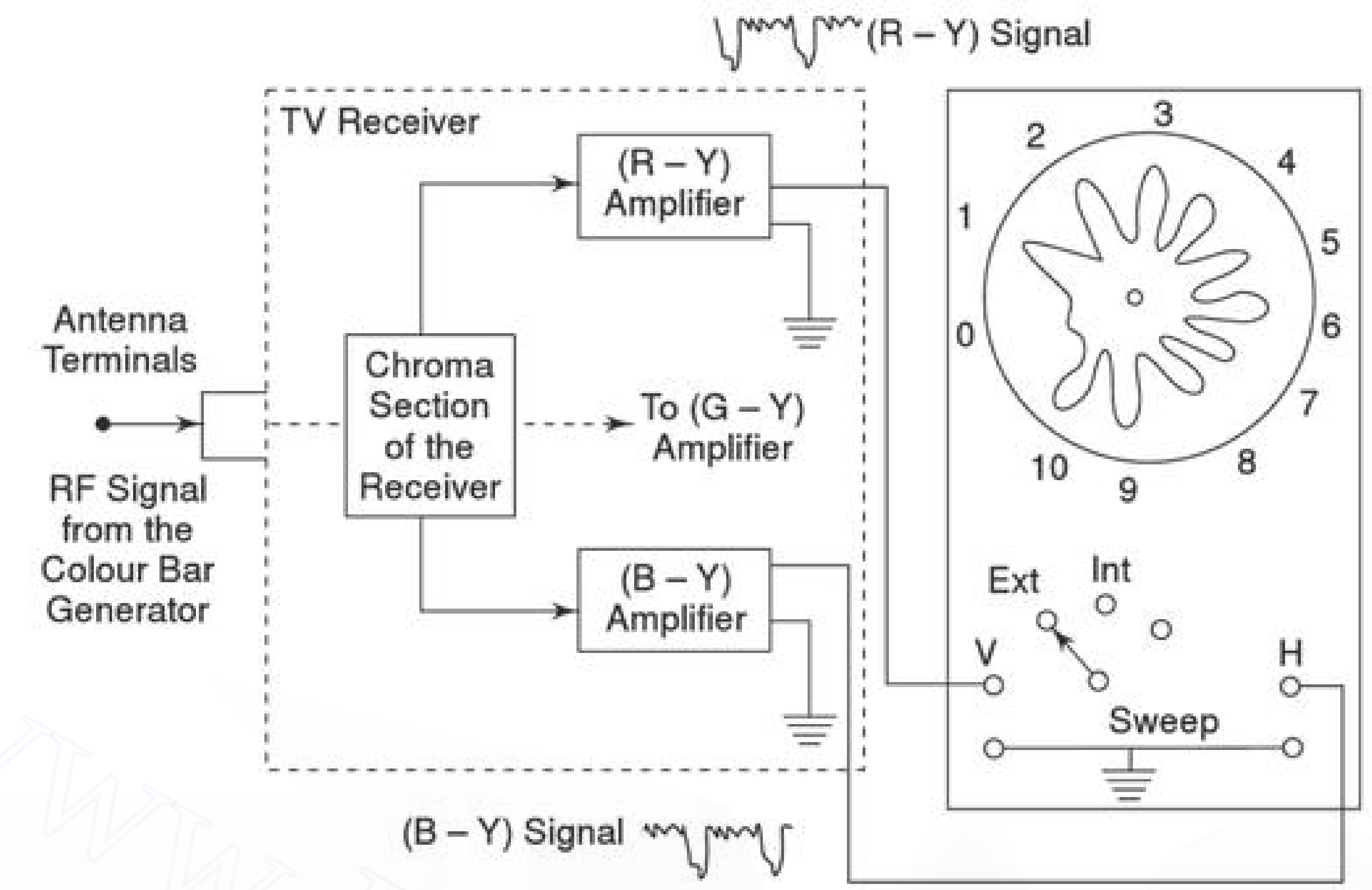


Fig. 8.19 Circuit connections for producing a vectrogram on the CRO

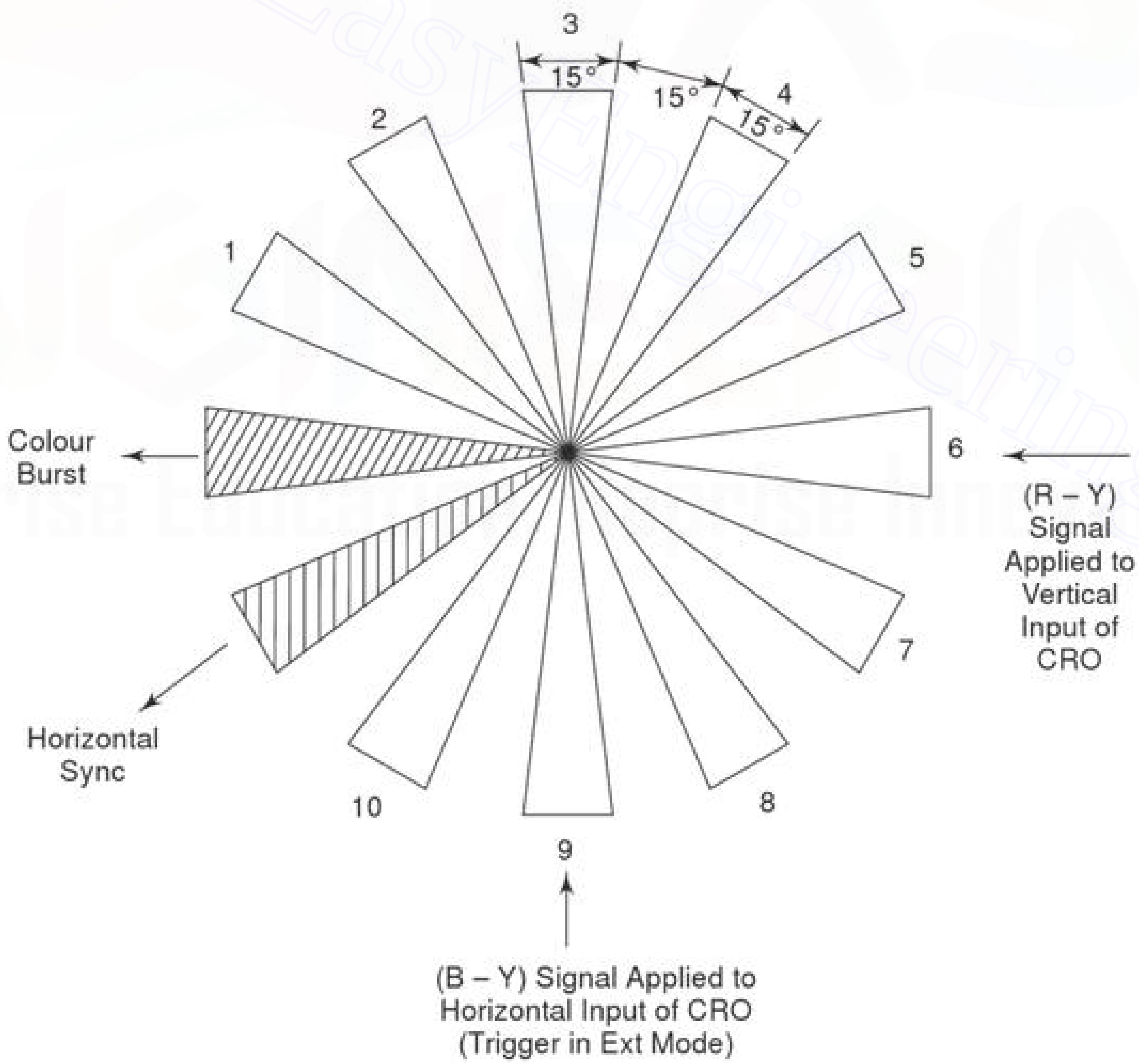


Fig. 8.20 Lissajous pattern

For example, petal 1, 3, R – Y, 6, B – Y and 10 (G – Y) correspond to angles 30°, 90°, 180°, and 360° respectively.

Vectroscopes usually have an overlay sheet on the scope screen, marked with segment numbers and corresponding phase angles. This enables the user to identify different colours and interpret the size and shape of each petal.

In actual practice, the top of (R – Y) and (B – Y) bar signals do not have sharp corners and the resultant pattern is somewhat feathered and rounded at the periphery. This is depicted in the actual pattern shown on the oscilloscope screen in Fig. 8.20.

Rounding of corners and feathering occurs due to limited HF response and non-zero rise-time of the amplifier in a colour bar generator and oscilloscope.

With a vectogram display, chroma troubles can be ascertained and servicing expedited.

For example the loss of an (R – Y) signal causes the vectrogram to be H-line only. Similarly, the absence of (B – Y) results in a single vertical line on the screen. Any change of the receiver colour control will alter the amplitude of both (R – Y) and (B – Y) signals and cause the diameter of the pattern to change.

The receiver fine tuning affects the size and shape of the reproduced pattern. Proper fine tuning produces the largest and best shaped vectrogram.

If some of the petals are longer than others, non-linear distortion is indicated. If the petal tops are flattened, some circuit overloading is occuring in the receiver.

It is also possible to check for defective colour stages, mistuned band-pass amplifier, misadjusted circuitry in the sub-carrier oscillator section and inoperative colour stages.

Vectroscopes are also used in TV recording studios to adjust the white balance of various cameras and to monitor colour signals during recording.

BEAT FREQUENCY OSCILLATOR (BFO) 8.19

In this circuit, the outputs of two RF oscillators are applied to a square law detector and the resulting difference frequency is amplified. The main advantage of this type of oscillator is that a stable continuous output covering the entire AF range can be realised by simple variation of the tuning capacitor in one of the oscillators.

In the circuit given in Fig. 8.21, the voltages obtained from two RF oscillators operating at slightly different frequencies are combined and applied to a mixer circuit. The difference frequency current that is thus produced represents the desired oscillations. The practical value of a BFO arises from the fact that a small or moderate percentage variation in the frequency of one of the individual oscillators (such as can be obtained by the rotation of the shaft controlling a variable tuning capacitor) varies the beat or difference output continuously from a few c/s to throughout the entire AF or video frequency range. At the same time,

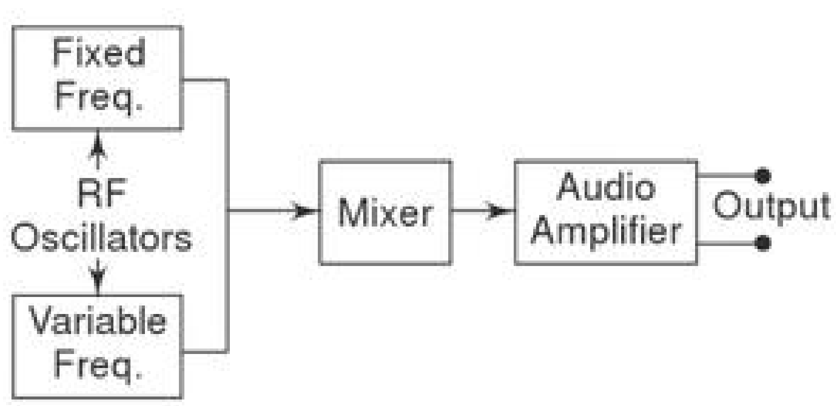


Fig. 8.21 Beat frequency oscillator

the amplitude of the difference frequency output is largely constant as frequency is varied. The principal factors involved in the performance of a BFO are the frequency stability of individual oscillators, the tendency of the oscillators to synchronise at very low difference frequencies, the wave shape of the difference frequency output, and the tendency for spurious beat notes to be produced.

Frequency stability of the individual oscillators is important, because a slight change in their relative frequency would cause a relatively large change in the difference frequency. To minimise the drift of the difference frequency with time, the individual oscillators should have high inherent frequency stability with respect to changes in temperature and to supply voltage variations, and they should be as alike electrically, mechanically and thermally, as possible.

In this way, frequency changes are minimised and the frequency changes that do take place tend to be the same in each of the individual oscillators and so have little effect on the difference in their frequencies.

The two RF oscillators must be completely isolated from each other. If coupling of any type exists between them, they will synchronise when the difference is small. Hence, low values of difference frequency are impossible to obtain, and in addition cause interaction between the oscillators that results in a highly distorted wave shape.

(To ensure low distortion, one of the voltages applied to the mixer, preferably the one derived from the fixed frequency oscillator, should be considerably smaller than the voltage derived from the other oscillator, and preferably free of harmonics.)

BFOs are commonly affected with spurious beat notes, sometimes called whistles. These effects are usually the result of cross-modulation in the AF amplifier between high order RF harmonics generated by the mixer. These spurious whistles often appear when the output frequency is high.

Whistles can be eliminated by operating the mixer so as to minimise the production of RF harmonics, and by using a filter and shielding to prevent the harmonics that are generated in the mixer from reaching the amplifier circuit.

STANDARD SPECIFICATIONS OF A SIGNAL GENERATOR 8.20

Table 8.2 gives the standard specifications of a signal generator

Table 8.2

Properties	*Specifications*
Calibration accuracy	± 2% under normal conditions
Frequency response	Within ± 1 db (of a 1 kHz reference) over the entire frequency range
Frequency stability	Negligible shift in output frequency for ± 10% line voltage variation
Distortion	Less than 0.5% below 500 kHz, (less than 1% above 500 kHz), independent of load impedance

Balanced output	May be obtained (at maximum output), with better than 1% balance, or may be operated single-ended (with low side grounded), at an internal impedance of 600 Ω, for any portion of output attenuation

Review Questions

1. Explain the operation of a basic signal generator.
2. Explain the operating principle of a modern standard signal generator.
3. Describe with the help of a neat block diagram the working of a standard signal Generator. State the limitations of a standard signal generator.
4. Describe with the help of a neat block diagram the operation of a modern laboratory signal generator. Explain the technique used to improve its stability.
5. Explain the operation and use of frequency dividers.
6. Describe with diagram the operation of an AF sine and wave generator. State the various controls on the front panels of a sine and square wave generator.
7. Explain the operating principle of a function generator.
8. Explain with the help of a block diagram the operation of a function generator.
9. Explain the method of producing sine waves in a function generator. Explain the operation of a resistance diode network.
10. Explain with the help of block diagram the working of a standard sweep generator.
11. How are broadband sweep frequencies generated using a sweep generator?
12. State with a diagram the working principle of a pulse generator. Describe with the help of a block diagram the operation of a pulse generator.
13. Define duty cycle. List the requirements of a pulse.
14. List the various control on the front panel of a pulse generator. Mention their uses.
15. State the function of symmetry control in a pulse generator.
16. State the function of frequency sweeper and marker generator in a sweep generator.
17. Explain with diagram the working of a marker generator. What is the necessity of using a marker generator?
18. State the application of a sweep generator.
19. Explain the term 'wobbluscope'.
20. Describe with a diagram the operation of a wobbluscope. State the applications of a wobbluscope.
21. Differentiate between a sweep generator and wobbluscope.
22. State the front panel controls of a wobbluscope.
23. Describe the procedure of alignment RF and IF sections using a wobbluscope.
24. Explain with a block diagram the operation of a pattern generator. State the various applications of a pattern generator.
25. List the various controls on the front panel of a pattern generator. List the various patterns generated by a pattern generator.
26. Differentiate between a function generator and pulse and square wave generator.
27. Compare a wobbluscope and sweep generator.

28. Explain in brief the alignment procedure of a TV receiver using a sweep generator.
29. What are the different methods of obtaining colour bar patterns? How are the colour bar patterns generated?
30. Explain with block diagram the operation of a gated rainbow colour bar generator.
31. List the main technical specifications of a colour bar pattern generator.
32. What is a vectroscope? Where is it used?
33. Explain with a diagram the operation of a vectroscope.
34. How is the vectrogram produced on the CRO? Explain with a diagram.
35. State the applications of a vectroscope.
36. Explain the working principle of a beat frequency oscillator. State its applications.
37. Explain with a diagram the working of a beat frequency oscillator.

Multiple Choice Questions

1. Modulation in modern signal generator is done internally by signals of frequency
   (a) 400 Hz and 1000 Hz
   (b) 600 Hz and 2000 Hz
   (c) 100 Hz and 5000 Hz
   (d) 10000 Hz and 4000 Hz
2. AF sine and square wave generator has an output impedance of
   (a) 600 Ω (b) 200 Ω
   (c) 1000 Ω (d) 50 Ω.
3. A frequency divider used in a modern signal generator
   (a) divides the frequency by 2
   (b) doubles the frequency
   (c) divides the frequency by 10
   (d) multiply the frequency by 2
4. Internal calibration in a modern signal generator is obtained by using
   (a) 2 MHz crystal oscillator
   (b) 1 MHz crystal oscillator
   (c) 5 MHz crystal oscillator
   (d) 5.5 MHz crystal oscillator
5. Frequency dividers are obtained by the use of
   (a) LC network (b) AND gate
   (c) flip-flop's (d) RC network
6. A Wien bridge oscillator is suitable for
   (a) RF generator
   (b) function generator
   (c) pulse generator
   (d) AF generators
7. In a function generator, the resistance diode network is used to produce
   (a) square wave (b) sine wave
   (c) triangular wave (d) pulse wave
8. The principle used in the operation of a function generator is by using an
   (a) *LC* oscillator (b) *RC* oscillator
   (c) integrator (d) derivation
9. The frequency of a function generator is varied by varying
   (a) *LC* network
   (b) *RC* network
   (c) constant current sources
   (d) constant voltage sources
10. A pulse generator generating a square wave has a duty cycle of
    (a) 25% (b) 50%
    (c) 75% (d) 40%
11. A pulse generating, generated a pulse waveform has a duty cycle of
    (a) 25% (b) 40%
    (c) 50% (d) 75%
12. The comparator used in a function generator produces
    (a) square wave
    (b) triangular wave
    (c) sine wave
    (d) pulse wave

13. The frequency sweeper provides the modulating voltage which varies the
    (a) inductance (b)capacitance
    (c) resistance (d) voltage
14. A sweep generator is used for
    (a) fault finding
    (b) frequency generation
    (c) amplification
    (d) alignment
15. A wobbluscope is used for alignment of a/an
    (a) radio receiver (b) TV receiver
    (c) oscilloscope (d) wave analyzer
16. Picture centering and aspect ratio using a pattern generator can be checked by the pattern
    (a) horizontal bar
    (b) vertical bar
    (c) cross hatch
    (d) checker board
17. In a function generator, the spectral purity of a sine wave is poor as compared to the Wein bridge type oscillator because
    (a) it is obtained using piecewise linear approximation
    (b) it uses crystal reactive element
    (c) inductor element used has a non-linear B-H relation
18. A digital counter IC is to be checked for it's performance up to 25 MHz. It can be done
    (a) RF signal generator
    (b) function generator
    (c) pulse generator
    (d) pattern generator
19. The number of colour burst generated by the colour bar pattern generated is
    (a) 10 (b) 20 (c) 5 (d) 15
20. If the number of colour bursts present are ten then the number of petals displayed are
    (a) 15 (b) 10 (c) 20 (d) 5

Further Reading

1. Oliver Cage, *Electronic Measurements and Instrumentation*, McGraw-Hill, 1975.
2. R.R. Gulati, *Monochrome and Colour TV*, Wiley Eastern, 1983.
3. Larry D. Jones and A. Foster Chin, *Electronic Instruments and Measurements*, John Wiley & Sons, 1987.

Wave Analyzers and Harmonic Distortion

Chapter 9

INTRODUCTION 9.1

It can be shown mathematically that any complex waveform is made up of a fundamental and its harmonics.

It is often desired to measure the amplitude of each harmonic or fundamental individually. This can be performed by instruments called wave analyzers. This is the simplest form of analysis in the frequency domain, and can be performed with a set of tuned filters and a voltmeter. Wave analyzers are also referred to as frequency selective voltmeters, carrier frequency voltmeters, and selective level voltmeters. The instrument is tuned to the frequency of one component whose amplitude is measured.

This instrument is a narrow band superheterodyne receiver, similar to a spectrum analyzer (discussed later). It has a very narrow pass-band. A meter is used for measurement, instead of a CRT. Wave analyzers are used in the low RF range, below 50 MHz and down through the AF range. They provide a very high frequency resolution.

Some wave analyzers have the facility of automatic frequency control, in which the tuning automatically locks to a signal. This makes it possible to measure the amplitude of signals that are drifting in frequency by amounts that would carry them outside the widest pass-band available.

When a sinusoidal signal is applied to the input of an ideal linear amplifier, it produces a sinusoidal output waveform. However, in most cases the output waveform is not an exact replica of the input signal because of different types of distortion. The amount by which the output waveform of an amplifier differs from the input waveform is a measure of the distortion introduced by the inherent non-linear characteristics of the active devices.

Harmonic distortion analyzers measure the total harmonic content in the waveforms. It can be shown mathematically that an amplitude distorted sine wave is made up of pure sine wave components, including the fundamental frequency f of the input signal, and harmonic multiples of the fundamental frequency, $2f$, $3f$, $4f$ etc.

Harmonic distortion can be quantitatively measured very accurately with a harmonic distortion analyzer, generally called a distortion analyzer.

The total harmonic distortion or factor is given by

$$D = \sqrt{D_2^2 + D_3^2 + D_4^2 \cdots}$$

where D_2, D_3, D_4 … represent the second harmonic, third harmonic, etc. respectively.

The distortion analyzer measures the total harmonic distortion without indicating the amplitude and frequency of each component waves.

Signal analysis of both random and periodic signals in the frequency domain is used extensively in electronic and telecommunications. The frequency stability and spectral purity of signal sources can be measured by the use of these signal analyzers.

These signal analyzers can be used along with a frequency generator or a source of white or pseudo-random noise to measure the frequency response of amplifiers, filters or other networks.

The operational characteristics of a transreceiver and communication system are determined by measuring various parameters, such as spectral purity of the carrier wave, spectral power distribution of the amplitude or frequency modulated wave, signal distortion, and the systems signal to noise ratio.

Such analysis is provided by a wave analyzer, distortion analyzer, spectrum analyzer, and digital fourier analyzer.

BASIC WAVE ANALYZER 9.2

A basic wave analyzer is shown in Fig. 9.1(a). It consists of a primary detector, which is a simple LC circuit. This LC circuit is adjusted for resonance at the frequency of the particular harmonic component to be measured.

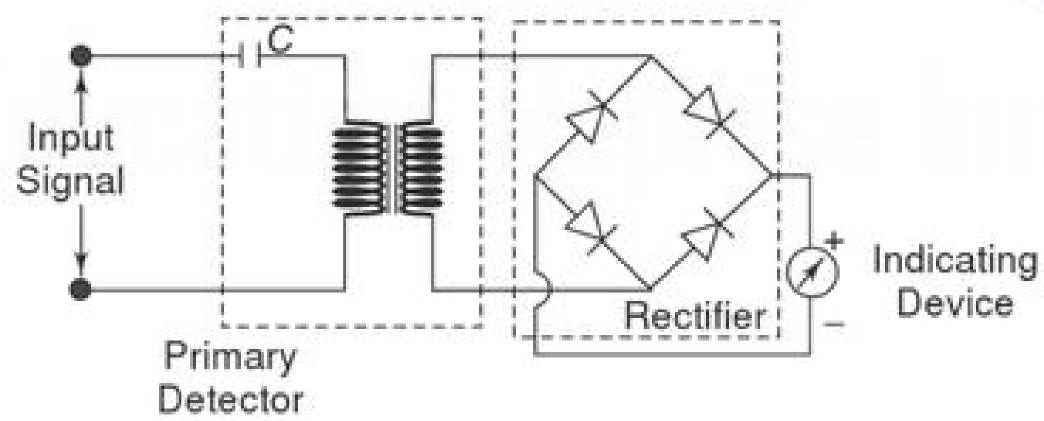


Fig. 9.1 (a) Basic wave analyzer

The intermediate stage is a full wave rectifier, to obtain the average value of the input signal. The indicating device is a simple dc voltmeter that is calibrated to read the peak value of the sinusoidal input voltage.

Since the LC circuit is tuned to a single frequency, it passes only the frequency to which it is tuned and rejects all other frequencies. A number of tuned filters, connected to the indicating device through a selector switch, would be required for a useful Wave analyzer.

FREQUENCY SELECTIVE WAVE ANALYZER 9.3

The wave analyzer consists of a very narrow pass-band filter section which can be tuned to a particular frequency within the audible frequency range (20 Hz – 20 kHz). The block diagram of a wave analyzer is as shown in Fig. 9.1(b).

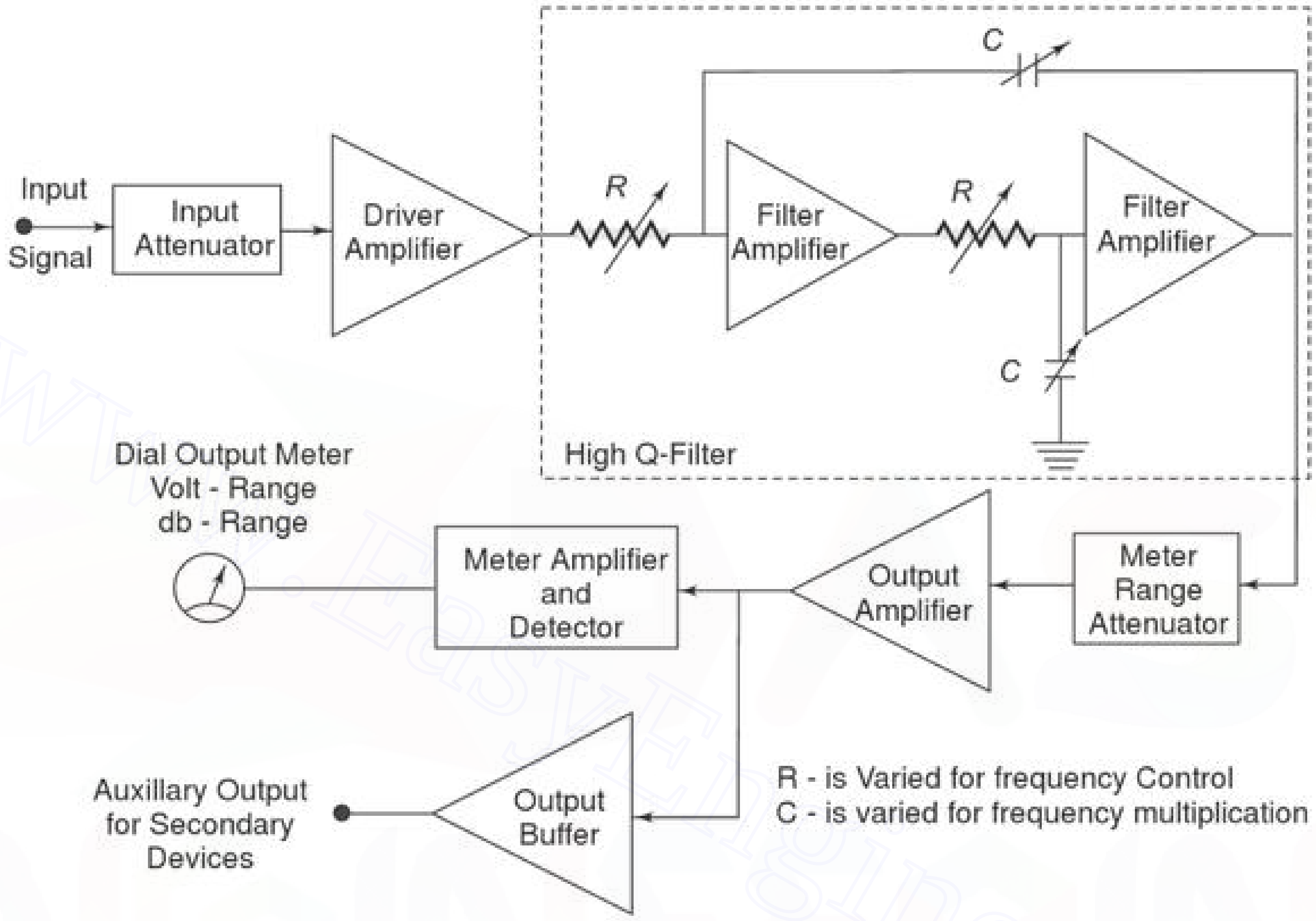


Fig. 9.1 (b) Frequency selective wave analyzer

The complex wave to be analyzed is passed through an adjustable attenuator which serves as a range multiplier and permits a large range of signal amplitudes to be analyzed without loading the amplifier.

The output of the attenuator is then fed to a selective amplifier, which amplifies the selected frequency. The driver amplifier applies the attenuated input signal to a high-Q active filter. This high-Q filter is a low pass filter which allows the frequency which is selected to pass and reject all others. The magnitude of this selected frequency is indicated by the meter and the filter section identifies the frequency of the component. The filter circuit consists of a cascaded RC resonant circuit and amplifiers. For selecting the frequency range, the capacitors generally used are of the closed tolerance polystyrene type and the resistances used are precision potentiometers. The capacitors are used for range changing and the potentiometer is used to change the frequency within the selected pass-band, Hence this wave analyzer is also called a Frequency selective voltmeter.

The entire AF range is covered in decade steps by switching capacitors in the RC section.

The selected signal output from the final amplifier stage is applied to the meter circuit and to an untuned buffer amplifier. The main function of the buffer amplifier is to drive output devices, such as recorders or electronics counters.

The meter has several voltage ranges as well as decibel scales marked on it. It is driven by an average reading rectifier type detector.

The wave analyzer must have extremely low input distortion, undetectable by the analyzer itself. The bandwidth of the instrument is very narrow, typically about 1% of the selective band given by the following response characteristics shown in Fig. 9.2).

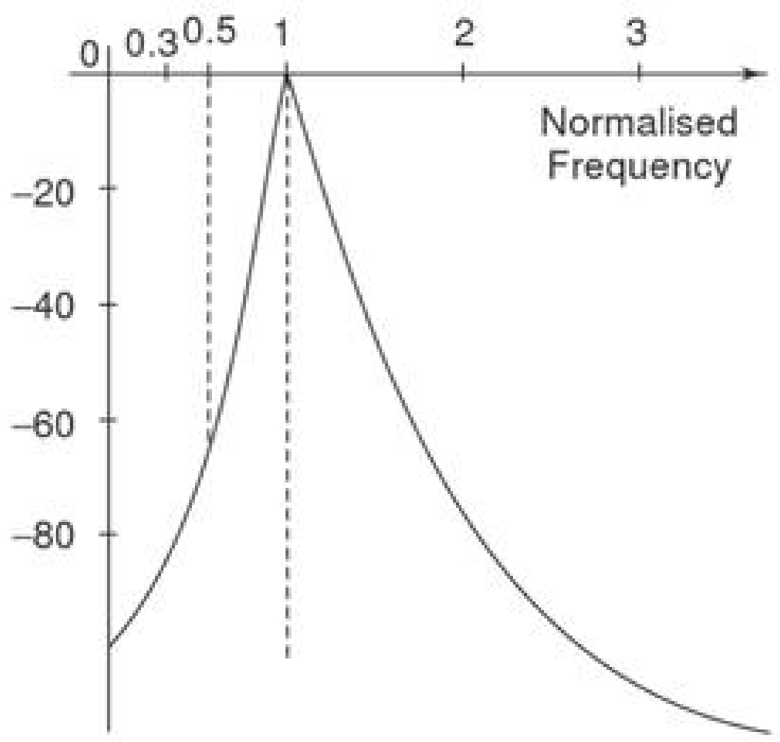


Fig. 9.2 Relative response in dBs

HETERODYNE WAVE ANALYZER 9.4

Wave analyzers are useful for measurement in the audio frequency range only. For measurements in the RF range and above (MHz range), an ordinary wave analyzer cannot be used. Hence, special types of wave analyzers working on the principle of heterodyning (mixing) are used. These wave analyzers are known as Heterodyne wave analyzers.

In this wave analyzer, the input signal to be analyzed is heterodyned with the signal from the internal tunable local oscillator in the mixer stage to produce a higher IF frequency.

By tuning the local oscillator frequency, various signal frequency components can be shifted within the pass-band of the IF amplifier. The output of the IF amplifier is rectified and applied to the meter circuit.

An instrument that involves the principle of heterodyning is the Heterodyning tuned voltmeter, shown in Fig. 9.3.

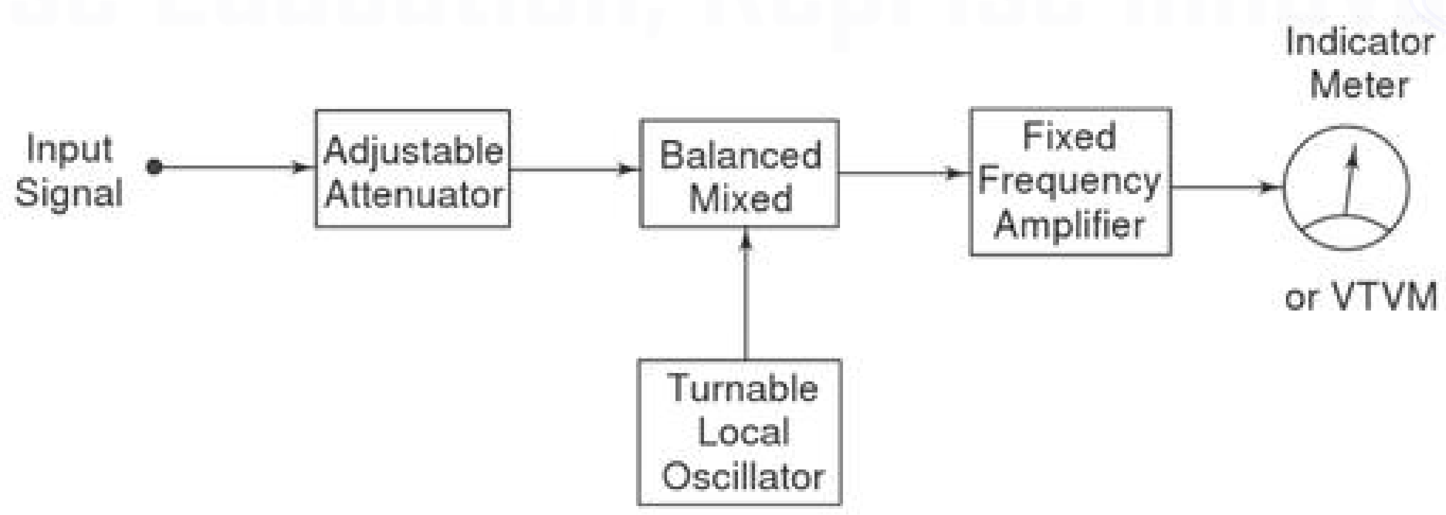


Fig. 9.3 Heterodyne wave analyzer

The input signal is heterodyned to the known IF by means of a tunable local oscillator. The amplitude of the unknown component is indicated by the VTVM or output meter. The VTVM is calibrated by means of signals of known amplitude.

The frequency of the component is identified by the local oscillator frequency, i.e. the local oscillator frequency is varied so that all the components can be identified. The local oscillator can also be calibrated using input signals of known frequency. The fixed frequency amplifier is a multistage amplifier which can be designed conveniently because of its frequency characteristics. This analyzer has good frequency resolution and can measure the entire AF frequency range. With the use of a suitable attenuator, a wide range of voltage amplitudes can be covered. Their disadvantage is the occurrence of spurious cross-modulation products, setting a lower limit to the amplitude that can be measured.

Two types of selective amplifiers find use in Heterodyne wave analyzers. The first type employs a crystal filter, typically having a centre frequency of 50 kHz. By employing two crystals in a band-pass arrangement, it is possible to obtain a relatively flat pass-band over a 4 cycle range. Another type uses a resonant circuit in which the effective Q has been made high and is controlled by negative feedback. The resultant signal is passed through a highly selective 3-section quartz crystal filter and its amplitude measured on a Q-meter.

When a knowledge of the individual amplitudes of the component frequency is desired, a heterodyne wave analyzer is used.

A modified heterodyne wave analyzer is shown in Fig. 9.4. In this analyzer, the attenuator provides the required input signal for heterodyning in the first mixer stage, with the signal from a local oscillator having a frequency of 30 – 48 MHz.

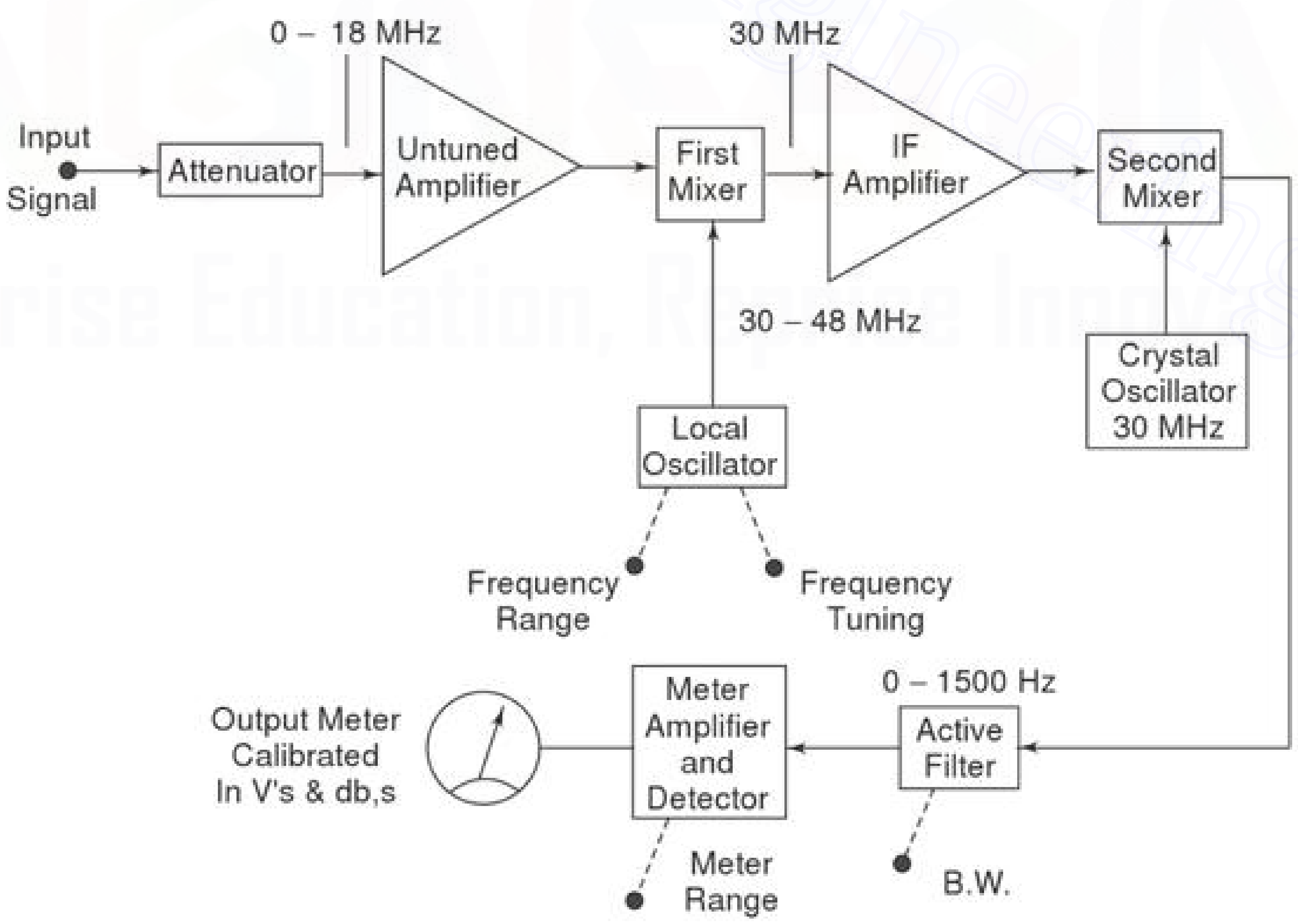


Fig. 9.4 RF heterodyne wave analyzer

The first mixer stage produces an output which is the difference of the local oscillator frequency and the input signal, to produce an IF signal of 30 MHz.

This IF frequency is uniformly amplified by the IF amplifier. This amplified IF signal is fed to the second mixer stage, where it is again heterodyned to produce a difference frequency or IF of zero frequency.

The selected component is then passed to the meter amplifier and detector circuit through an active filter having a controlled band-width. The meter detector output can then be read off on a db-calibrated scale, or may be applied to a secondary device such as a recorder.

This wave analyzer is operated in the RF range of 10 kHz – 18 MHz, with 18 overlapping bands selected by the frequency range control of the local oscillator. The bandwidth, which is controlled by the active filter, can be selected at 200 Hz, 1 kHz and 3 kHz.

HARMONIC DISTORTION ANALYZER 9.5

9.5.1 Fundamental Suppression Type

A distortion analyzer measures the total harmonic power present in the test wave rather than the distortion caused by each component. The simplest method is to suppress the fundamental frequency by means of a high pass filter whose cut off frequency is a little above the fundamental frequency. This high pass allows only the harmonics to pass and the total harmonic distortion can then be measured. Other types of harmonic distortion analyzers based on fundamental suppression are as follows.

1. Employing a Resonance Bridge The bridge shown in Fig. 9.5 is balanced for the fundamental frequency, i.e. L and C are tuned to the fundamental frequency. The bridge is unbalanced for the harmonics, i.e. only harmonic power will be available at the output terminal and can be measured. If the fundamental frequency is changed, the bridge must be balanced again. If L and C are fixed components, then this method is suitable only when the test wave has a fixed frequency. Indicators can be thermocouples or square law VTVMs. This indicates the rms value of all harmonics. When a continuous adjustment of the fundamental frequency is desired, a Wien bridge arrangement is used as shown in Fig. 9.6.

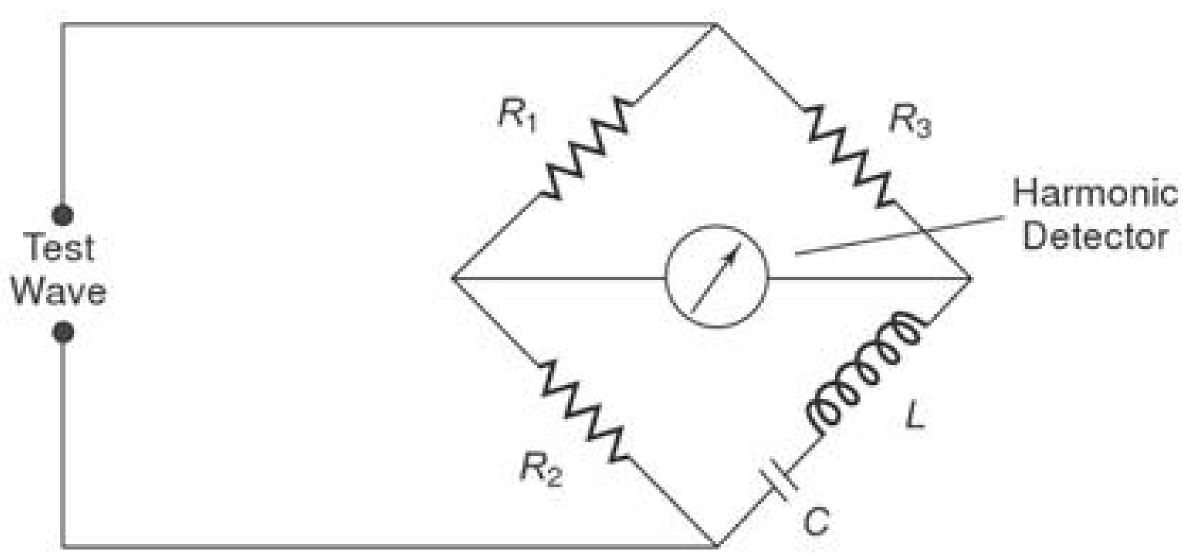


Fig. 9.5 Resonance bridge

2. Wien's Bridge Method The bridge is balanced for the fundamental frequency. The fundamental energy is dissipated in the bridge circuit elements. Only the harmonic components reach the output terminals. The harmonic distortion output can then be measured with a meter. For balance at the fundamental frequency, $C_1 = C_2 = C$, $R_1 = R_2 = R$, $R_3 = 2R_4$.

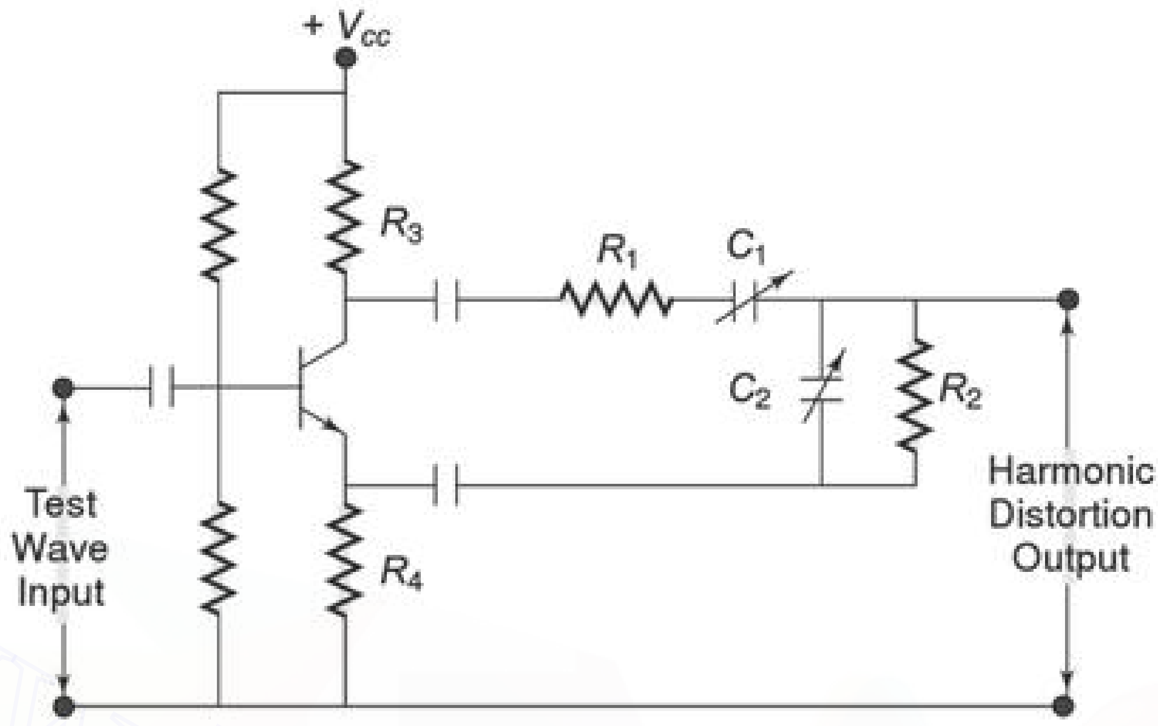


Fig. 9.6 Wien's bridge method

3. Bridged T-Network Method Referring to Fig. 9.7 the, L and C's are tuned to the fundamental frequency, and R is adjusted to bypass fundamental frequency. The tank circuit being tuned to the fundamental frequency, the fundamental energy will circulate in the tank and is bypassed by the resistance. Only harmonic components will reach the output terminals and the distorted output can be measured by the meter. The Q of the resonant circuit must be at least 3–5.

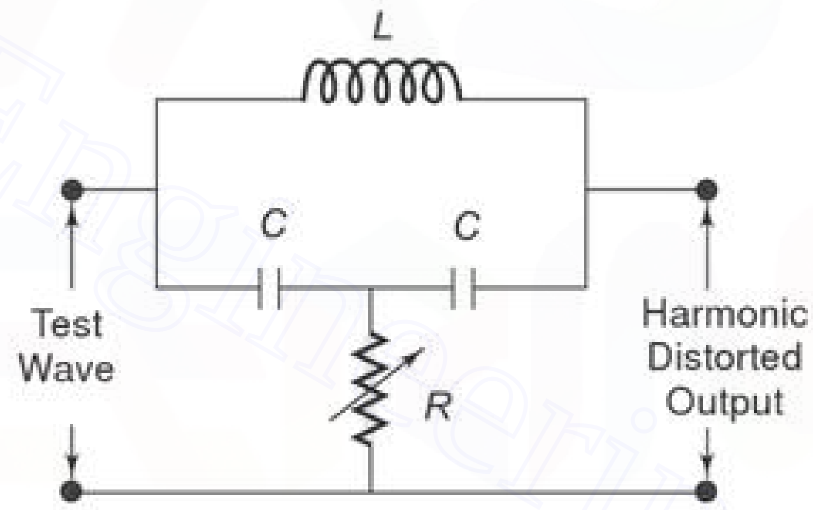


Fig. 9.7 Bridged T-network method

One way of using a bridge T-network is given in Fig. 9.8.

The switch S is first connected to point A so that the attenuator is excluded and the bridge T-network is adjusted for full suppression of the fundamental frequency, i.e. minimum output. Minimum output indicates that the bridged T-network is tuned to the fundamental frequency and that the fundamental frequency is fully suppressed.

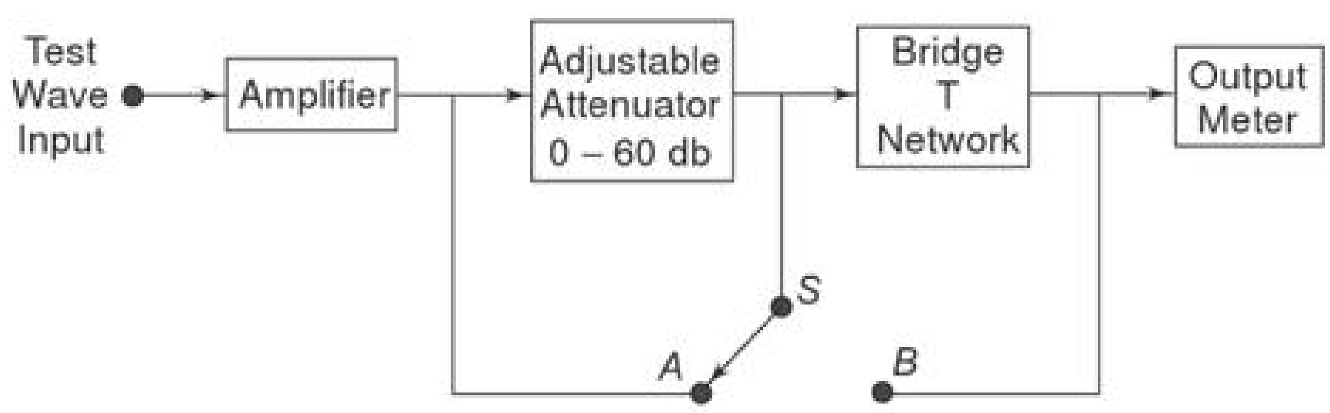


Fig. 9.8 Harmonic distortion analyzer using bridged T-network

The switch is next connected to terminal B, i.e. the bridged T-network is excluded. Attenuation is adjusted until the same reading is obtained on the meter. The attenuator reading indicates the total rms distortion. Distortion measurement can also be obtained by means of a wave analyzer, knowing the amplitude and the frequency of each component, the harmonic distortion can be calculated. However, distortion meters based on fundamental suppression are simpler to design and less expensive than wave analyzers. The disadvantage is that they give only the total distortion and not the amplitude of individual distortion components.

SPECTRUM ANALYZER 9.6

The most common way of observing signals is to display them on an oscilloscope, with time as the X-axis (i.e. amplitude of the signal versus time). This is the time domain. It is also useful to display signals in the frequency domain. The instrument providing this frequency domain view is the spectrum analyzer.

A spectrum analyzer provides a calibrated graphical display on its CRT, with frequency on the horizontal axis and amplitude (voltage) on the vertical axis.

Displayed as vertical lines against these coordinates are sinusoidal components of which the input signal is composed. The height represents the absolute magnitude, and the horizontal location represents the frequency.

These instruments provide a display of the frequency spectrum over a given frequency band. Spectrum analyzers use either a parallel filter bank or a swept frequency technique.

In a parallel filter bank analyzer, the frequency range is covered by a series of filters whose central frequencies and bandwidth are so selected that they overlap each other, as shown in Fig. 9.9(a).

Typically, an audio analyzer will have 32 of these filters, each covering one third of an octave.

For wide band narrow resolution analysis, particularly at RF or microwave signals, the swept technique is preferred.

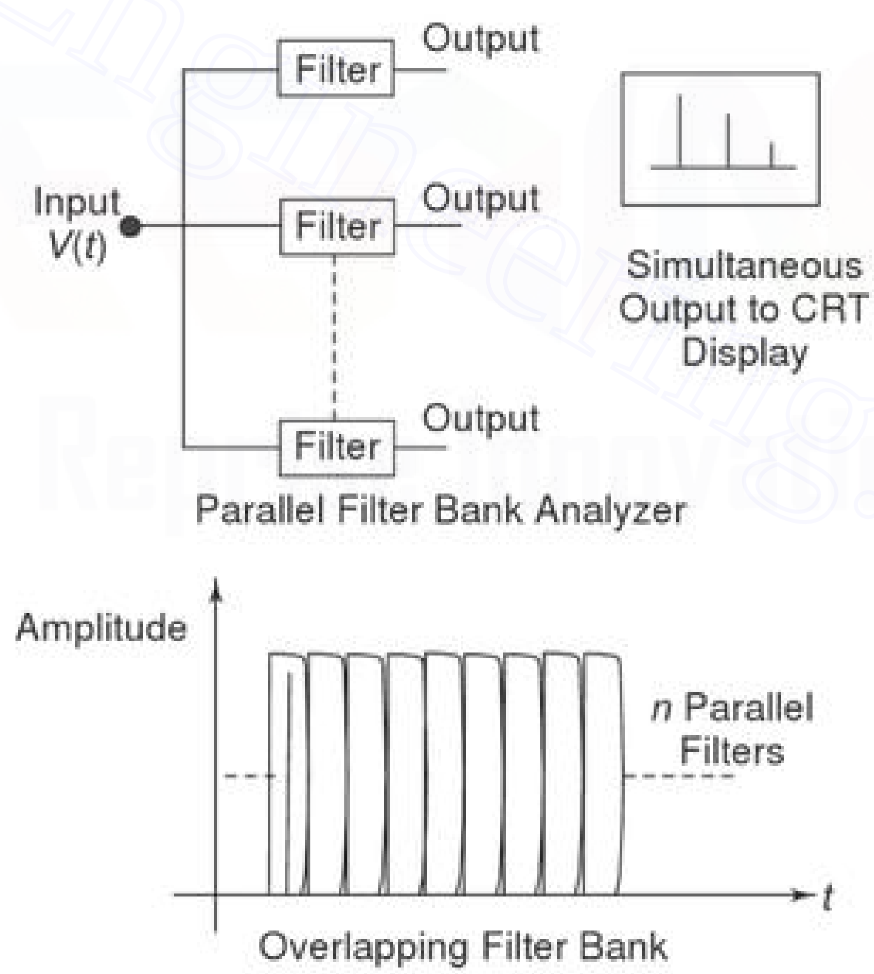


Fig. 9.9 (a) Spectrum analyzer (Parallel filter bank analyzer)

9.6.1 Basic Spectrum Analyzer Using Swept Receiver Design

Referring to the block diagram of Fig. 9.9(b), the sawtooth generator provides the sawtooth voltage which drives the horizontal axis element of the scope and this sawtooth voltage is the frequency controlled element of the voltage tuned oscillator. As the oscillator sweeps from f_{min} to f_{max} of its frequency band at a linear recurring rate, it beats with the frequency component of the input signal and produce an IF, whenever a frequency component is met during its sweep. The frequency component and voltage tuned oscillator frequency beats together to produce a difference frequency, i.e. IF. The IF corresponding to the component is amplified and detected if necessary, and then applied to the vertical plates of the CRO, producing a display of amplitude versus frequency.

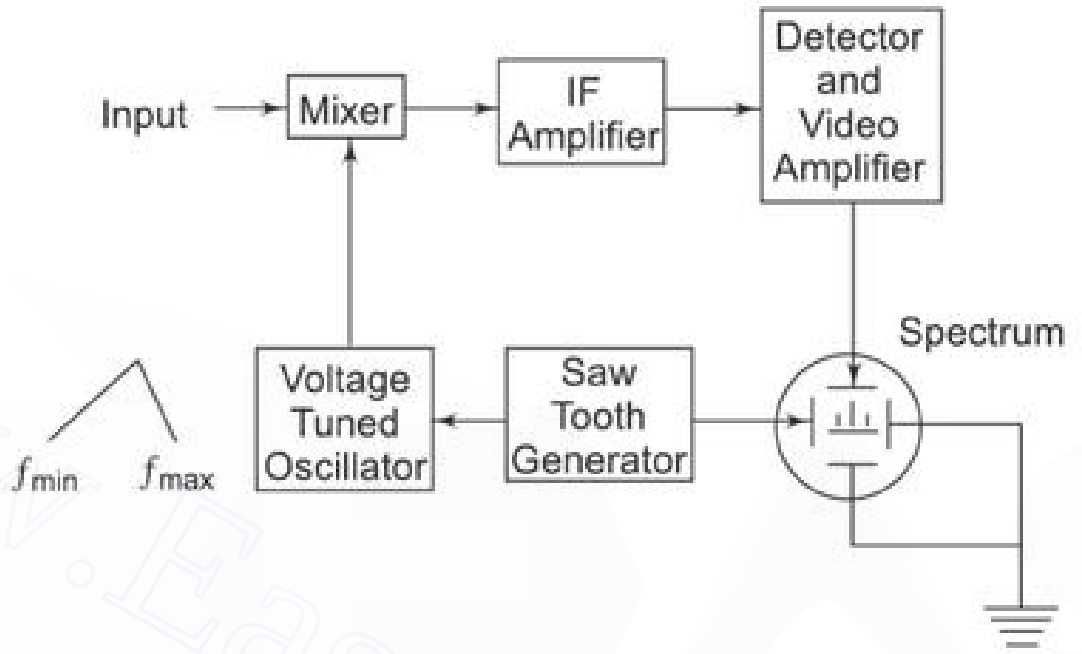


Fig. 9.9 (b) Spectrum analyzer

The spectrum produced if the input wave is a single toned A.M. is given in Figs 9.10, 9.11, and 9.12.

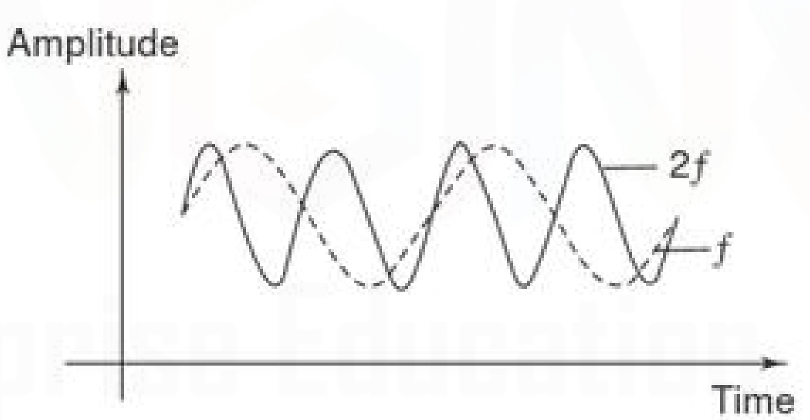


Fig. 9.10 Test wave seen on ordinary CRO

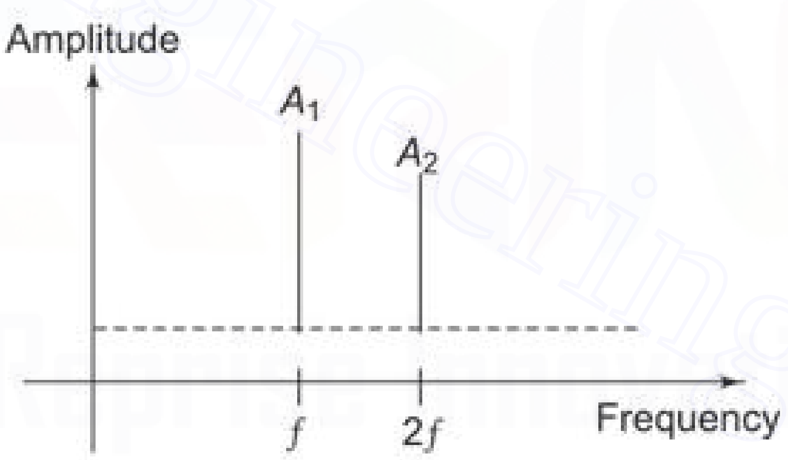


Fig. 9.11 Display on the spectrum CRO

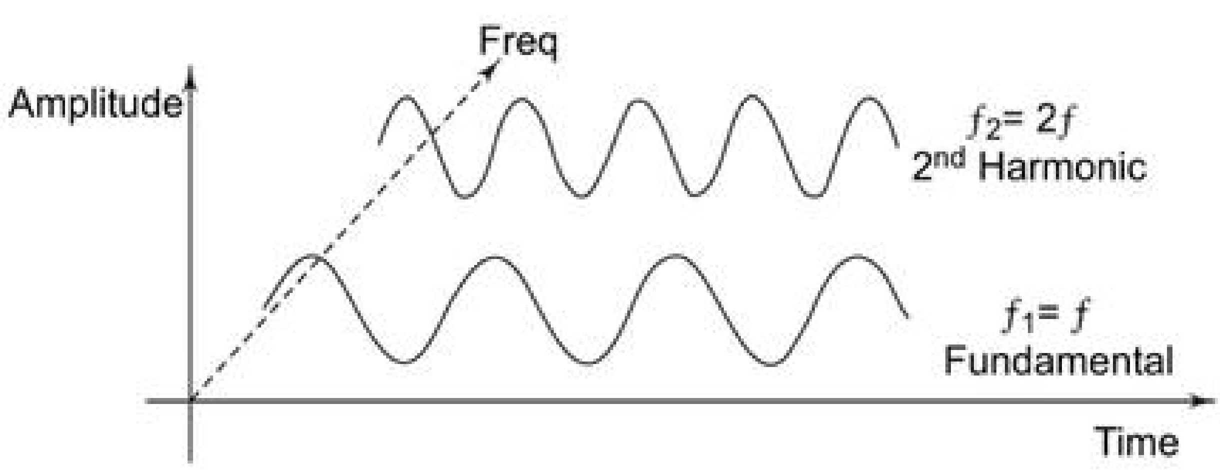


Fig. 9.12 Test waveform as seen on X-axis (Time) and Z-axis (Frequency)

One of the principal applications of spectrum analyzers has been in the study of the RF spectrum produced in microwave instruments. In a microwave instrument, the horizontal axis can display as a wide a range as 2 – 3 GHz for a broad survey and as narrow as 30 kHz, for a highly magnified view of any small portion of the spectrum. Signals at microwave frequency separated by only a few kHz can be seen individually.

The frequency range covered by this instrument is from 1 MHz to 40 GHz. The basic block diagram (Fig. 9.13) is of a spectrum analyzer covering the range 500 kHz to 1 GHz, which is representative of a superheterodyne type.

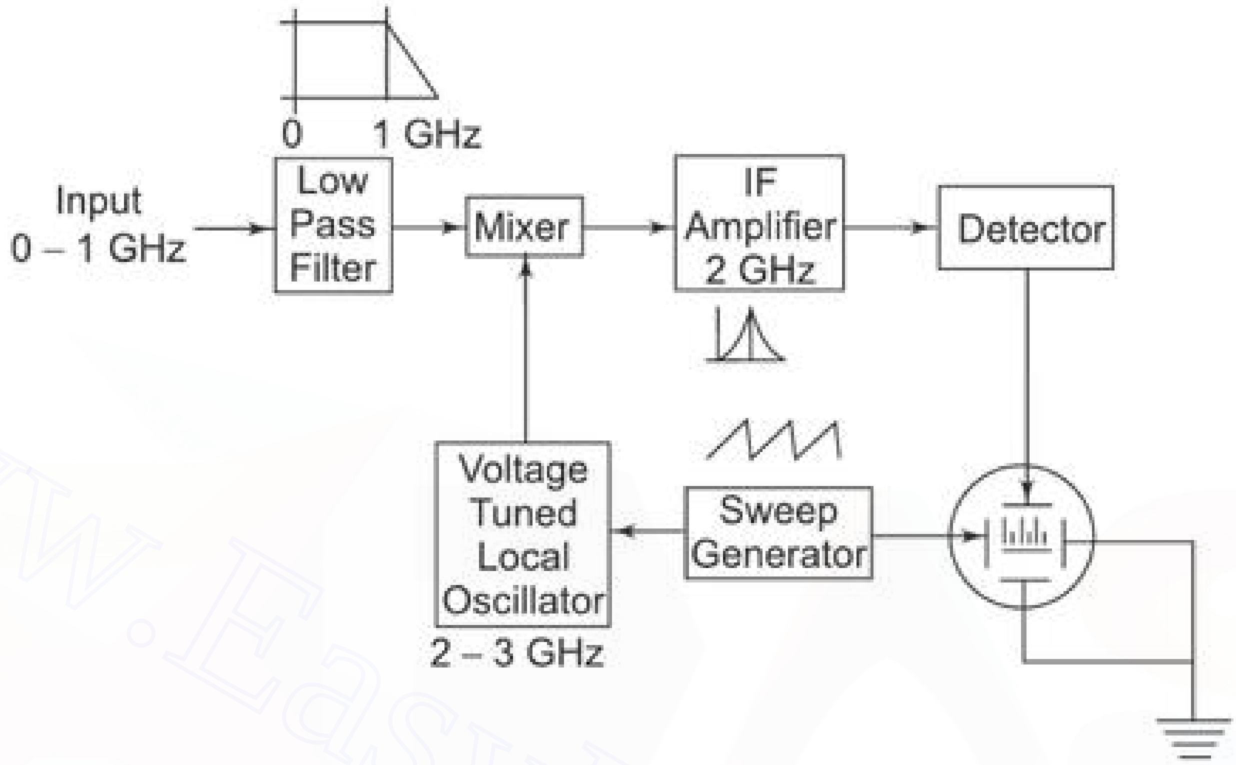


Fig. 9.13 RF spectrum analyzer

The input signal is fed into a mixer which is driven by a local oscillator. This oscillator is linearly tunable electrically over the range 2 – 3 GHz. The mixer provides two signals at its output that are proportional in amplitude to the input signal but of frequencies which are the sum and difference of the input signal and local oscillator frequency.

The IF amplifier is tuned to a narrow band around 2 GHz, since the local oscillator is tuned over the range of 2 – 3 GHz, only inputs that are separated from the local oscillator frequency by 2 GHz will be converted to IF frequency band, pass through the IF frequency amplifier, get rectified and produce a vertical deflection on the CRT.

From this, it is observed that as the sawtooth signal sweeps, the local oscillator also sweeps linearly from 2 – 3 GHz. The tuning of the spectrum analyzer is a swept receiver, which sweeps linearly from 0 to 1 GHz. The sawtooth scanning signal is also applied to the horizontal plates of the CRT to form the frequency axis. (The spectrum analyzer is also sensitive to signals from 4 – 5 GHz referred to as the image frequency of the superheterodyne. A low pass filter with a cutoff frequency above 1 GHz at the input suppresses these spurious signals.) Spectrum analyzers are widely used in radars, oceanography, and bio-medical fields.

DIGITAL FOURIER ANALYZER 9.7

The basic principle of a digital fourier analyzer is shown in Fig. 9.14. The digital fourier analyzer converts the analogue waveform over time period T into N samples.

The discrete spectral response $S_x(k\,\Delta f)$; $k = 1, 2, ..., N$ which is equivalent to simultaneously obtaining the output from N filters having a bandwidth given by

$\Delta f = 1/T$, is obtained by applying a Discrete Fourier Transform (DFT) to the sampled version of the signal. The spectral response is thus given by

$$S_x(k\,\Delta\,f) = \frac{T}{N}\sum_{n=1}^{N} x(n\cdot\Delta t)\,\exp\left(\frac{-j\,2\,\Pi\,k\,n}{N}\right)$$

where $k = 1, 2, 3, ..., N$.

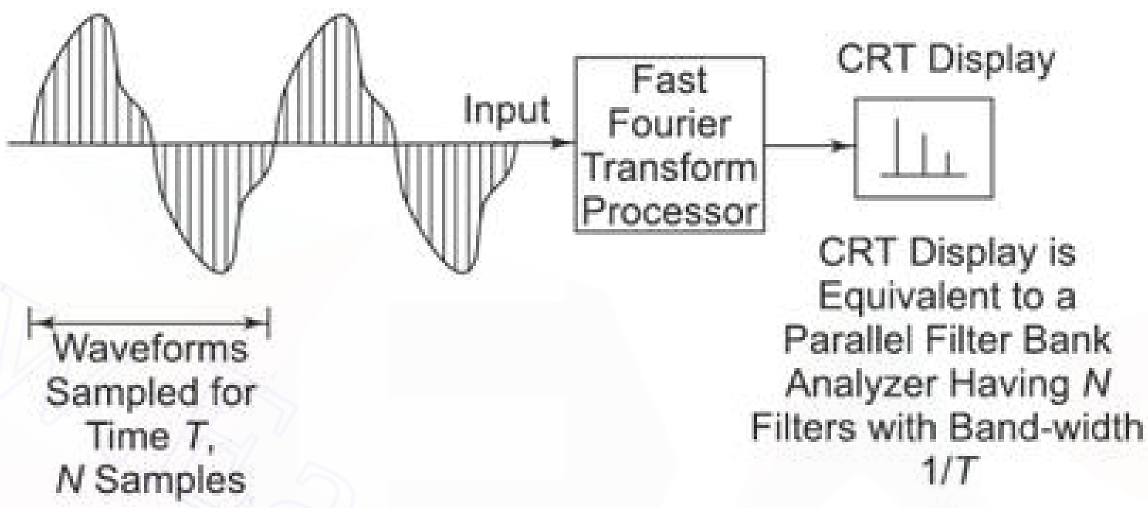


Fig. 9.14 Basic of a digital fourier analyzer

$S_x(k\,\Delta\,f)$ is a complex quantity, which is obtained by operating on all the sample $x(n\cdot\Delta\,t)$; $n = 1, 2, 3, ..., N$ by the complex factor $\exp[-j\,[(2\,\Pi\,kn)/N]]$.

The discrete inverse transform is given by

$$x(n\cdot\Delta t) = \frac{N}{T}\sum_{n=1}^{N} S_x(k\cdot\Delta f)\,\exp\left(\frac{-j\,2\,\Pi\,k\,n}{N}\right)$$

where $n = 1, 2, ..., N$.

Since $S_x(k\cdot\Delta f)$; $k = 1, 2, ..., N$ is a complex quantity, the DFT provides both amplitude and phase information at a particular point in the spectrum.

The discrete transforms are usually implemented by means of the Fast Fourier Transform (FFT), which is particularly suitable for implementation in a digital computer, since N is constrained to the power of 2, i.e. $2^{10} = 1024$.

A digital signal analyzer block diagram is shown in Fig. 9.15. This digital signal analyzer employs an FFT algorithm.

The block diagram is divided into three sections, namely the input section, the control section and the display section.

The input section consists of two identical channels. The input signal is applied to the input amplifier, where it is conditioned and passed through two or more anti-aliasing filters. The cut-off frequencies of these filters are selected with respect to the sampling frequency being used. The 30 kHz filter is used with a sampling rate of 102.4 kHz and the 300 kHz filter with a sampling rate of 1.024 MHz.

To convert the signal into digital form, a 12 bit ADC is used. The output from the ADC is connected to a multiplier and a digital filter.

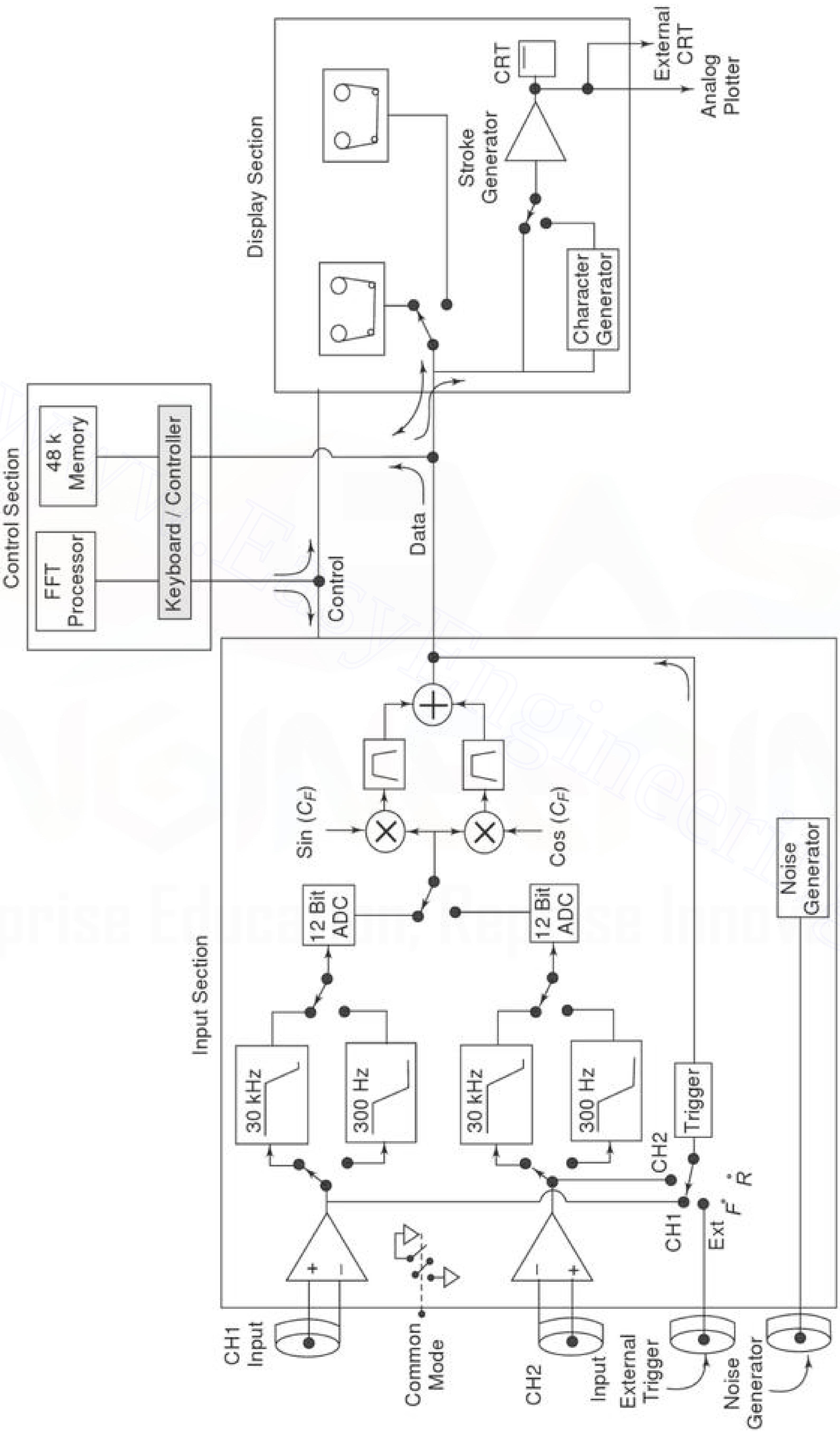


Fig. 9.15 Block diagram of a digital signal analyzer

Depending on the mode of the analyzer to be used, either in Base-band mode (in which the spectrum is displayed from a dc to an upper frequency within the bandwidth of the analyzer) or in the band selectable mode (which allows the full resolution of the analyzer to be focussed in a narrow frequency band), the signal is multiplied either by a sine or cosine function.

The processing section of the analyzer provides FFT processing on the input signal (linear or logarithm).

For one channel this can provide the real (magnitude) and imaginary (phase) of the linear spectrum $S_x(f)$ of a time domain signal

$$S_x(f) = F(x(t))$$

where $F(x(t))$ is the Fourier transform of $x(t)$. The autospectrum $G_{xx}(f)$ which contains no phase information is obtained from $S_x(f)$ as

$$G_{xx}(f) = S_x(f)\, S_x(f)^*$$

where $S_x(f)^*$ indicates the complex conjugate of $S_x(f)$.

The Power Spectral Density (PSD) is obtained by normalising the function $G_{xx}(f)$ to a bandwidth of 1 Hz, which represents the power in a bandwidth of 1 Hz centered around the frequency f.

The Inverse Fourier Transform of $G_{xx}(f)$ is given by

$$R_{xx}(\tau) = F^{-1}(G_{xx}(f))$$
$$R_{xx}(\tau) = F^{-1}(S_x(f)\, S_x(f))^*$$

writing the above equation in terms of the time domain characteristics of the signal $x(t)$, its autocorrelation function is defined as

$$R_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t)\, x(t+\tau)\, dt$$

By the use of two channels, the combined properties of the two signals can be obtained. The cross-power spectrum of the two signals $x(t)$ and $y(t)$ can be computed as

$$G_{yx}(f) = S_y(t)\, S_x(t)^*$$

where $S_y(t)$ is the linear spectrum of $y(t)$ and $S_x(t)^*$ is the complex conjugate spectrum of $x(t)$.

If $x(t)$ represents the input to a system and $y(t)$ the output of the system, then its transfer function $H(f)$, which contains both amplitude and phase information can be obtained by computing

$$H(f) = \frac{\overline{G_{yx}(f)}}{\overline{G_{xx}(f)}}$$

where the bars indicate the time averaged values.

The input signal used for such measurements is often the internal random noise generator.

PRACTICAL FFT SPECTRUM ANALYSIS USING A WAVEFORM PROCESSING SOFTWARE (SS-36) 9.8

The Waveform Processing Software (SS-36) enables one to analyze waveforms very easily. The waveform is captured on a Digital Storage Oscilloscope (DSO) and is transferred to a PC via an RS 232 Serial Interface, which may be in-built in some DSOs.

Further, the software is programmed to work with almost any configuration of PC. The software automatically senses the system and configures itself for it (i.e. whether you are using a monochrome or colour monitor, whether you have a co-processor or not etc.).

Suppose a voltage and current waveform in a circuit, is captured on a DSO.

If the voltage is multiplied with the current, power is obtained and if voltage is divided by current, impedance is obtained. If this is done for all 1000 values of the voltage and the current captured on the DSO and plotted, a power and impedance curve is obtained. This process is performed by the software itself. The software can also perform multiplication, division, addition, and subtraction of two simple waveforms, as shown in Fig. 9.16. Figures 9.16(d) and (e) shows one waveform can be added and subtracted by another waveform using FFT analysis.

FFT spectrum analysis is also a very powerful tool. The conventional CRO gives a display of voltage versus time, but by using FFT, the amplitudes of the various frequencies that constitute the waveform can be obtained. The voltage versus frequency plot then shows the spectral content of the waveform. For instance, if a mains voltage is captured and analyzed, its harmonic content can be obtained.

The frequency range of FFT spectrum analysis is from 0.002 Hz to 10 MHz. The minimum step or frequency resolution possible is 0.002 Hz. The display can be linear or logarithmic.

Another example of waveform processing is of an amplitude modulated signal (100 kHz modulated by 8 kHz). This waveform, along with its fourier analysis, is illustrated in Fig. 9.17.

Figure 9.17(2a) shows a AM 100 kHz waveform modulated by 8 kHz, captured on a digital storage oscilloscope and on a PC.

Figure 9.17(2b) and (2c) shows its FFT analysis (carrier and sidebands).

Figure 9.17(1a) illustrates the captured waveform of an electrical or mechanical impulse.

Figure 9.17(1b and 1c) shows the FFT spectral analysis.

Figure 9.18 Shows a pictorial set up of FFT spectrum analysis.

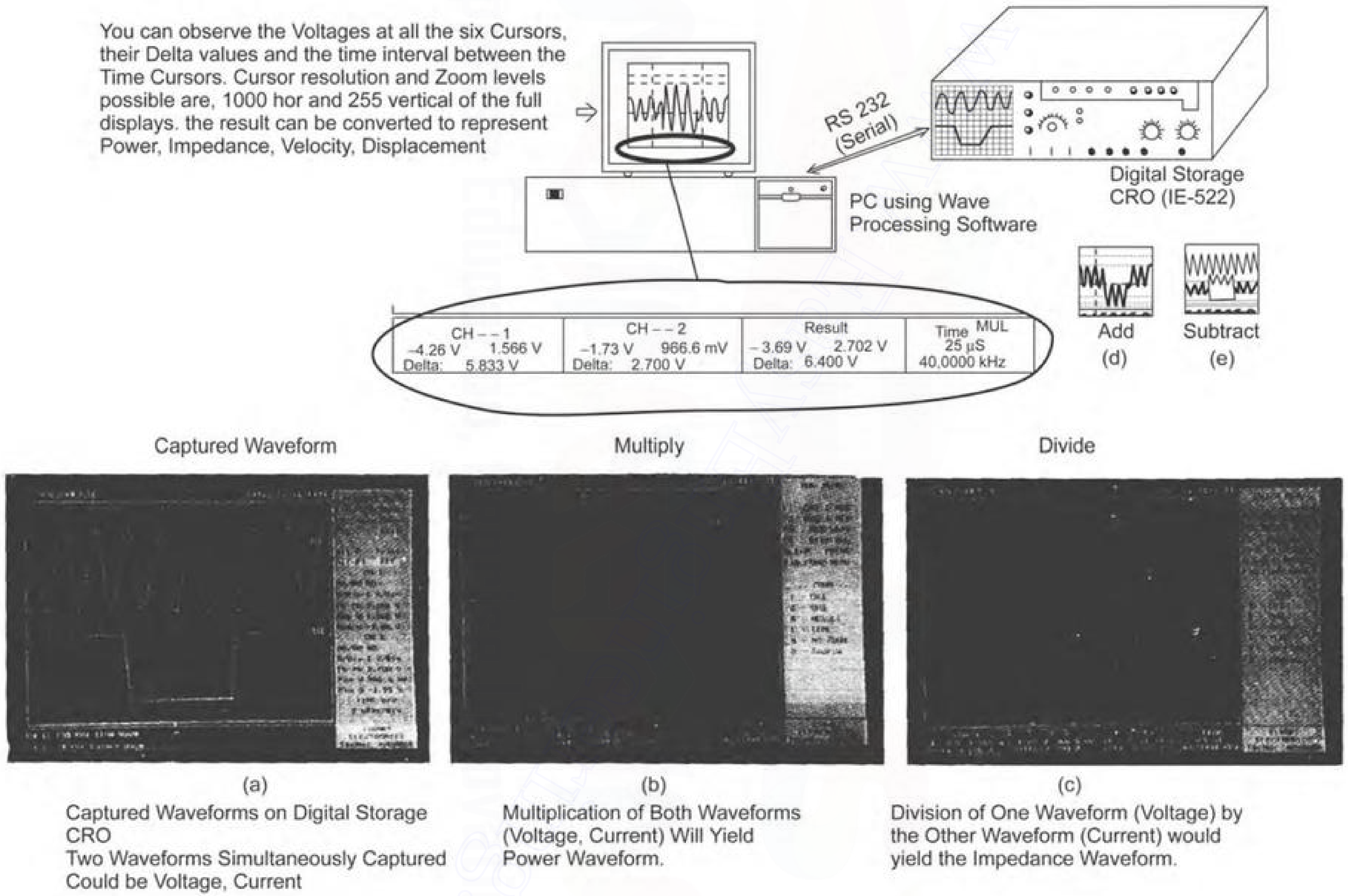
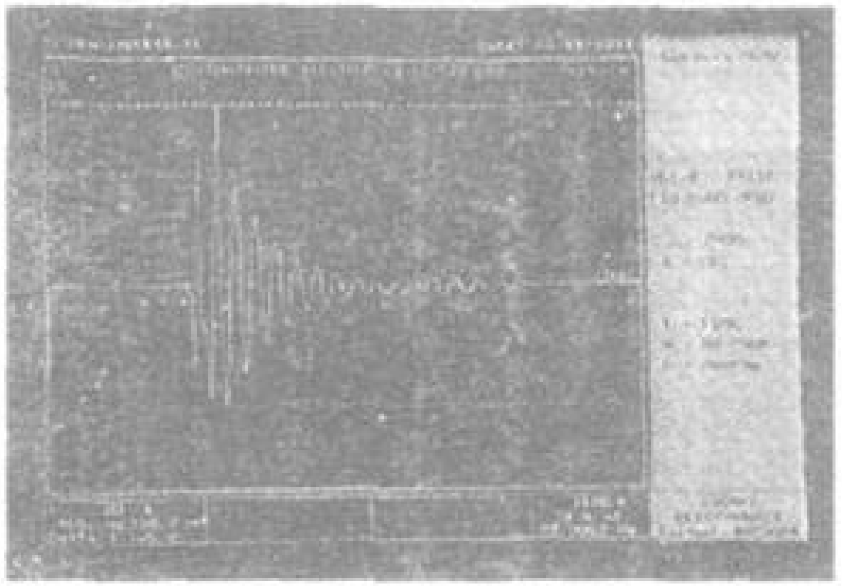
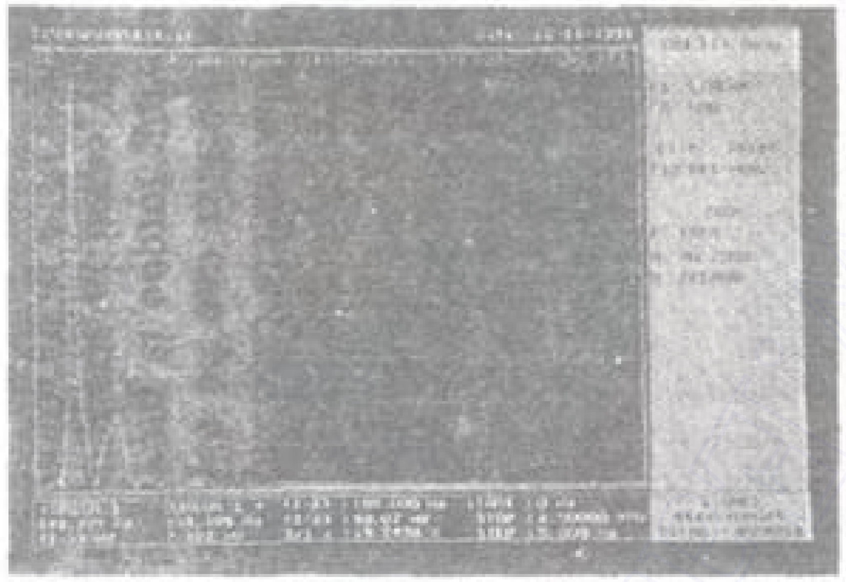


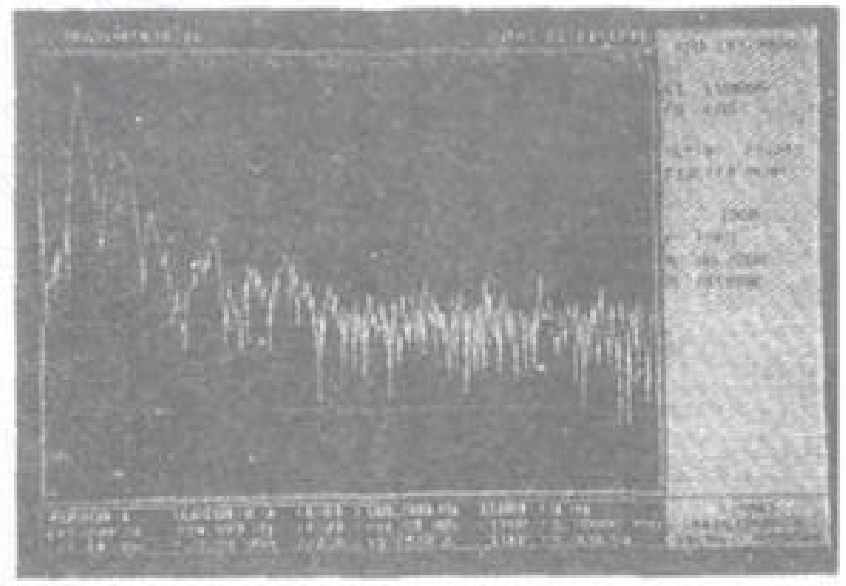
Fig. 9.16 Software waveform processing using digital storage CRO and a PC [Courtesy: International Electronics Ltd] [Marketed: Signatics Elec-



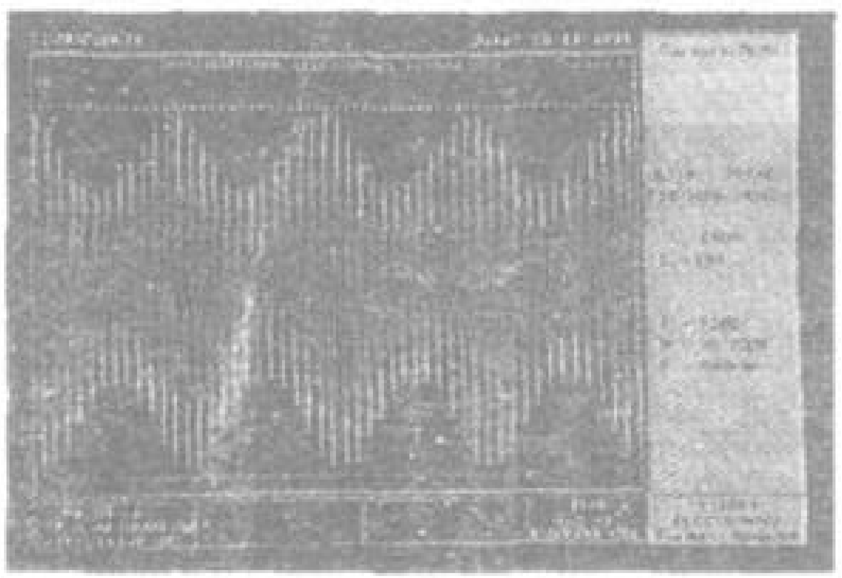
1(a) Impulse Captured on DSO can be Electrical, Mechanical



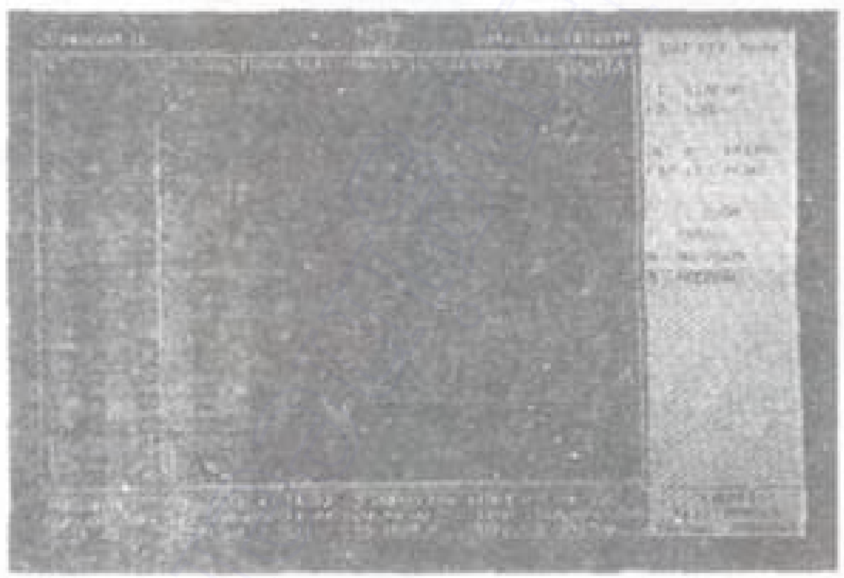
1(b) Spectral Display in LINEAR Mode, (B) in LOG Mode



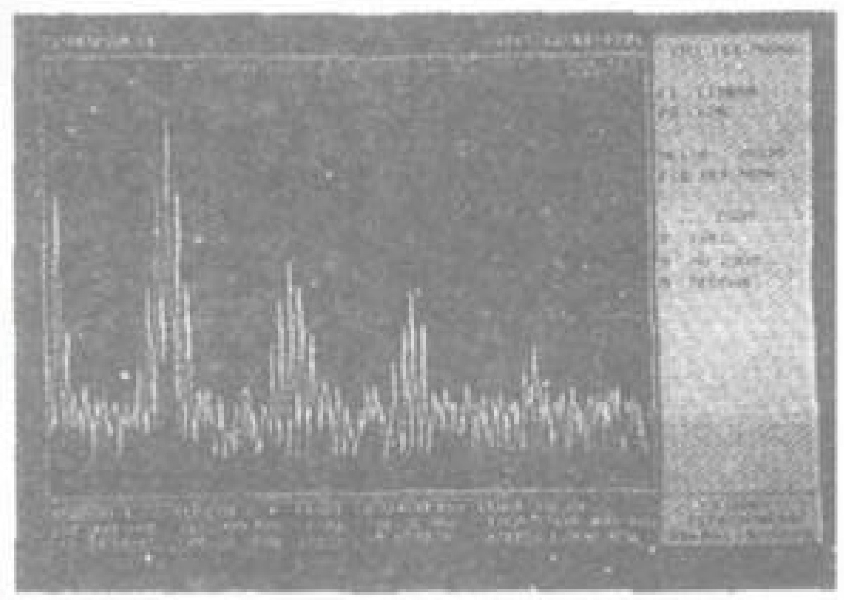
1(c) FFT Analysis of Impulse-Cursor Measure Amplitude & Freq. (T)



2(a) AM Modulated 100 kHz by 8 kHz

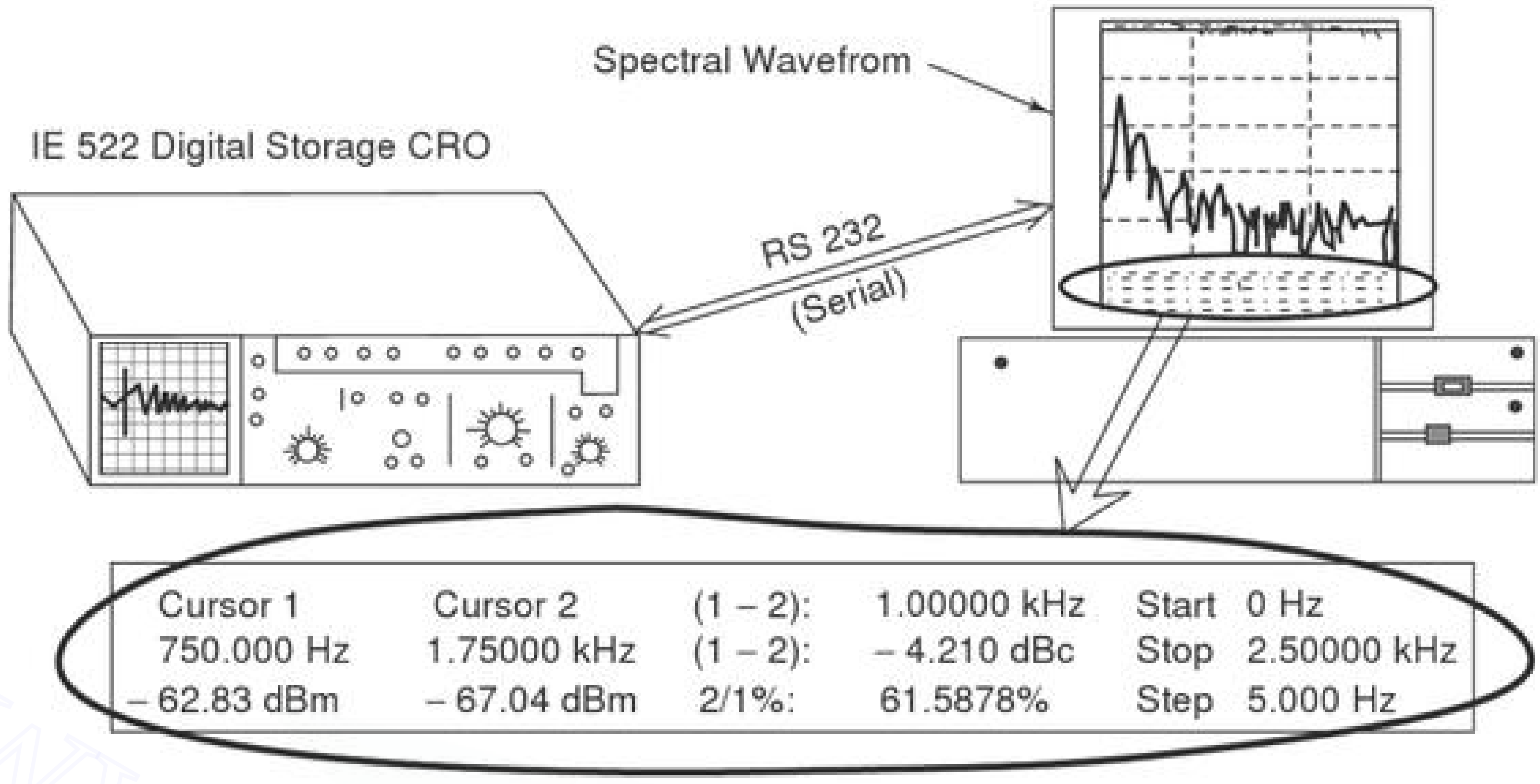


2(b) FFT Analysis Shows the Carrier and the Sidelobes



2(c) Cursors gives Ampl, Freq, % Modulation, 2nd Harmonics

Fig. 9.17 Spectral analyses using 1. Impulse (electrical/mechanical) 2. AM modulated 100 kHz by 8 kHz. Courtesy: Manfactured by International Electronics Ltd Marketd by Signetics Electronics Ltd. Bombay



Cursor 1 and Cursor 2 Amplitudes / Frequencies / Freq Difference / Amplitude Diff / Harmonic Content Ratio etc. are displayed and will be computed dynamically as the cursors are moved. The "START" and "STOP" frequency denote the min and max frequency range of the display. The STOP frequency can range from 1 Hz to 10 MHz. Thus the minimum STEP or frequency resolution possible is 0.002 Hz. Display can be in Lin/Log. Horizontal Zoom level is 500.

Fig. 9.18 Set-up of FFT spectrum analysis

Review Questions

1. Define a wave analyzer. List different types of wave analyzers.
2. Explain with a diagram the operation of a basic wave analyzer.
3. Explain with a diagram the operation of a frequency selective wave analyzer.
4. Explain heterodyning. State the working principle of a heterodyne wave analyzer.
5. Describe with a diagram the operation of a heterodyne wave analyzer.
6. Explain with help of a block diagram the operation of an AF wave analyzer.
7. Describe the term real time analysers.
8. Explain with a diagram the working principle of a spectrum analyzer.
9. Explain with help of a block diagram the operation of a spectrum analyzer. State applications of a spectrum analyzer.
10. Differentiate between AF wave analyzer and RF wave analyzer.
11. Differentiate between wave analyzer and spectrum analyzer.
12. Define distortion. Define harmonics and the term 'total harmonic distortion'.
13. Explain the meaning of distortion factor. Explain how these distortion factors can be measured.
14. Why is it necessary to measure distortion? List various methods used for measurement of harmonic distortion.
15. Define a distortion analyzer. State the working principle of a distortion analyzer.
16. State different types of harmonic distortion analyzer.
17. Explain with a diagram, the suppression method of a harmonic distortion analyzer.
18. Explain with a diagram, the Wien bridge method of a harmonic distortion analyzer.
19. Describe with a diagram the operation of a harmonic distortion analyzer using a bridged-T network.

20. Explain the procedure of measurement of a harmonic distortion analyzer using a bridged-T type.
21. Describe the operation of a distortion analyzer using resonance to suppress the fundamental frequency
22. Compare resonance bridge to a Wien bridge harmonic distortion analyzer.
23. Compare Wien Bridge to a bridged-T network type harmonic distortion analyzer.
24. State applications of a distortion factor meter.
25. Explain the front panel controls and applications of a distortion factor meter in trouble shooting.
26. Describe the causes of harmonic distortions.
27. Explain the basic principle of a digital Fourier analyzer.
28. Describe with diagram the operation of a digital Fourier analyzer.
29. Explain in brief the operation of a practical FFT spectrum analyzer.

Multiple Choice Questions

1. Wave analyzers are used in the frequency range of
   (a) VHF (b) UHF
   (c) lower RF (d) higher RF
2. Wave analyzers are used to measure the
   (a) amplitude and phase
   (b) phase and frequency
   (c) amplitude and frequency
   (d) frequency band
3. Wave analyzers are also called a
   (a) phase meters
   (b) frequency selective voltmeter
   (c) distortion analyzer
   (d) spectrum analyzer
4. A heterodyne wave analyzer operates on the principle
   (a) mixing (b) amplification
   (c) addition (d) subtraction
5. A wave analyzer consists of
   (a) RC circuit (b) LC circuit
   (c) oscillator (d) rectifier
6. The bandwidth of a wave analyzer is
   (a) wide (b) narrow (c) medium
7. A spectrum analyzer works in
   (a) time domain (b) amplitude
   (c) frequency domain (d) phase
8. A spectrum analyzer uses at the output a
   (a) frequency meter (b) TVM
   (c) rectifier (d) circuit
9. The frequency axis in a spectrum analyzer is the
   (a) X-axis (b) Y-axis (c) Z-axis
10. A spectrum analyzer is used to display
    (a) frequency band spectrum
    (b) amplitude
    (c) time (d) phase
11. A distortion is defined as
    (a) unwanted frequency
    (b) unwanted amplitude
    (c) change in shape of the waveform
    (d) unwanted signal
12. A distortion analyzer measures the total
    (a) average power (b) RMS power
    (c) peak power (d) dc power

Further Reading

1. Terman and Petit, *Electronic Measurements*, McGraw-Hill, 1952.
2. Jones, *Instrument Technology*, Vol. 4, *Instrumentation Systems*, B.E. Notlingk Butterworth, 1987.
3. *Handbook of Electronic Measurement*, Volumes I & II, Polytechnic Inst. of Brooklyn, 1956 (Microwave Research Inst.).
4. Oliver Cage, *Electronic Measurements and Instrumentation*, McGraw-Hill, 1975.

Measuring Instruments

Chapter 10

INTRODUCTION 10.1

Meters and measuring instruments play an important role in all phases of electronics. Meters helps us to determine how an electronic circuit, is performing.

The most fundamental electrical measurements are those of voltage, current and impedance. The instruments used in measuring these quantities form the building blocks of more complex equipment used in power, frequency, attenuation, and other special measurements.

A measuring device converts a primary indication into some form of energy that can be easily displayed on a scale.

OUTPUT POWER METERS 10.2

The output power Wattmeter is designed to directly measure the output power in an arbitrary load. The instrument provides a set of resistive loads to be selected for power measurements. In addition to power, the output meter can be used to measure impedance and frequency response characteristics. A simple circuit is illustrated in Fig. 10.1.

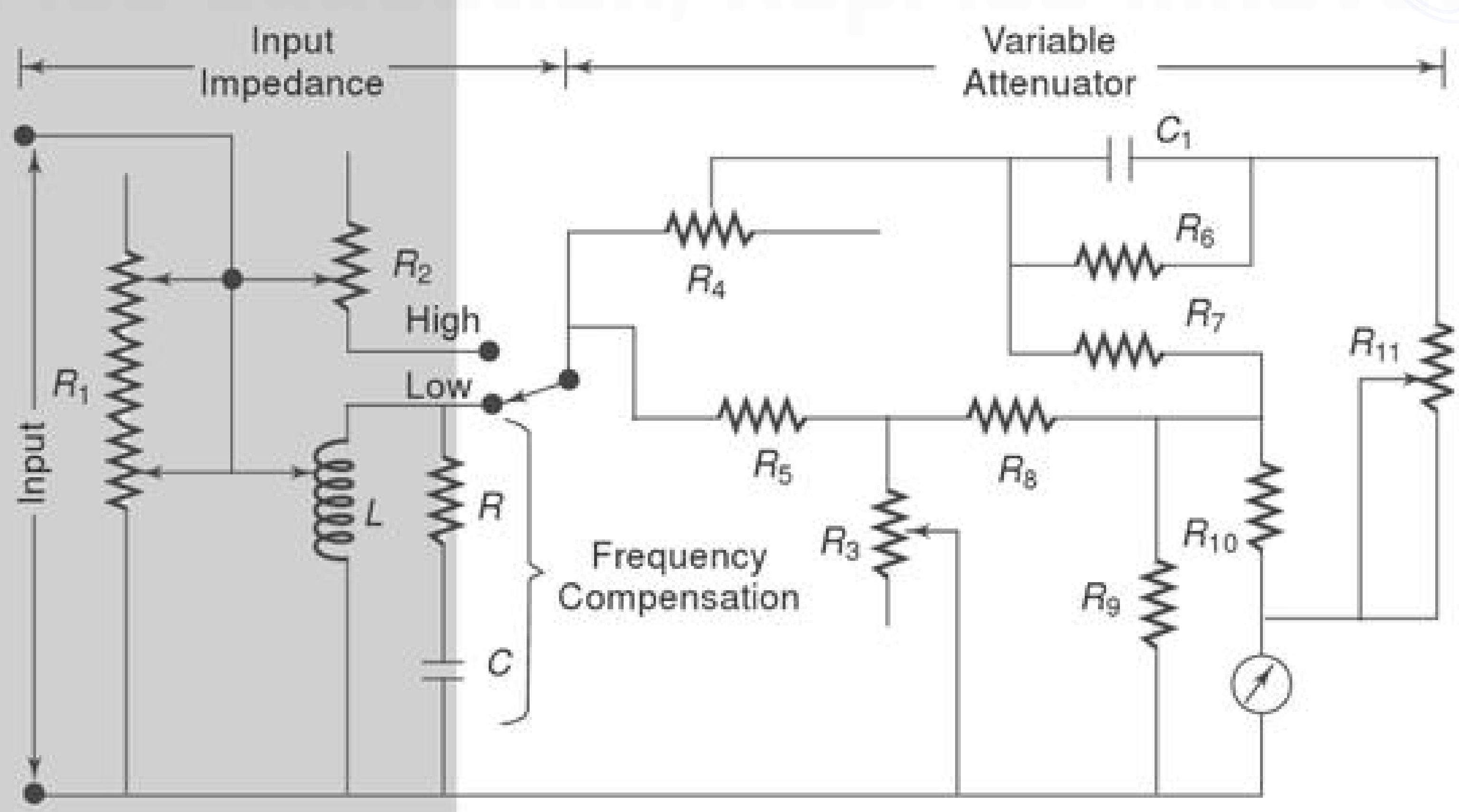


Fig. 10.1 Output-meter circuit

The input impedance network consist of two tapped resistances and a coil. The input impedance can be varied in steps from 2.5 Ω to 40 kΩ. At low impedance values, the coil shunts a portion of R_1 – an increase in resistance results in fewer turns of the coil. This arrangement keeps the meter reading proportional to the energy dissipated by the resistor. At high impedance values, the coil is replaced by another tapped resistance R_2.

The RC frequency compensator is in parallel with the coil. At low frequency, the capacitive reactance X_c is high; it decreases as frequency increases. This compensates for the losses of the coil at low frequencies. The frequency range is generally between 20 Hz and 20 kHz. R_3 is the control in a variable *T*-network. This amounts to a variable meter shunt, which is used to extend the range of the meter. The lowest meter range is normally 5 mW, but it can be extended in decade steps of 50 mW, 500 mW, etc.

The remaining circuit is a combination of a calibration and frequency compensation network. A meter of this type may have a midscale accuracy of ± 2% at 1 KHz. Over the frequency range of 20 Hz – 15 KHz, the accuracy may be within ± 2% of the 1 kHz value.

The input meter is subjected to an waveform error when the input is other than sinusoidal. (Practical instruments for measuring the power output of oscillators, amplifiers, transformers, transducers and low frequency lines use an input impedance of a tapped transformer with 48 impedance setting). It can be used to measure output impedance by adjusting the maximum power. It can also be used to check the frequency response characteristics of audio frequency devices.

FIELD STRENGTH METER 10.3

The field strength meter is used to measure the radiation intensity from a transmitting antenna at a given location. With its own small antenna, it is essentially a simple receiver with an indicator.

The wavemeter circuit with a rectifier-meter indicator, as shown in Fig. 10.2(a), is often equipped with a small whip antenna, and is called as a Field strength meter. (Although it is possible to obtain an indication with this setup when the whip antenna of the meter is positioned fairly close to the transmitting antenna, the sensitivity is generally not high enough for use with ordinary low-powered transmitters or test radiations.)

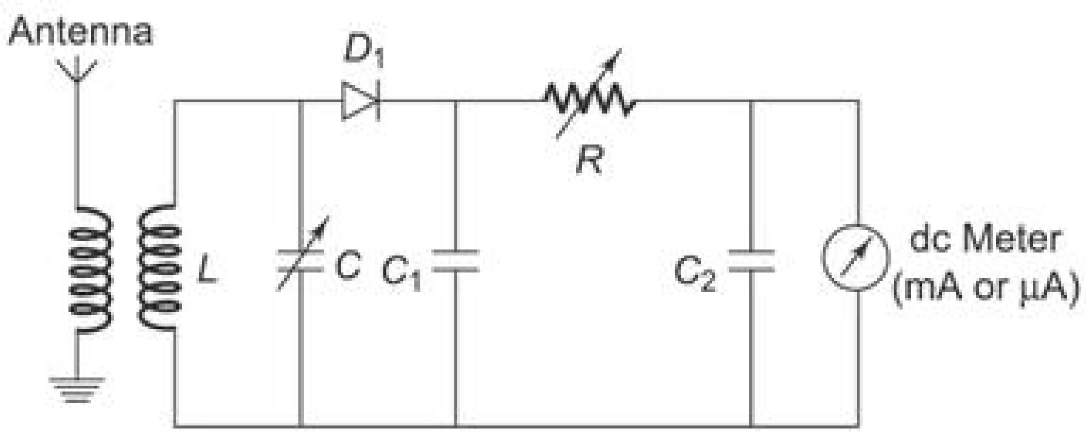


Fig. 10.2 (a) Field strength meter

The field strength measurement should be made at a distance of several wavelengths from the transmitting antenna, to avoid misleading readings when the pickup is obtained from a combination of radiation field with the induction field close to the transmitter. To enable the wavemeter combination to act as a field strength meter, greater sensitivity can be easily obtained with the addition of a transistor dc amplifier, as shown in Fig. 10.2(b). (The coil L is held near an oscillating circuit to provide loose coupling, and the capacitor C is tuned to resonance. When the dial of the variable capacitor is calibrated in terms of frequency, the unit becomes very useful as a rough frequency meter. Since the wavemeter is tuned to resonance, it will absorb the greatest amount of energy, and cause a detectable change in an indicating meter of the transmitter.)

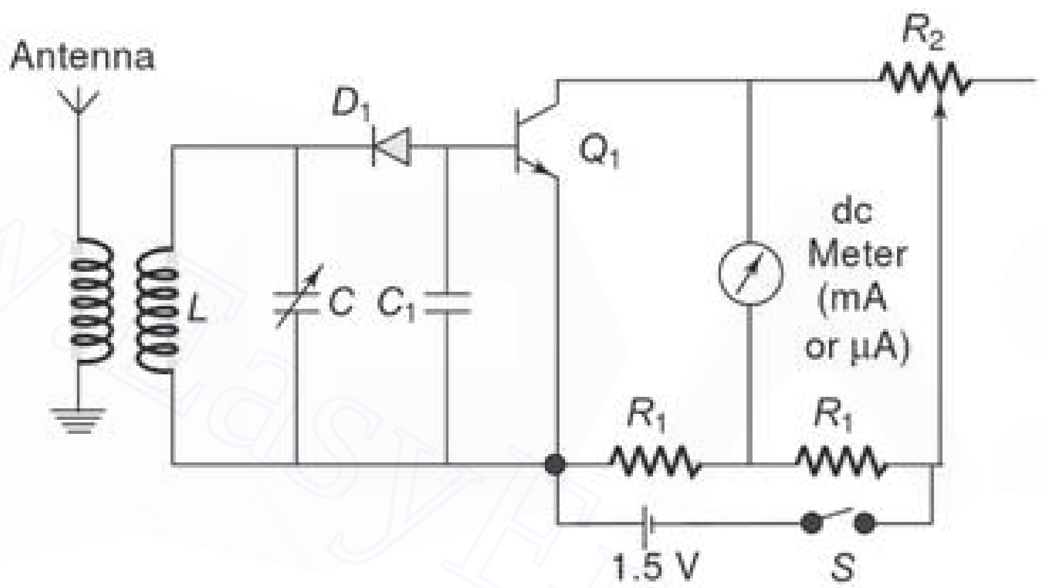


Fig. 10.2 (b) Field strength meter (transistor)

The transistor provides ample current gain, so that satisfactory sensitivity is obtained. The transistor is connected in a common emitter configuration. With no signal being received, the quiescent current is balanced out by the back up current, through the variable resistor R_2. This zero balance should be checked at intervals, since the quiescent current is sensitive to temperature changes.

The collector current through the meter provides an indication of the strength of the RF wave being picked up. This current is not strictly proportional to the field strength, because of the combined non-linearities of the semiconductor diode and transistor. However, the response is satisfactory for the relative comparison of field strength.

STROBOSCOPE 10.4

The stroboscopic principle uses a high intensity light which flashes at precise intervals. This light may be directed upon a rotating or vibrating object. The stroboscopic effect is apparent when the rotational or vibratory speed is in a proper ratio with the frequency of the light flashes.

Most stroboscopes consist of an oscillator, a reed, and a flasher, as illustrated in Fig. 10.3. The oscillator provides trigger pulses to the flasher mechanism to control the flashing rate. The oscillator is generally an externally triggered multivibrator. The vibrating reed serves as a reference for accurately calibrating the stroboscope. The reed is driven from the ac lines and vibrates at 7200 times per minute. This steady rate is used to standardise the calibration scale over a narrow range. The flasher produces the illumination for the measurements.

Fig. 10.3 Basic stroboscope block diagram

The flasher tube is fired by a capacitor discharge, which is, in turn, controlled by trigger pulses from the oscillator. The tube is filled with a suitable inert gas which produces light when it is ionised. The tube life ranges from 200 to 1000 hours, depending upon the operating conditions.

When the frequency of movement exactly matches the stroboscope frequency, the moving object is viewed clearly only once during each revolution. This causes the moving object to appear as a single stationary image. A stationary image also appears when the speed of rotation is some exact multiple of the stroboscope frequency. The highest scale reading that produces the single still image is the fundamental frequency.

Multiple still images appear when the stroboscope frequency is some multiple of the rotation frequency. In this case the light flashes more than once during each rotation of the object. (The radial line at the end of the shaft may appear as several equally spaced lines. If lamp frequency is twice the rotational frequency, two images are produced, 180° apart. If the lamp frequency is three times the rotational frequency, three images appear, each at a spacing of 120°.)

Moving images are obtained when the light frequency and rotational frequency are not synchronised. When the image appears to rotate in a direction opposite to that of actual rotation, the rotation frequency is less than the flasher frequency. When it appears to rotate in the same direction as the actual rotation, the rotation frequency is higher than the flasher frequency.

A stroboscope may be used to check motor or generator speeds ranging from 60 to 1,000,000 rpm. The stroboscope is highly versatile, uses no power from the circuit being measured and when calibrated, has an accuracy as close as 0.1%. (Some scopes, use the line frequency for calibration. The flash lamp and reflector assembly rotates 360° for maximum flexibility. The case may be mounted on a tripod. The flash rate is 110 to 150,000 flashes per minute, enabling measuring speeds of up to 1,000,000 rpm. The light output varies with the flash rate, from 3 μs to 0.5 μs.)

PHASE METER 10.5

Figure 10.4 shows a phase sensitive detector (or phase meter) for comparing an ac signal with a reference signal.

The detector produces a rectified output, which is fed to a dc meter, to illustrate clearly that the output of the phase sensitive detector swings the zero centre pointer in one direction for an in-phase error voltage and in the opposite direction for an out-phase condition. Thus, the function of this dual rectifier circuit is to deflect the zero centre galvanometer (or dc voltmeter) not only to indicate the value of the signal voltage V_s (that is, a measure of the error of imbalance), but also the direction of this error, and the phase polarity of the error compared to a reference voltage. Phase polarity implies that the detector distinguishes only between in phase and 180° out of phase conditions, without regard for other phase angles.

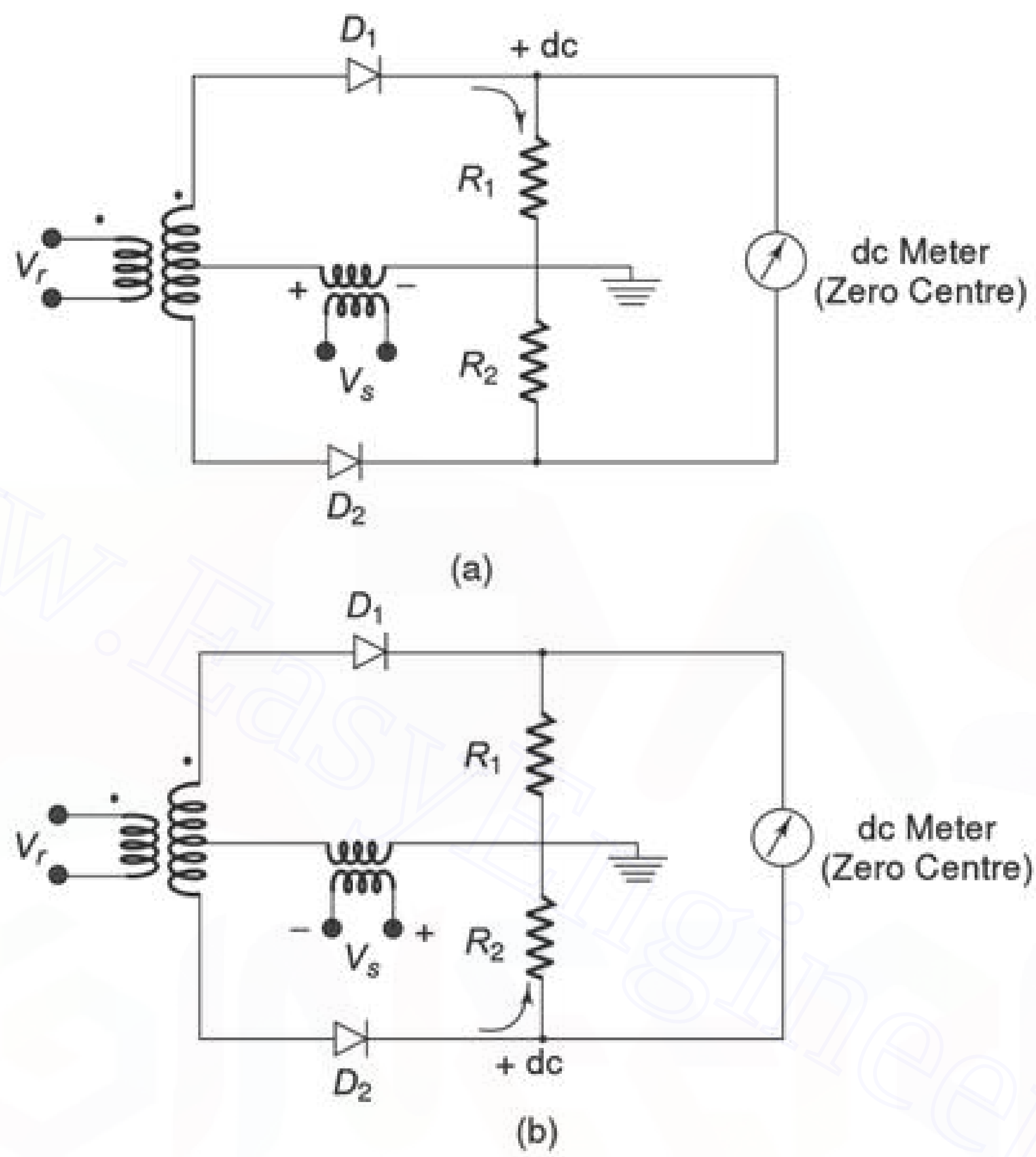


Fig. 10.4 Phase sensitive detector (a) Positive half (b) Negative half

The circuits of Figs 10.4(a) and (b) follows the action for a signal voltage V_s, which is in phase with the reference voltage V_r, starting with an initial condition when the input signal V_s is zero.

In Fig. 10.4(a), for the first half cycle the instantaneous polarity of the reference voltage V_r causes the rectified current to flow through the conduction rectifier D_1, producing a positive voltage to ground across R_1 and a tendency for the meter to deflect to the right.

On the second half cycle, Fig. 10.4(b), the instantaneous polarity of the reference voltage V_r, causes an equal rectified current to flow through diode D_2, producing an equal tendency for the meter to deflect to the left. Since these two equal and opposite tendencies are averaged over the full cycle, the galvanometer reads zero over the full cycle, with input $V_s = 0$.

When an input signal V_s is applied, it either aids or opposes the reference voltage, depending upon whether it is in phase or out of phase with it. If V_s is in phase with V_r, the signal voltage will aid the instantaneous ac voltage in the upper half of the transformer secondary, producing a larger current through D_1

and a larger dc output voltage on the first half. D_2 does not conduct unless V_s is greater than V_r, so that the voltage across R_2 is the rectified result of $V_s - V_r$, and that across R_1 is $V_s + V_r$.

On the other half cycle, the signal voltage is in the opposite direction. Diode D_1 will not conduct in the upper half and the signal voltage will oppose the instantaneous ac voltage, to produce a smaller dc voltage across R_2. The galvanometer therefore deflects to the right in proportion to the magnitude of the in-phase input signal V_s. Similarly, if V_s is 180° out of phase with V_r, the voltages add on the lower half on the transformer secondary, and the galvanometer deflects to the left in proportion to the magnitude of that input signal.

VECTOR IMPEDANCE METER (DIRECT READING) 10.6

If some knowledge of the reactive and resistive factors is needed, in addition to obtaining a direct reading of the magnitude of the impedance (Z), a test method for determining the vector impedance may be employed.

This method determines Z in polar form, that is, it gives the magnitude $|Z|$ and the phase angle (θ) of the impedance being tested, rather than the individual resistance and reactance in rectangular form, ($R + j X$). The test circuit is shown in Fig. 10.5. Two resistors of equal value R is used. The voltage drop across R_{AB} and R_{BC}, that is E_{AB} and E_{BC} will be equal (each value is equal to half the supply voltage, E_{AC}). Since the same current I_1 flows through the variable standard resistor R_{st}, the unknown impedance in series. The magnitude of Z_x can be determined by the equal deflection method by obtaining equal voltage drops across R_{st} and Z_x, i.e. E_{AD} and E_{DC}, and reading the calibrated standard resistor R_{st}, required to produce this condition.

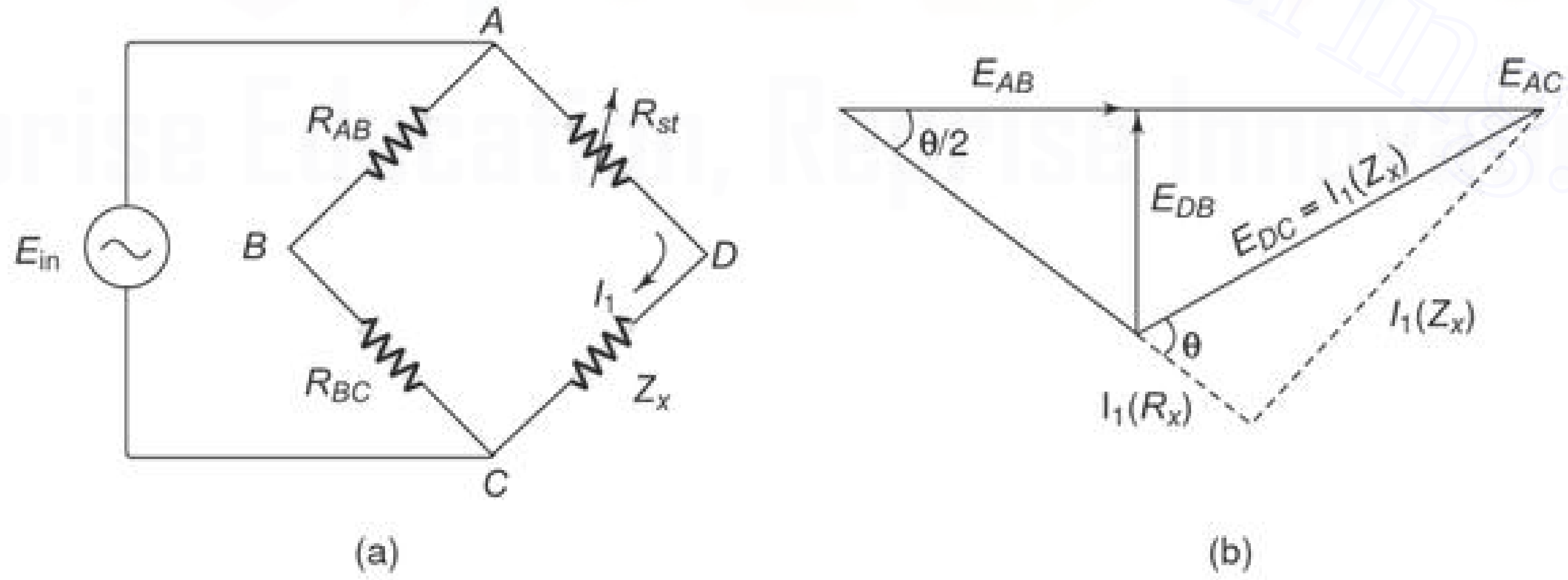


Fig. 10.5 (a) Vector impedance method (b) Vector diagram

The phase angle θ of the impedance Z_x can be obtained from the reading of the voltage at points B and D, that is, E_{DB}. The deflection of the meter will be found to vary with the Q of the unknown impedance Z_x. The VTVM ac voltage reading will vary from 0 V, when the phase angle of 0° ($Q = 0$) to the maximum voltage, with an angle of 90° (Q = infinite). The angle between the voltages E_{AB} and E_{AD} is half the phase angle θ, since E_{AD} is made equal to E_{DC}.

$$\frac{\theta}{2} = \tan \frac{E_{DB}}{E_{AB}}$$

Since E_{AB} is known to be half the known input voltage E_{in}, the voltmeter reading of E_{DB} can be interpreted in terms of $\theta/2$, and hence the phase angle θ of the unknown Z_x can be determined.

While this method for obtaining both Z and θ is approximate because of the crowding caused by the non-linear relation, it is useful for obtaining a first approximation. A commercial vector impedance meter is used for greater accuracy.

10.6.1 Commercial Vector Impedance Meter

A commercial instrument that measures impedance directly in the polar form, giving the magnitude of Z in ohms, at a phase angle θ, requires only one balancing control for both values.

It measures any combination of R, L and C, and includes not only pure resistive, capacitive or inductive elements but also complex impedances. Since the determination of magnitude and angle requires only one balance control, the awkward condition of sliding balance, frequently encountered when measuring low Q reactors with conventional bridge circuits, which necessitates so much successive adjustments, is avoided.

Measurements of impedances ranging from 0.5 – 100,000 Ω can be made over the frequency range from 30 Hz to 40 kHz, when supplied by an external oscillator. Internally generated frequencies of 60 Hz, 400 Hz or 1 kHz are available. At these internal frequencies and external frequencies up to 20 kHz, the readings have an accuracy of ± 1% for the magnitude of Z and ± 2% for θ.

The fundamental circuit, which is basic for both Z and phase angle measurement, is shown in Figs 10.6(a) and (b).

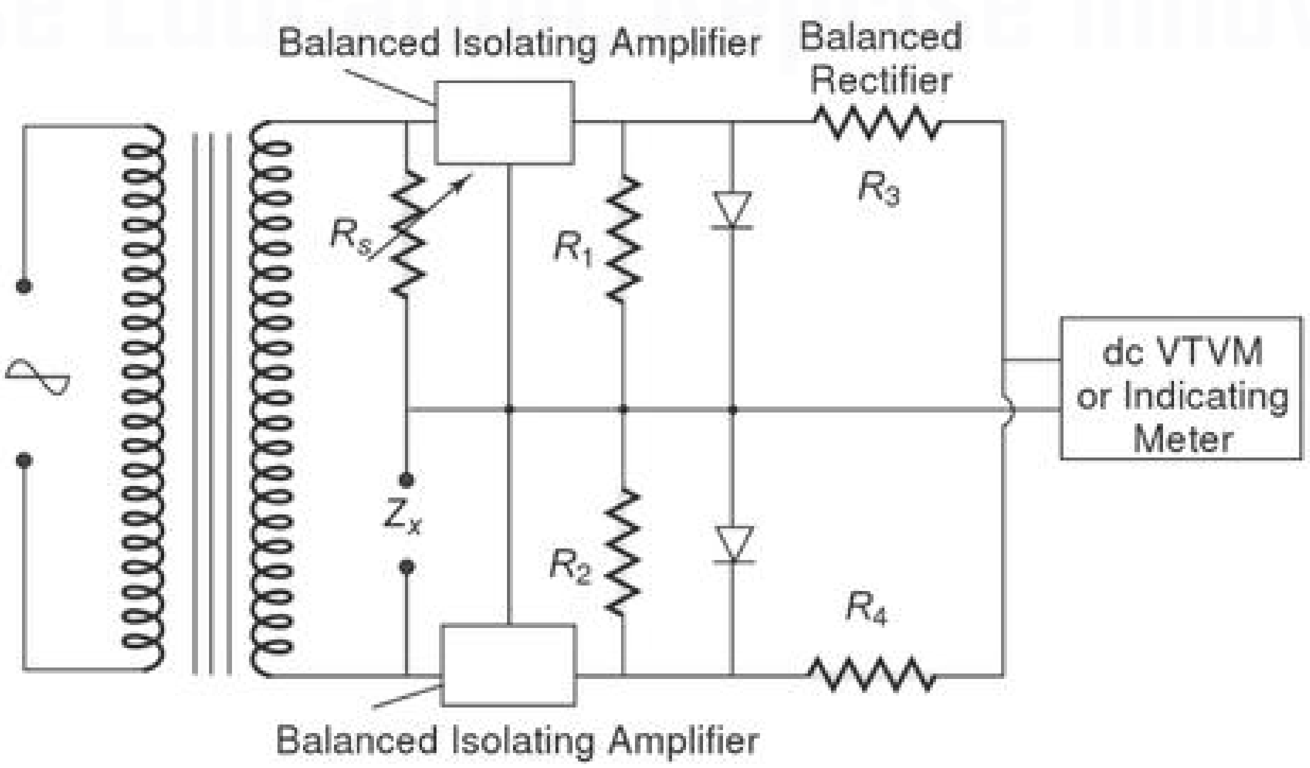


Fig. 10.6 (a) Commercial vector impedance meter (Magnitude of impedance measurement)

In both parts, the measurement makes use of the equal deflection method, by comparing the voltage drop across the unknown Z to the drop across a standard resistance, with the same current in both.

In the impedance measuring circuit of Fig. 10.6(a), Z_x is the unknown impedance and the variable resistance R_s is the standard resistance, which is varied by the calibrating impedance dial. The dial is adjusted until the voltage drops across Z_x and R_s are equal. Each voltage drop is amplified in the two sections of the balanced amplifier and applied to each section of a dual rectifier. The algebraic sum of the rectified outputs will then be zero, as indicated by the null reading of the dc VTVM, regardless of the phase angle of Z_x since rectified voltage depends only on the magnitude $|Z|$ of the unknown Z. This unknown Z, in ohms, is read directly on the dial of the variable standard R_s.

The circuit shown in Fig. 10.6(b) is used for the measurement of phase angle, after the Z balance has been obtained.

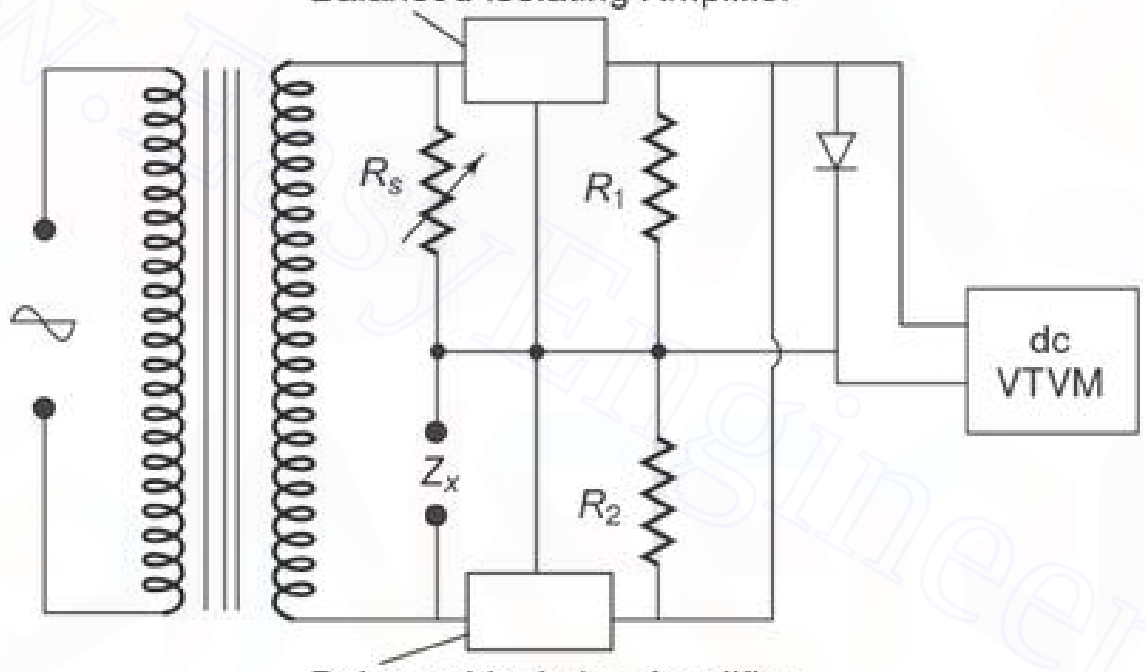


Fig. 10.6 (b) Vector impedance meter circuit for measurement of phase angle

With the switch is in the calibration position, the injection voltage is calibrated by adjusting it for full scale deflection on the indicating meter or the VTVM. The function switch is then set to the phase position. In this position, the function switch of the instrument parallels the output of the balanced amplifier, before rectification. The sum of ac output voltages from the amplifiers is now a function of the vector difference between the ac voltages impressed on the amplifiers.

The rectified voltage resulting from this vector difference is shown on the dc VTVM, as a measure of the phase angle between the voltage across Z_x and R_s, which are equal in magnitude but different in phase. Thus the meter is able to indicate direct reading values for the phase angle. If required, this angle can be converted to measure the corresponding values for dissipation factor D and quality factor Q.

Where it is necessary to determine the phase angle to a high degree of accuracy, a phase meter is usually employed, e.g. in servos and precise control applications.

Q METER 10.7

The overall efficiency of coils and capacitors intended for RF applications is best evaluated using the Q value. The Q meter is an instrument designed to measure some electrical properties of coils and capacitors. The principle of the Q meter is based on series resonance; the voltage drop across the coil or capacitor is Q times the applied voltage (where Q is the ratio of reactance to resistance, X_L/R). If a fixed voltage is applied to the circuit, a voltmeter across the capacitor can be calibrated to read Q directly.

At resonance $X_L = X_C$ and $E_L = I\,X_L$, $E_C = I\,X_C$, $E = I\,R$

where E — applied voltage $\quad E_C$ — capacitor voltage
E_L — inductive voltage $\quad X_L$ — inductive reactance
X_C — capacitive reactance $\quad R$ — coil resistance
I — circuit current

Therefore $$Q = \frac{X_L}{R} = \frac{X_C}{R} = \frac{E_C}{E}$$

From the above equation, if E is kept constant the voltage across the capacitor can be measured by a voltmeter calibrated to read directly in terms of Q.

A practical Q meter circuit is shown in Fig. 10.7.

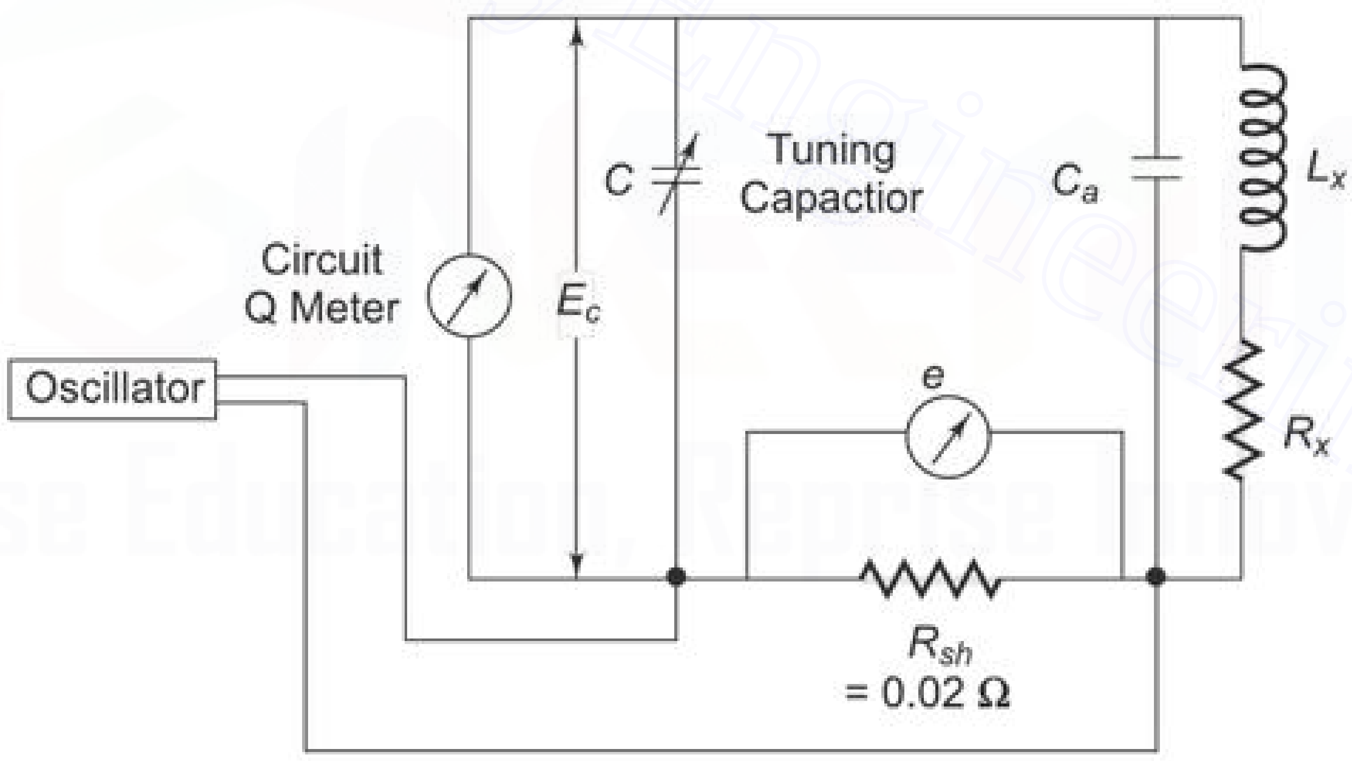


Fig. 10.7 Circuit diagram of a Q-meter

The wide range oscillator, with frequency range from 50 kHz to 50 MHz, delivers current to a resistance R_{sh} having a value of 0.02 Ω. This shunt resistance introduces almost no resistance into the tank circuit and therefore represents a voltage source of a magnitude e with a small internal resistance. The voltage across the shunt is measured with a thermocouple meter. The voltage across the capacitor is measured by an electronic voltmeter corresponding to E_c and calibrated directly to read Q.

The oscillator energy is coupled to the tank circuit. The circuit is tuned to resonance by varying C until the electronic voltmeter reads the maximum value.

The resonance output voltage E, corresponding to E_c, is $E = Q \times e$, that is, $Q = E/e$. Since e is known, the electronic voltmeter can be calibrated to read Q directly.

The inductance of the coil can be determined by connecting it to the test terminals of the instrument. The circuit is tuned to resonance by varying either the capacitance or the oscillator frequency. If the capacitance is varied, the oscillator frequency is adjusted to a given frequency and resonance is obtained. If the capacitance is pre-setted to a desired value, the oscillator frequency is varied until resonance occurs. The Q reading on the output meter must be multiplied by the index setting or the "Multiply Q by" switch to obtain the actual Q value. The inductance of the coil can be calculated from known values of the coil frequency and resonating capacitor (C).

$$X_L = X_C, f = \frac{1}{2\pi\sqrt{LC}} \text{ or } L = \frac{1}{(2\pi f)^2 C} \tag{10.1}$$

The Q indicated is not the actual Q, because the losses of the resonating capacitor, voltmeter and inserted resistance are all included in the measuring circuit. The actual Q of the measured coil is somewhat greater than the indicated Q. This difference is negligible except where the resistance of the coil is relatively small compared to the inserted resistance R_{sh}.

10.7.1 Factors that May Cause Error

1. At high frequencies the electronic voltmeter may suffer from losses due to the transit time effect. The effect of R_{sh} is to introduce an additional resistance in the tank circuit, as shown in Fig. 10.8.

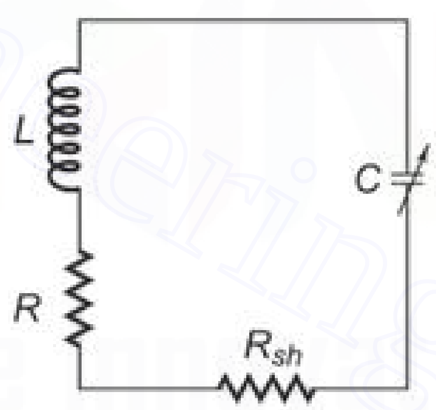


Fig. 10.8 Effect of R_{sh} on Q

$$Q_{\text{act}} = \frac{\omega L}{R} \text{ and } Q_{obs} = \frac{\omega L}{R + R_{sh}}$$

$$\therefore \quad \frac{Q_{\text{act}}}{Q_{\text{obs}}} = \frac{R + R_{sh}}{R} = 1 + \frac{R_{sh}}{R}$$

$$\therefore \quad Q_{\text{act}} = Q_{\text{obs}}\left(1 + \frac{R_{sh}}{R}\right)$$

where Q_{act} = actual Q
Q_{obs} = observed Q

To make the Q_{obs} value as close as possible to Q_{act}, R_{sh} should be made as small as possible. An R_{sh} value of 0.02 – 0.04 Ω introduces negligible error.

2. Another source of error, and probably the most important one, is the distributed capacitance or self capacitance of the measuring circuit. The presence of distributed or stray capacitances modifies the actual Q and

the inductance of the coil. At the resonant frequency, at which the self capacitance and inductance of the coil are equal, the circuit impedance is purely resistive—this characteristic can be used to measure the distributed capacitance.

One of the simplest methods of determining the distributed capacitance (C_s) of a coil involves the plotting of a graph of $1/f^2$ against C in picofarads.

The frequency of the oscillator in the Q meter is varied and the corresponding value of C for resonance is noted. $1/f^2$ is plotted against C in picofarads, as shown in Fig. 10.9(a). The straight line produced to intercept the X-axis gives the value of C_s, from the formula given on the next page. The value of the unknown inductance can also be determined from the equation.

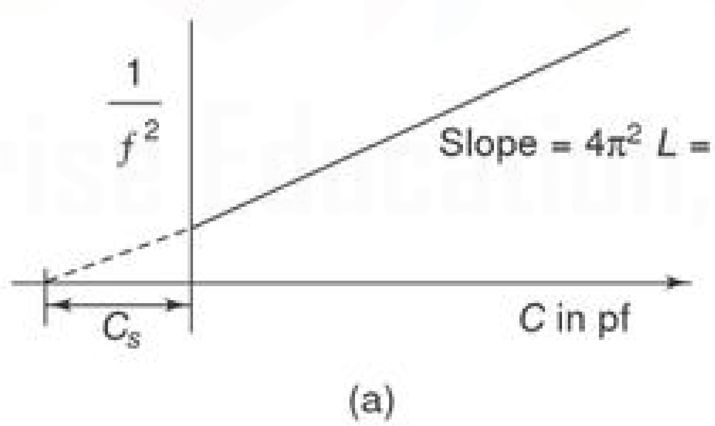
$$L = \frac{\text{slope}}{4\pi^2}, \text{ therefore slope} = 4\pi^2 L$$

and
$$f = \frac{1}{2\pi\sqrt{L(C + C_s)}}$$

Therefore
$$\frac{1}{f^2} = 4\pi^2 L(C + C_s)$$

If
$$\frac{1}{f^2} = 0, \text{ then } C = -C_s.$$

Another method of determining the stray or distributed capacitance (C_s) of a coil involves making two measurements at different frequencies. The capacitor C of the Q meter is calibrated to indicate the capacitance value. The test coil is connected to the Q meter terminals, as shown in Fig. 10.9(b).



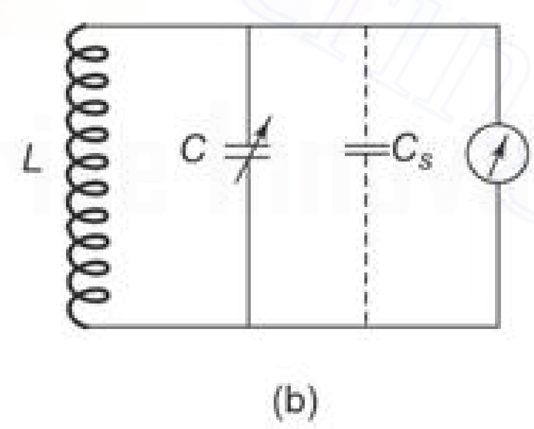


Fig. 10.9 Measurement of stray capacitance

The tuning capacitor is set to a high value position (to its maximum) and the circuit is resonated by varying the oscillator frequency. Suppose the meter indicates resonance and the oscillator frequency is found to be f_1 Hz and the capacitor value to be C_1.

The oscillator frequency, of the Q-meter is now increased to twice the original frequency, that is, $f_2 = 2f_1$, and the capacitor is varied until resonance occurs at C_2. The resonant frequency of an LC circuit is given by

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Therefore, for the initial resonance condition, the total capacitance of the circuit is $(C_1 + C_s)$ and the resonant frequency equals

$$f_1 = \frac{1}{2\pi\sqrt{L(C_1 + C_s)}}$$

After the oscillator and the tuning capacitor are varied for the new value of resonance, the capacitance is $(C_2 + C_s)$, therefore

$$f_2 = \frac{1}{2\pi\sqrt{L(C_2 + C_s)}}$$

But $f_2 = 2f_1$.

Therefore

$$\frac{1}{2\pi\sqrt{L(C_2 + C_s)}} = \frac{2}{2\pi\sqrt{L(C_1 + C_s)}}$$

$$C_1 + C_s = 4(C_2 + C_s)$$

$$C_1 + C_s = 4C_2 + 4C_s$$

$$C_1 = 4C_2 + 3C_s$$

$$3C_s = C_1 - 4C_2$$

$$C_s = \frac{C_1 - 4C_2}{3} \tag{10.2}$$

The distributed capacitance can be calculated using the equation above.

Example 10.1 *The self-capacitance of the coil is measured by using the method outlined in the previous section. The first measurement is at f_1 = 2MHz and the value of capacitance C_1 = 600 pf. The second measurement is at f_2 = $2f_1$ = 4 MHz and the value of capacitance C_2 = 100 pf. Find the value of distributed capacitance and the value of L.*

Solution Using the equation

$$C_s = \frac{C_1 - 4C_2}{3} = \frac{600\text{ pf} - 4(100\text{ pf})}{3} = \frac{200\text{ pf}}{3} = 66.67\text{ pf}$$

Therefore $C_s = 66.67$ pf

The resonant frequency is given by

Step 1:
$$f_1 = \frac{1}{2\pi\sqrt{L(C_1 + C_s)}}$$

Therefore

Step 2:
$$L = \frac{1}{4 \times \pi^2 \times f_1^2 \times (C_1 + C_s)}$$

$$L = \frac{1}{4 \times 9.8696 \times 4 \times 10^{12} \times (600\text{ pf} + 66.67\text{ pf})}$$

$$L = \frac{1}{4 \times 9.8696 \times 4 \times (666.67)} = \frac{1}{16 \times 9.8696 \times 666.67}$$

$$L = 9.498\ \mu\text{H}$$

Example 10.2 *The self capacitance of a coil is measured by using the method outlined in the previous section. The first measurement is at $f_1 = 1$ MHz and $C_1 = 500$ pf. The second measurement is at $f_2 = 2$ MHz and $C_2 = 110$ pf. Find the distributed capacitance. Also calculate the value of L.*

Solution The distributed capacitance is given by the equation

$$C_s = \frac{C_1 - 4C_2}{3}$$

$$C_s = \frac{500\text{ pf} - 4(110\text{ pf})}{3}$$

$$C_s = \frac{500\text{ pf} - 440\text{ pf}}{3} = \frac{60\text{ pf}}{3}$$

$$C_s = 20\text{ pf}$$

The resonant frequency is given by the formula

$$f_1 = \frac{1}{2\pi\sqrt{L(C_1 + C_s)}}$$

$$L = \frac{1}{4\pi^2 f_1^2 (C_1 + C_s)}$$

$$L = \frac{1}{4 \times (3.14159)^2 \times (1 \times 10^6)^2 \times (500 \times 10^{-12} + 20 \times 10^{-12})}$$

$$L = \frac{1}{4 \times 9.8696 \times 10^{12} \times (520 \times 10^{-12})}$$

$$L = \frac{1}{4 \times 9.8696 \times 520}$$

$$L = \frac{1}{20528.777} = 48.712 \times 10^{-6}\text{ H}$$

$$L = 48.712\ \mu\text{H}$$

Example 10.3 *Calculate the value of the self capacitance when the following measurements are performed.*

$f_1 = 2$ MHz and $C_1 = 500$ pf; $f_2 = 6$ MHz and $C_2 = 50$ pf

Solution Given that $f_2 = 3f_1$

$$\frac{1}{2\pi\sqrt{L(C_2+C_s)}} = \frac{3}{2\pi\sqrt{L(C_1+C_s)}}$$

$$C_1 + C_s = 9\,(C_2 + C_s)$$

$$C_1 + C_s = 9C_2 + 9C_s$$

$$C_1 - 9C_2 = 9C_s - C_s$$

$$C_1 - 9C_2 = 8C_s$$

Therefore

$$C_s = \frac{C_1 - 9C_2}{8}$$

$$C_s = \frac{500\text{ pf} - 9(50\text{ pf})}{8}$$

$$C_s = \frac{500\text{pf} - 450\text{ pf}}{8}$$

$$C_s = \frac{50\text{ pf}}{8} = 6.25\text{ pf}$$

10.7.2 Impedance Measurement Using Q Meter

An unknown impedance can be measured using a Q meter, either by series or shunt substitution method. If the impedance to be measured is small, the former is used and if it is large the latter method is used.

In the Q meter method of measurement of Z, the unknown impedance Z_x is determined by individually determining its components R_x and L_x. The technique utilises an LC tank of a Q meter, L being an externally connected standard coil.

Figure 10.10(a) shows the method of series substitution while Fig. 10.10(b) shows the shunt substitution method.

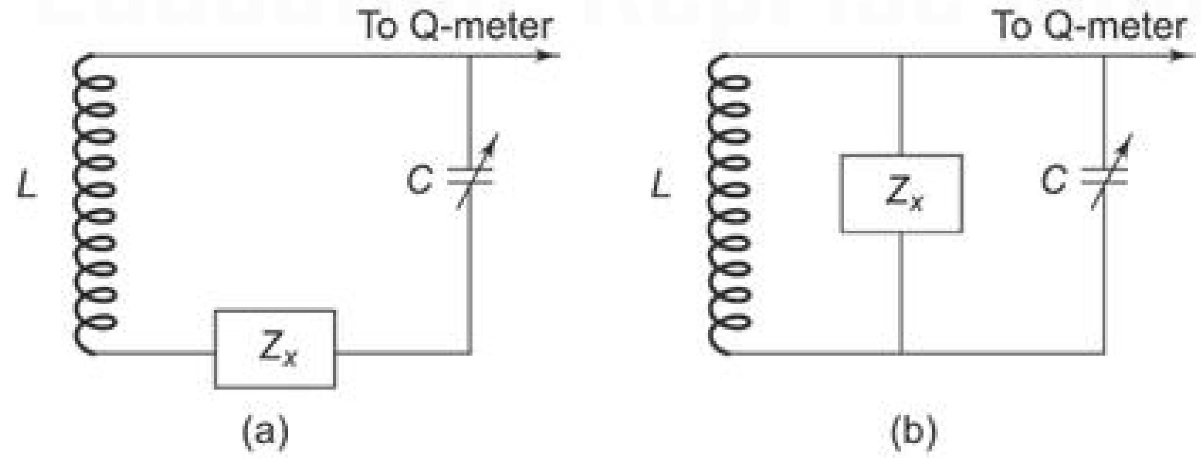


Fig. 10.10 (a) Series substitution (b) Shunt substitution

Referring to Fig. 10.10(a), the unknown impedance is shorted or otherwise not connected and the tuned circuit is adjusted for resonance at the oscillator frequency. The value of Q and C are noted. The unknown impedance is then connected, the capacitor is varied for resonance, and new values Q' and C' are noted.

From part 1, we have $\omega L = 1/\omega C$ (10.3)

From part 2, we have $\omega L + X_x = \dfrac{1}{\omega C'}$ (10.4)

Subtracting Eq. (10.4) from Eq. (10.3), we have

$$X_x = \frac{1}{\omega C'} - \frac{1}{\omega C} = \frac{1}{\omega C}\left(\frac{C - C'}{C'}\right) = \frac{1}{\omega}\left(\frac{C - C'}{CC'}\right)$$

Since $R' = R + R_x$, $R_x = R' - R$, where R is the resistance of the auxillary coil.

$$R_x = R' - R = \frac{\omega L}{Q'} - \frac{\omega L}{Q} = \omega L\left(\frac{Q - Q'}{QQ'}\right)$$

The unknown impedance Z_x can be calculated from the equation

$$Z_x = R_x + j X_x$$

A positive value of X_x indicates inductive reactance and a negative value indicates capacitive reactance.

If Z_x is considerably greater than X_L, the unknown impedance is shunted across the coil and the capacitor, as shown in Fig. 10.10(b).

Y_x represents the shunt admittance of the unknown impedance. It consists of two shunt elements, conductance G_x and susceptance B_x. In this method, Y_x is disconnected and the capacitor C is tuned to the resonant value. At the oscillator frequency, the values of Q and C are noted. With Y_x connected, the capacitor is tuned again for resonance at the oscillator frequency and the new values Q' and C' are noted.

Hence $\quad Y_x = G_x + jB_x$

and $\quad B_x = \omega C - \omega C'$

also $\quad G_x = \dfrac{1}{\omega L}\left(\dfrac{Q - Q'}{QQ'}\right)$

Therefore $\quad Y_x = \dfrac{Q - Q'}{\omega L Q Q'} + j\omega (C - C')$

The accuracy with which the reactance can be determined by the method of substitution is quite high. Error may mainly be because

(i) C' cannot be accurately determined since the resonance curve may be flat due to additional resistance, and

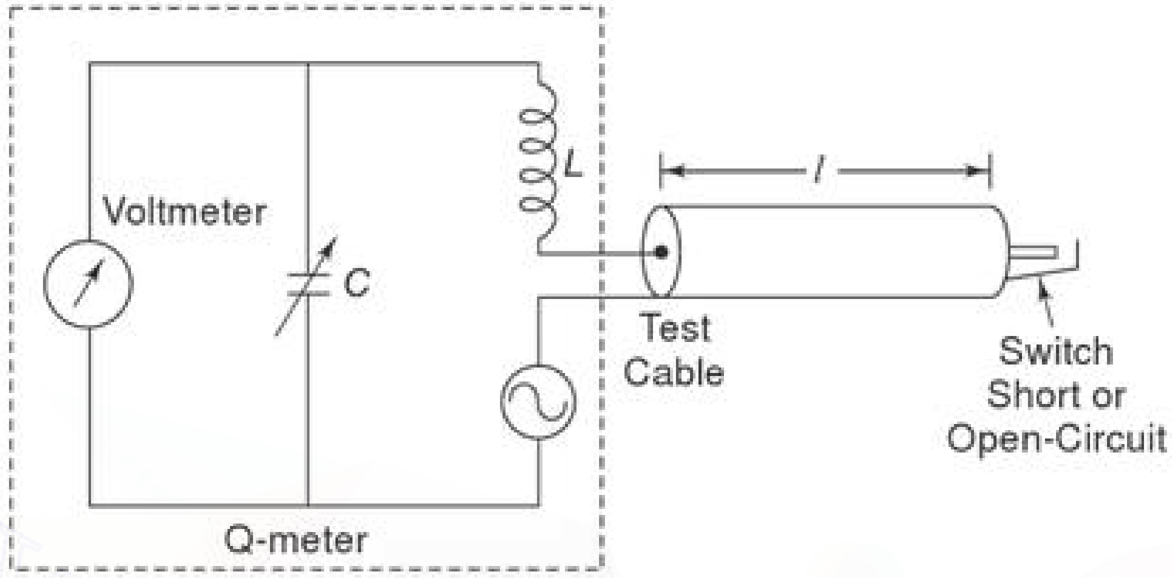
(ii) The stray inductance associated with the tuning capacitor causes errors at VHF.

The accuracy with which the resistance component of the unknown impedance is obtained is poor. If the losses in the unknown impedance are too small to introduce any change in the Q, the substitution method is quite satisfactory.

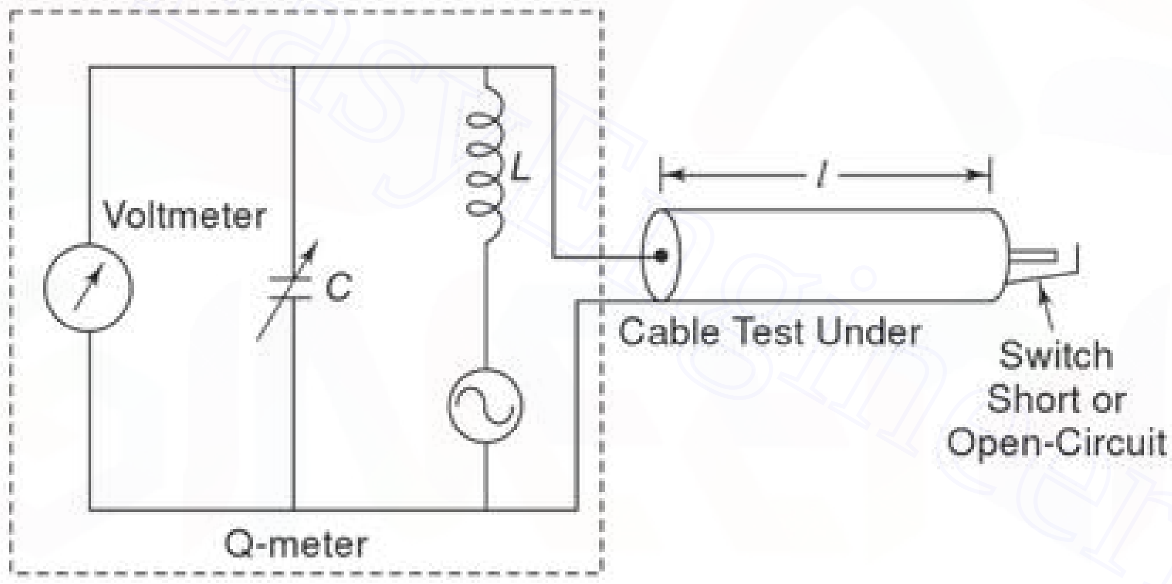
The substitution method can also be used for measuring the losses of the coil. It is not satisfactory for measuring the losses of an air-dielectric capacitor, since they are too small to be detected by this method.

10.7.3 Measurement of Characteristic Impedance (Z_0) of a Transmission Line Using Q Meter

Figure 10.11(a) shows a series substitution method for determining the characteristic impedance of a transmission line and Fig. 10.11(b) shows a shunt or parallel method of substitution for the same purpose.



(a)



(b)

Fig. 10.11 (a) Series substitution method of measurement of Z_0 (b) Shunt substitution Method of measurement of Z_0

In Fig. 10.11(a), the transmission line or cable under test is tuned for series resonance. Since the input impedance is low, the method of series substitution can be used to determine $Z_0 = R_0 + jX_0$ for the transmission line, as explained in the previous section.

The reactance/unit length of the line is the total reactance divided by the length l.

Series resonance occurs when the line is short-circuited and the line length is an even multiple of a $\lambda/4$ and when open-circuited an odd multiple of $\lambda/4$.

Parallel resonance occurs when the line is short-circuited and the length is an odd multiple of $\lambda/4$, or open-circuited it is an even multiple of $\lambda/4$.

10.7.4 Measurement of Q by Susceptance Method

The coil under test is connected in series with a calibrated low loss variable capacitor. With the use of the meter as an indicator, the circuit is tuned for resonance to the oscillator frequency, by tuning the variable capacitor to a value C_r, as shown in Fig. 10.12(a). The capacitor is then detuned to a value C_b on the low capacitance side of resonance at which the meter reading falls to 70.7% of the resonant voltage. Next, the capacitor is set on the higher capacitance side of resonance to a value C_a, where the voltmeter deflection again drops to 70.7% of the resonant voltage, as shown in Fig. 10.12(b).

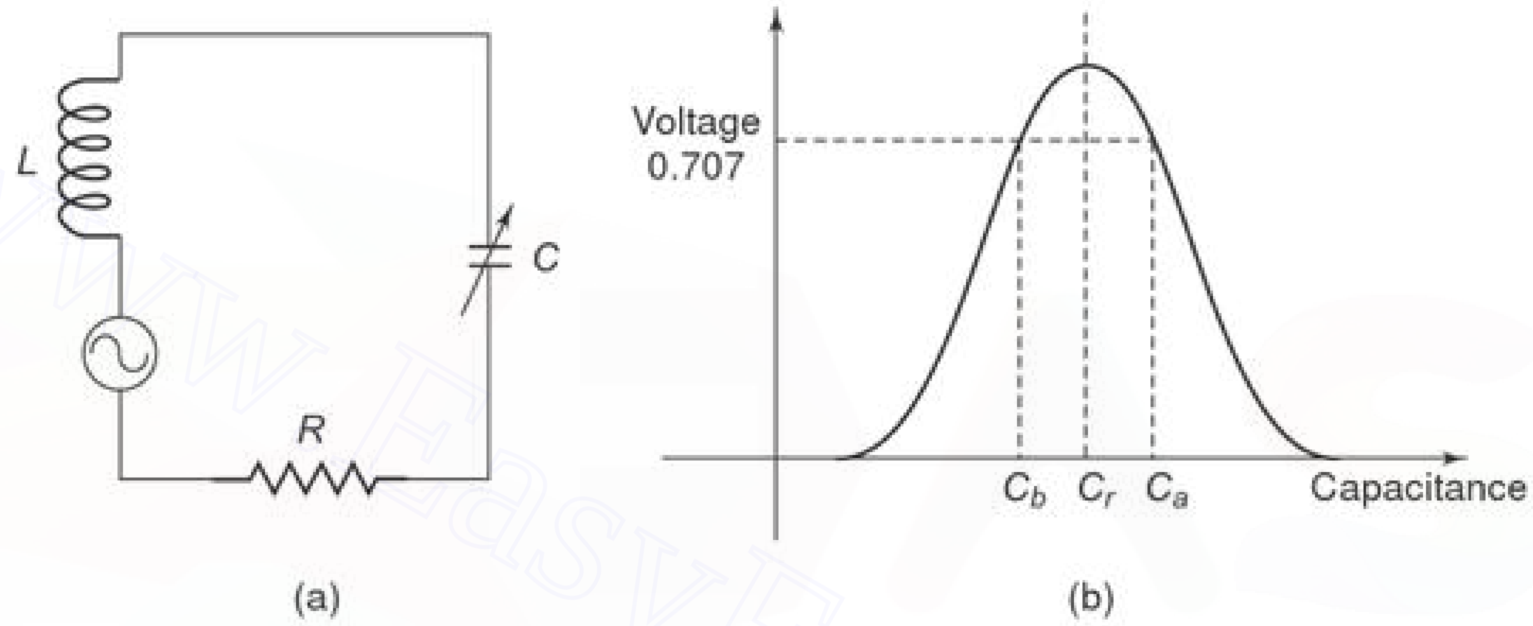


Fig. 10.12 (a) Susceptance method of Q measurement (b) Response curve

The points C_a, C_b and C_r are closer together when coil Q is high (sharp tuning) and far apart when Q is low (broad tuning). The value of Q can be then determined as follows.

C_a and C_b are the value of capacitances at the half power point and C_r is the value of the capacitance at resonance.

$\therefore \quad X_{Ca} = 1/\omega C_a$ and $X_{Cb} = 1/\omega C_b$

At half power points

$$\omega L - 1/\omega C_a = R \text{ and } 1/\omega C_b - \omega L = R$$

Adding the two equations, we have

$$\frac{1}{\omega C_b} - \frac{1}{\omega C_a} = 2R \qquad \frac{\omega C_a - \omega C_b}{\omega^2 C_a C_b} = 2R$$

i.e. $$\frac{C_a - C_b}{\omega C_a C_b} = 2R \quad \text{But} \quad C_r^2 = C_a C_b$$

$$\therefore \quad \frac{C_a - C_b}{\omega C_r R C_r} = 2 \quad \text{But} \quad Q = \frac{1}{\omega C_r R}$$

Therefore $$\frac{Q(C_a - C_b)}{C_r} = 2$$

$$Q(C_a - C_b) = 2C_r$$

Therefore $$Q = \frac{2C_r}{C_a - C_b} \tag{10.5}$$

In this method, the coil under test is connected in series with a calibrated low loss capacitor. The frequency of the signal generator is kept at a suitable value and the output across the capacitor is measured by an electronic voltmeter. This method requires less expensive components than the Q meter.

LCR BRIDGE 10.8

10.8.1 Basic LCR Bridge (Skeleton Type)

A simple bridge for the measurement of resistance, capacitance and inductance may be constructed with four resistance decades in one arm, and binding post terminals to which external resistors or capacitors may be connected, to complete the other arms. Such a skeleton arrangement is useful in the laboratory, since it permits the operator to set up a number of different bridge circuits simply by plugging standards and unknown units into the proper terminals.

The schematic circuit diagram of a skeleton type bridge and its accessories for the measurement of R, L and C is shown in Figs 10.13(a) and 10.13(b).

In Fig. 10.13(a), R_b is self contained. The other arms are completed by connecting the unknown and standard component to terminals 1-2, 3-4, 7-8, 9-10, and 11-12, a null detector to 5-6, and a generator to 13-14. This bridge can be used for both ac and dc measurements.

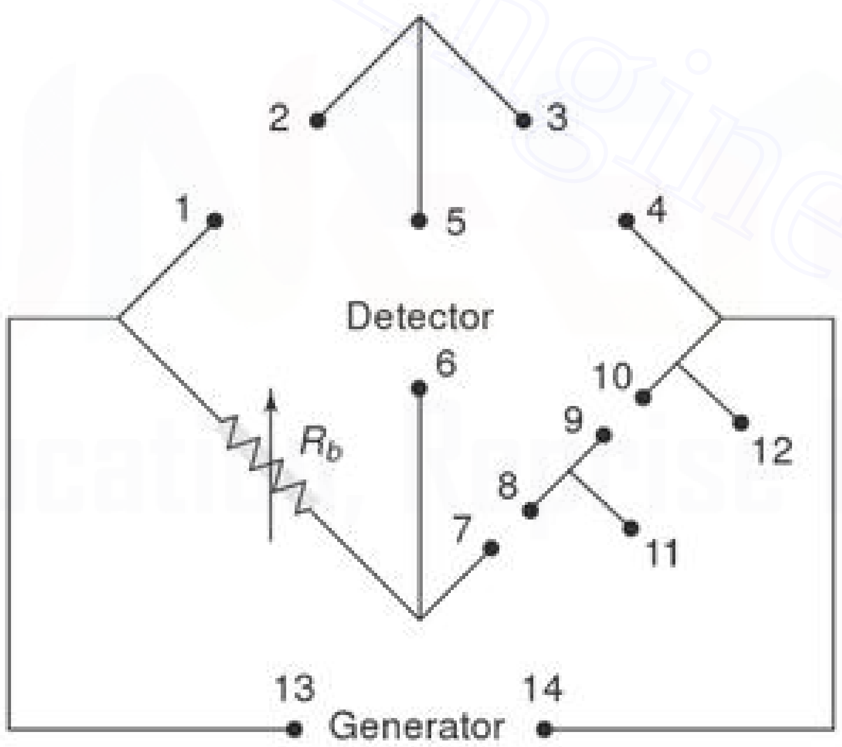


Fig. 10.13 (a) Skeleton type LCR bridge

By proper arrangement of the bridge arms, the Wheatstone's bridge shown in Fig. 10.14(a) may be set up for resistance measurement (ac and dc), a comparison circuit shown in Fig. 10.14(b) for measurement of C, and a Maxwell's circuit shown in Fig. 10.14(c) for the measurement of inductance L.

The skeleton bridge permits resistance measurements from 0.001 Ω to 11.11 MΩ, capacitance measurements from 1 pf (if stray capacitance permits) to 1111 μF and inductance measurements from 1 μH (if stray inductance and capacitance permit) to 111.1 H.

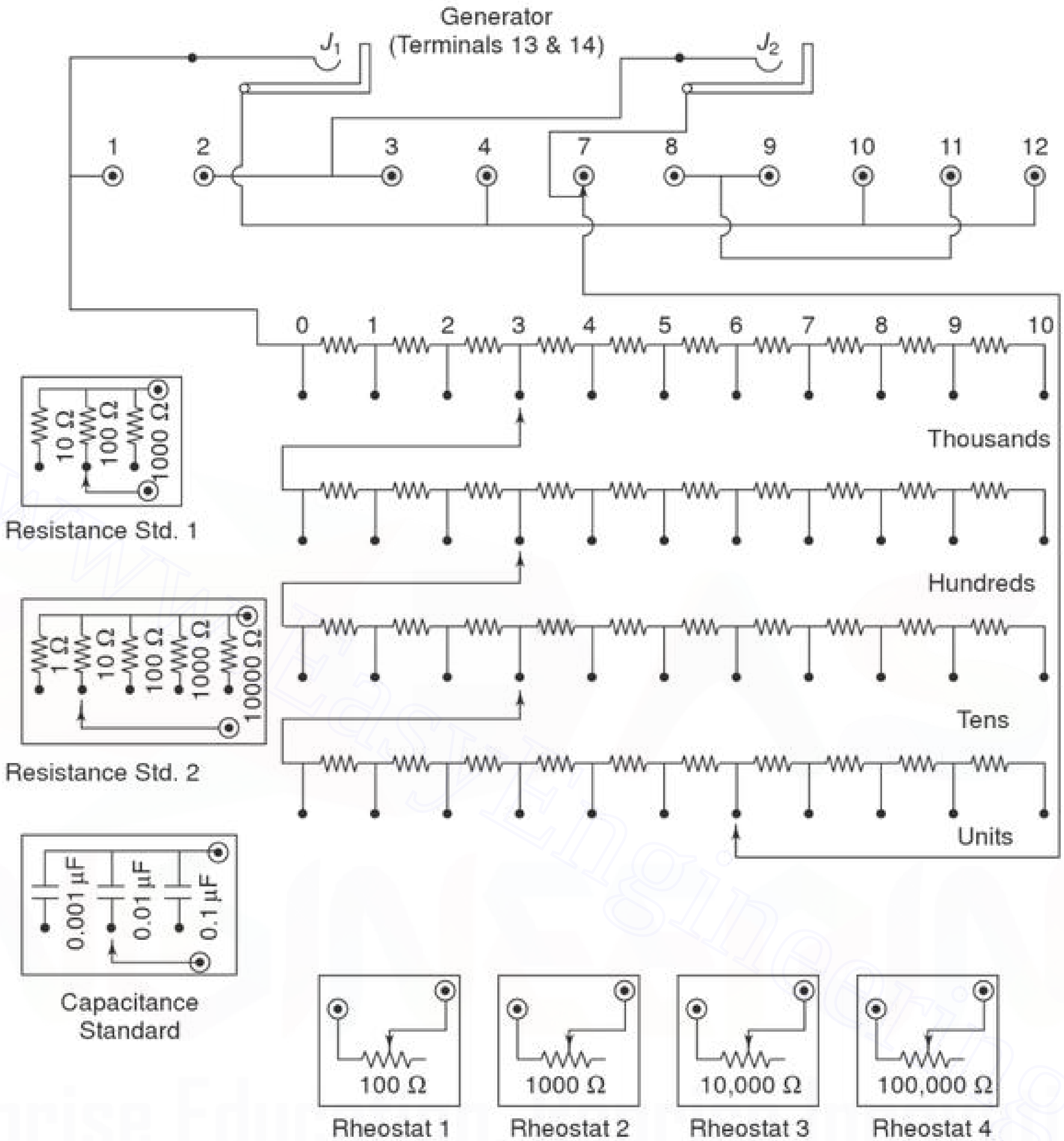


Fig. 10.13 (b) Complete circuit of the skeleton bridge and accessories

The bridge accessories are shown in Fig. 10.13(b). There are two switched resistance standard boxes (one 10 – 100 – 1000 Ω precision resistance and another 1 – 10 – 100 – 1000 – 10000 Ω precision resistance), one switched capacitor standard box containing 0.001 – 0.01 – 0.1 μF, a close tolerance capacitor, and four mounted dial calibrated rheostats having values of 100 – 1 k – 10 k – 100 kΩ.

For dc measurements 1.5 – 7.5 V batteries are used and connected to terminals 13 – 14. A centre zero 50 – 0 – 50 or 100 – 0 – 100 dc microammeter is connected to terminals 5 – 6.

For ac measurements of *R*, *L* and *C* connect a signal source or AF oscillator tuned to a frequency of 1 kHz to terminals 13 – 14 and a null detector (headphone, AC VTVM, CRO, etc) to terminal 5 – 6. The mode of operation for the measurement of *R*, *C* and *L* are as follows.

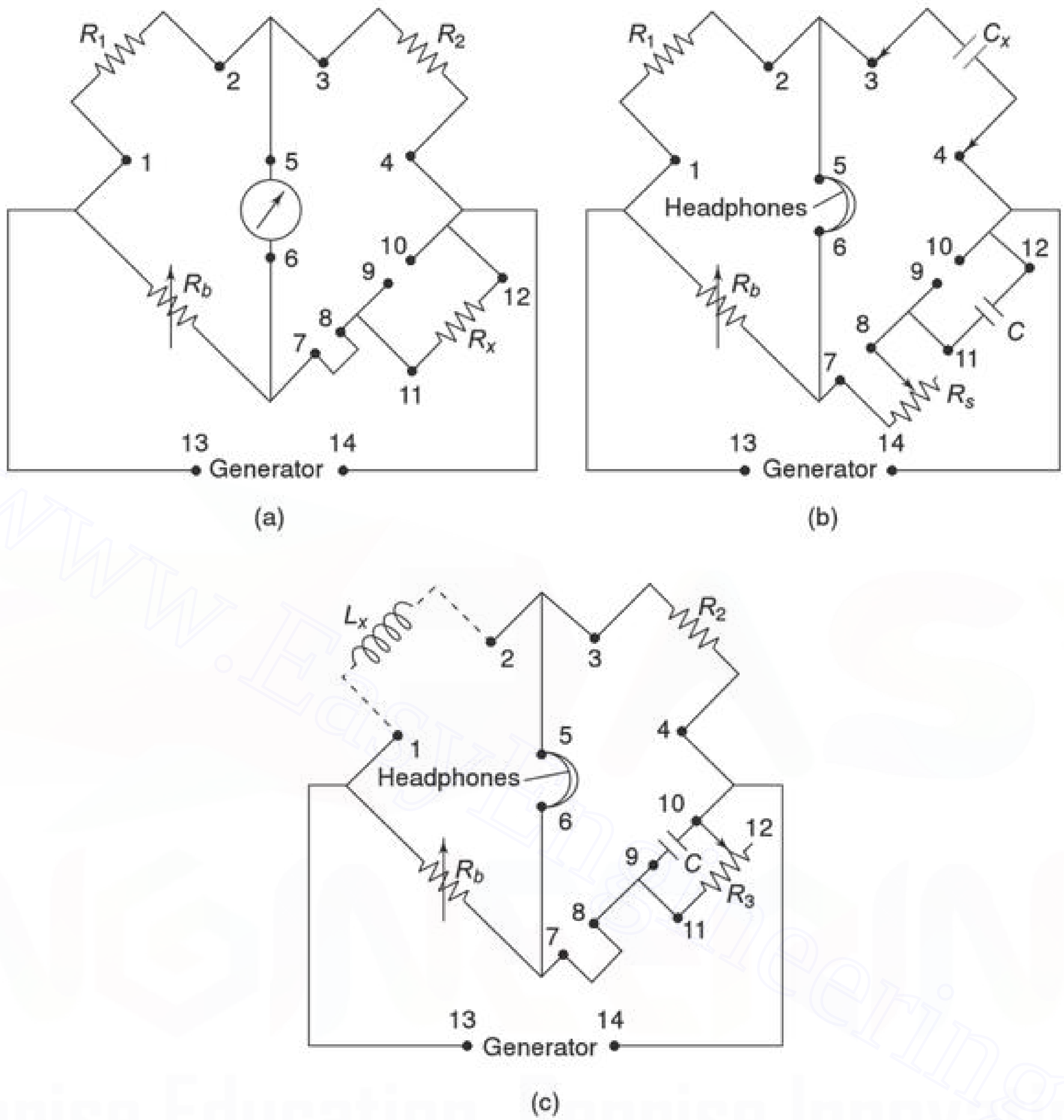


Fig. 10.14 (a) Wheatstone's bridge for resistance measurement (b) Capacitance comparison bridge for capacitance measurement (c) Maxwell's inductance bridge

For Resistance Measurements

1. Connect resistance standard 1 (set to 1000 Ω) to terminals 1–2.
2. Connect resistance standard 2 (set to 1 Ω) to terminals 3–4.
3. Terminals 11 – 12 are connected to the unknown resistance.
4. Connect a heavy wire jumper to terminals 7–8.
5. Terminals 9–10 are kept open circuit.
6. Connect generator to 13–14, detection is done by using a centre zero dc microammeter if the generator used is dc, or if an ac source is used the detector must be an ac type null detector.
7. Adjust the decade switches for null. If null is not obtained with the resistance standard settings given in steps 1 and 2, try other settings and repeat the decade adjustments.

8. At null, determine the unknown resistance R_x from the readings of the decades (R_b), resistance standard 1 and resistance 2 using the following equation.

$$R_x = \frac{R_2 R_b}{R_1} \tag{10.6}$$

The possible ranges are given in Table 10.1.

Table 10.1

Resistance 1 (Ω)	*Resistance 2 (Ω)*	*Range (Ω)*
1000	1	0.001– 11.11
1000	10	.01 – 111.11
1000	100	.1 – 1111
1000	1000	1.0 – 11110
1000	10000	10.0 – 111100
100	10000	100.0 – 1111000
10	10000	1000.0 – 11110000

For Capacitance Measurement

1. Connect resistance standard 1 (set to 1 kΩ) to terminals 1 – 2.
2. Connect capacitor standard (set to 0.001 μF) to terminals 11 – 12.
3. Connect the unknown capacitance to terminals 3 – 4.
4. Keep terminals 9 – 10 open-circuit.
5. Connect the 100 Ω rheostat to terminals 7 – 8.
6. Connect an ac generator to terminals 13 – 14 and a headphone or ac null detector to terminals 5 – 6.
7. Adjust the decade switches for null. If null is not obtained with the standard settings given in steps 1 and 2, try other standard resistance and capacitor settings.
8. At null determination the value of the unknown capacitor is determined from the readings of the decades R_b, resistance standard 1, and capacitor standard (C) by using the following equation.

$$C_x = \frac{C R_b}{R_1} \mu\text{F} \tag{10.7}$$

where R_1 and R_b are in ohms and C is in microfarads.

The possible ranges are given in Table 10.2.

Table 10.2

Resistance 1 (Ω)	*Capacitor standard (µ F)*	*Ranges (Ω)*
1000	0.001	1 – 11.110
1000	0.01	10 – 0.1111
100	0.01	100 – 1.1111
1000	1.00	0.001 – 11.11
100	1.00	0.01 – 111.1
10	1.00	0.1 – 1111

The power factor of the unknown capacitor can be determined from the rheostat dial reading (R_s), and from the value of the unknown capacitor by the following equation.

$$\text{Power factor (PF)} = 0.000628 \times f \times R_s \times C_x \,\% \tag{10.8}$$

For Inductive Measurements

1. Connect the capacitor standard (set to 0.01 µF) to terminals 9 – 10.
2. Connect the resistance standard 2 (set to 100 Ω) to terminal 3 – 4.
3. Connect the 100 Ω rheostat to terminals 11 – 12.
4. Connect a heavy jumper to terminals 7 – 8.
5. Connect the unknown inductances to terminals 1 – 2.
6. Connect an ac generator to terminals 13 – 14 and also connect an ac detector to terminals 5 – 6.
7. Adjust the decade switches for null. Adjust the rheostat for a sharper null.
8. If null is not obtained with the standard R and C settings given in steps 1 and 2, try other settings.
9. At complete null, determine the unknown impedance (L_x) from the readings of the decades R_b, resistance standard 2 (R_2) and capacitor standard (C) by means of the following equation.

$$L_x = C\, R_b\, R_2\, H \tag{10.9}$$

where R_2 and R_b are in Ω's and C in F's.

The possible ranges are given in Table 10.3.

Table 10.3

Resistance standard 2	*Capacitor standard (F)*	*Range*
100 Ω	0.01	1 µH – 11.11 mH
1000 Ω	0.01	10 µH – 111.1 mH
10 kΩ	0.01	100 µH – 1.111 H
10 kΩ	1.0	10 mH – 111.1 H

The complete circuit of an LCR bridge is shown in Fig. 10.15 (kit type bridge).

A wide range of resistance (ac and dc), inductance and capacitance measurements can be done using a Kit type impedance bridge.

This bridge measures inductance (L) from 1 μH – 100 H, capacitance (C) from 10 μμF – 100 μF, resistance (R) from 0.01 Ωs – 10 MΩ, dissipation factor (D) from 0.001 – 1 and Q from 1 – 1000. Resistance, capacitance and inductance units are read directly on the same dial scale, graduated 0 – 1, and are multiplied by settings of a multiplier switch.

Referring to Fig. 10.15, six inductance ranges are provided

(i) 10 – 100 μH (ii) 50 μH – 10 mH
(iii) 0.5 – 100 mH (iv) 5 mH – 1 H
(v) 50 mH – 10 H (vi) 0.5 – 100 H

These ranges include all common inductances of coils of all types employed in electronics.

Also eight resistance ranges are provided.

(i) 0.01 – 1 Ω (ii) 0.05 – 10 Ω
(iii) 0.5 – 100 Ω (iv) 5 – 1000 Ω
(v) 50 – 10,000 Ω (vi) 500 – 100,000 Ω
(vii) 5,000 – 1 MΩ (viii) 50,000 – 10 MΩ

There are six capacitance ranges provided:

(i) 10 – 1000 μμF (ii) 50 μμF – 0.01 μF
(iii) 0.0005 – 0.1 μF (iv) 0.005 – 1 μF
(v) 0.05 – 10 μF (vi) 0.5 – 100 μF

The two pole, eight position Multiplier Switch sets the bridge to the desired R, C or L range. This switch cuts the various precision resistors, R_1 to R_9 in or out of the circuit. The dial settings of the multiplier switch show the various R, C and L factors by which the settings of the main control dial must be multiplied to obtain the correct value of the component under test.

The function of the Detector Switch is to connect an appropriate null detector across the bridge output terminals. When this switch is thrown to its external position, the two terminals labelled external detector are connected across the bridge output, and an external null detector may be connected to these terminals. (Satisfactory external detectors are high resistance headphones, ac VTVMs, oscilloscopes, sensitive centre zero dc galvanometers, etc.). The galvanometer is used only in resistance measurements when the internal 6 V battery (or a higher voltage external battery) is used to power the bridge.

When the detector switch is thrown to its galvanometer position, the self contained centre zero (100 – 0 – 100) dc microammeter is connected, as a dc null detector across the bridge output. When the detector switch is thrown to its shunted galvanometer position, the microammeter is connected across the bridge output, but in parallel with the 100 Ω resistor R_{10}. This resistor decreases the microammeter sensitivity and acts to prevent meter damage when an unknown resistance is first checked.

Two self contained bridge power (signal) sources are employed. One is a General Radio 1000 Hz oscillator (an electromechanical type of oscillator) which supplies the signal voltage for inductance, capacitance and resistance measurements at ac. The second source is a 6 V battery used only to power the bridge when dc measurements of resistance are made with a microammeter (or an external galvanometer) as a null detector.

The function of the Generator Switch is to connect an appropriate power (signal) source across the input points of the bridge circuit. When this switch is in its 1 kHz position, the output of the self contained 1000 cycles per second oscillator is connected to the bridge input, and the 6 V battery is switched in automatically to drive the oscillator. When the switch is in its dc position, the self contained 6 V battery is switched across the bridge input circuit. When the Generator Switch is in its External position, the bridge input points are connected to the two terminals labelled external generator. A suitable external generator may now be connected to these terminals. When an ac type null detector is used, a satisfactory generator is an audio oscillator. When a self contained microammeter or external galvanometer is used as the bridge detector, a battery would be employed as the external generator.

The main control is a 10,000 Ω wire-wound rheostat having a logarithmic taper. The dial attached to this component is graduated 0 – 10 and is read directly in μμf, μF, μH, mH, H, Ω and MΩ, depending upon the setting of the multiplier switch. Thus the reading "4" on this dial is read as 400 mH if the bridge is set up for inductance measurement, and the multiplier switch is in position D, as shown in Fig. 10.15. But it would be read as 40,000 Ω if the bridge were set up for resistance measurement and the multiplier switch were in position F. Two separate pairs of unknown terminals are provided. Resistors under test are connected to the pair labelled R, and capacitors and coil to the pair labelled C-L.

The Selector Switch performs two functions. The first is to set up the bridge automatically for either resistance, capacitance or inductance measurements. For resistance, the circuit is a standard Wheatstone bridge, while for capacitance it is a conventional four arm bridge with capacitances in two legs and a resistance in the ratio arm. The Maxwell bridge circuit is employed for measuring inductors with Q factors of 10 or less, and the Hay bridge circuit for inductors with a Q factor higher than 10. The second function of the Selector Switch is to select the proper rheostat for reading the dissipation factor of capacitors or the Q of coils. When this switch is in its C – D position, the bridge is set up for measuring capacitance, and rheostat D is selected for dissipation factor readings from 0.001 – 0.1 (corresponding to a capacitor power factor ranging from 0.1 – 10%). When the switch is in its CDQ position, the bridge is set for capacitance measurements, and the rheostat DQ is selected for dissipation factor readings from 0.01 – 1. When the switch is in its LQ position, the bridge is set for inductance measurements, and the rheostat Q is selected for Q readings from 10 – 1000. When the switch is in its LDQ position, the bridge is set up for inductance measurement, and the rheostat DQ is selected for Q readings from 1 – 10. When the Selector Switch is in its R position, the bridge is set up for resistance measurement only, and the rheostats D, Q and DQ are automatically switched out of the circuit.

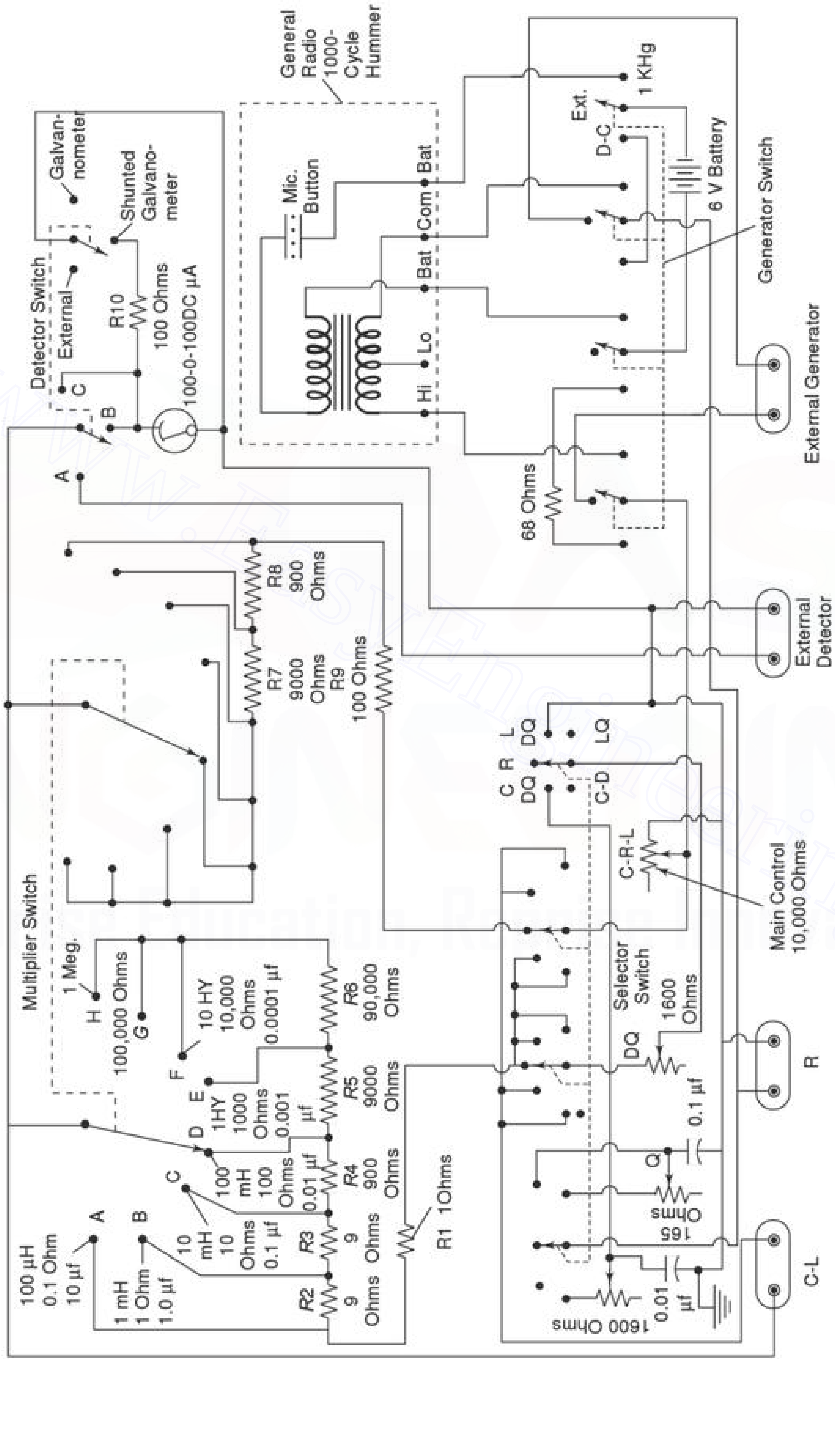


Fig. 10-15 Kit type impedence bridge

Rheostat Q has a logarithmic taper while rheostats D and DQ have a linear taper.

The reactive standards are self contained 0.01 and 0.1 μF precision capacitors. Both capacitance and inductance measurements are made against these capacitors as standards.

Initial Calibration The settings of the Main Control dial pointer must agree (when referred to the printed scale under this pointer) with the settings of the Main Control rheostat. It is the purpose of the initial calibration to align the scale and rheostat.

1. Set the Detector Switch to its shunted galvanometer position.
2. Set the Generator Switch to its D – D position.
3. Set the D, Q, and DQ rheostats to their zero or minimum resistance readings.
4. Set the Multiplier Switch to its 1000 Ω position (position D).
5. Set the Selector Switch to its R position.
6. Connect an accurately known 10,000 Ω resistor to the pair of terminals labelled R.
7. Adjust the Main Control rheostat for null, as indicated by zero reading of the internal microammeter.
8. Set the Detector Switch to its galvanometer position, and read just the main control for a sharper null indication.
9. The Main Control could read exactly 10 (which is an indication of 10,000 Ω. The value of the resistor connected to the R terminals). If it fails to do so, loosen the set screw of the Main Control knob without disturbing the setting of the rheostat, set the pointer exactly to 10, and retighten the set screw.

Since precision resistors are used in positions R_1 to R_9 and accurate capacitors are used for the 0.01 and 0.1 μF standards, this one-point calibration automatically calibrates all ranges of the bridge for ac and dc. If a highly precise, point by point calibration is required on the various ranges, this may be accomplished with a number of precision resistors, capacitors and inductors. Each component is connected to the bridge set up in the proper manner, a null adjustment is made, and the value of the component recorded against the setting of the main control. The direct readings of the D, Q and DQ rheostat dials are accurate only for a 1000 cycles per second bridge signal frequency.

RX METERS 10.9

An RX meter is used to measure the separate resistive and reactive components of a parallel Z network. It is especially useful in the design of RF tank circuits but can be used with any parallel "Z". The basic circuit of a typical RX meter is shown in Fig. 10.16.

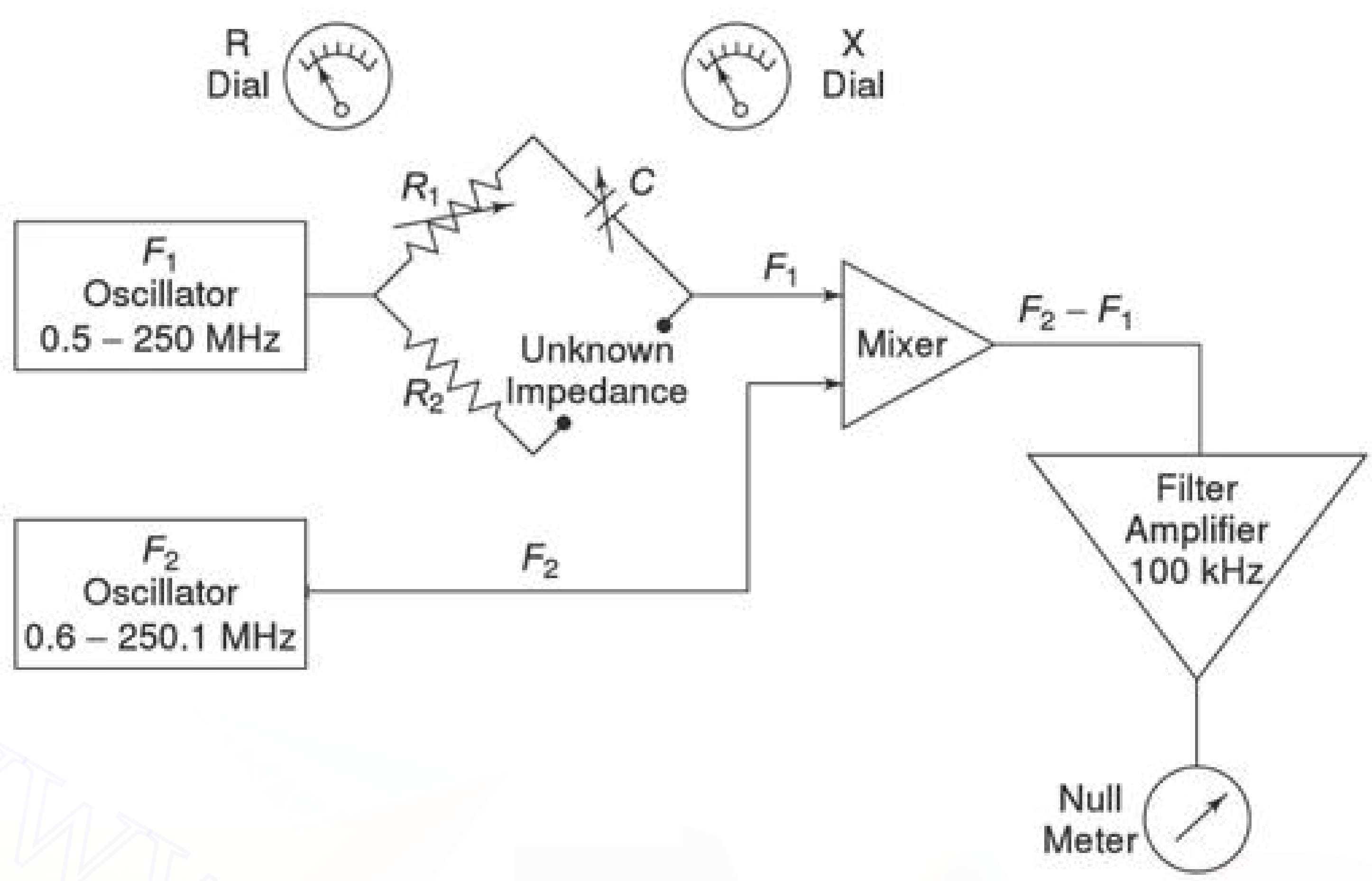


Fig. 10.16 Basic circuit of R-X meter

As shown in Fig. 10.16, there are two variable frequency oscillators that track each other at frequencies 100 kHz apart. The output of a 0.5 – 250 MHz oscillator, F_1 is fed into a bridge. When the impedance network to be measured is connected across one arm of the bridge, the equivalent parallel resistance and reactance (capacitive or inductive) unbalances the bridge and the resulting voltage is fed to the mixer. The output of the 0.6 – 250.1 MHz oscillator F_2, tracking 100 kHz above F_1, is also fed to the mixer.

This results in a 100 kHz difference frequency proportional in level to the bridge unbalance. The difference frequency signal is amplified by a filter amplifier combination and is applied to a null meter. When the bridge resistive and reactive controls are nulled, their respective dials accurately indicate the parallel impedance components of the network under test. For example, if balance is achieved with 50 Ω of resistance and 300 Ω of reactance, the network under test has the same values.

AUTOMATIC BRIDGES 10.10

The bridges discussed so far require that the controls be adjusted for balance after each capacitor (or other devices being tested) is connected to the bridge. In effect, they are manual. In recent years a number of automatic bridges have been developed. These bridges provide an automatic readout without adjustment of balance controls.

In some cases, the automatic bridges also provide a Binary Coded Digital (BCD) readout to external equipment. Automatic bridges are similar in operation to digital meters. To understand their operation, it is necessary to understand logic and digital circuit methods.

A typical automatic bridge circuit is shown in Fig. 10.17. The circuit is transformer-ratio-arm bridge for the automatic measurement of capacity. The circuit is in balance when the currents through the standard capacitor and the unknown capacitor are equal, so that the current in the phase detector is zero. The range is chosen automatically by relays that select decade taps on the ratio transformer. The phase detector determines whether the current passing through the unknown arm, of the bridge is higher or lower than that through the standard arm and produces an error signal that indicates whether more or less voltage is required on the standard capacitor to reach a balance.

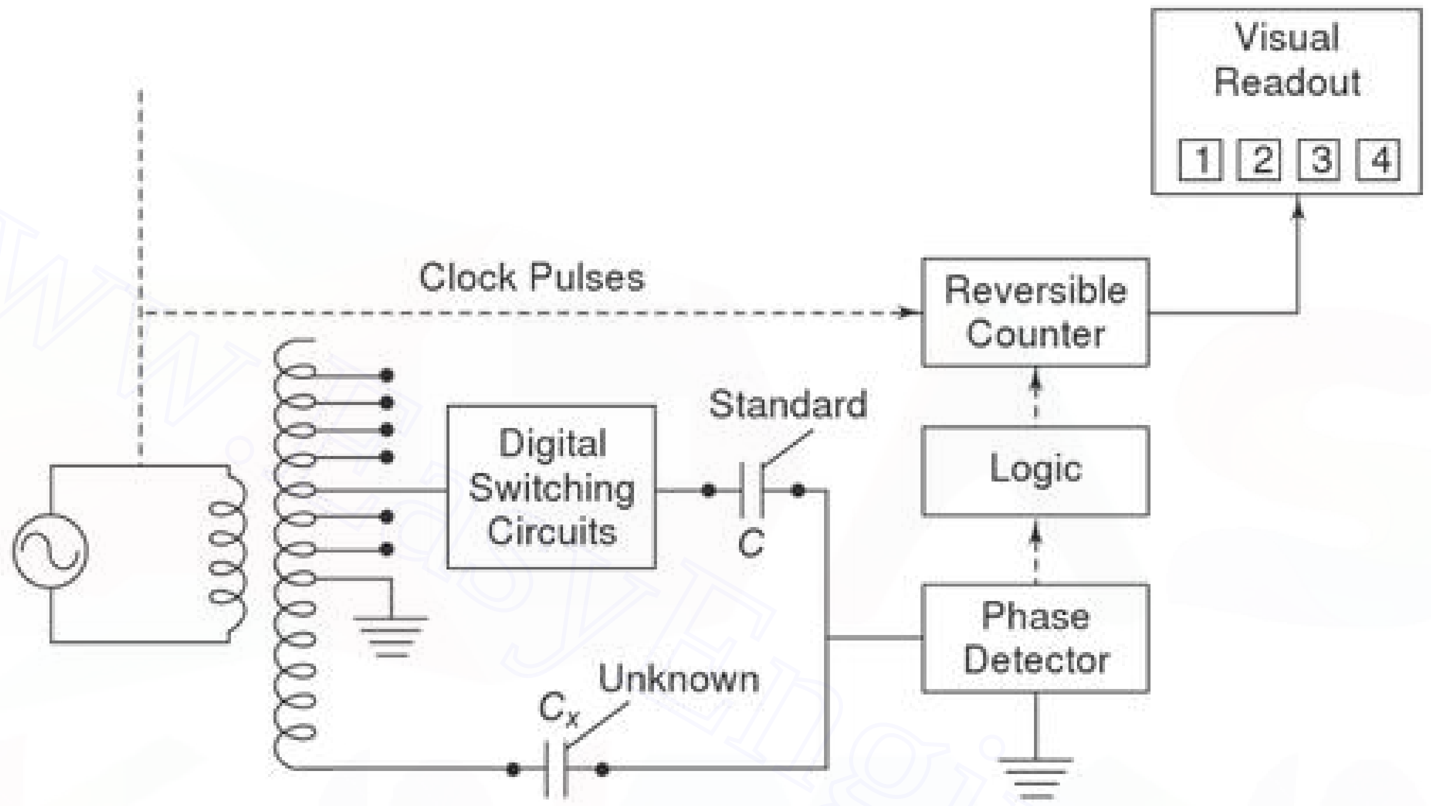


Fig. 10.17 Typical automatic bridge circuit

This information is used by a decade counter that controls the voltage on the standard capacitor through electronic switching circuits. The counter then counts in the direction which minimises the error signal, until a balance is reached. At balance, the value of the unknown is displayed on an in-line digital readout that indicates capacitance. This information is also presented in BCD form for use with printers and other data handling equipments.

TRANSISTOR TESTER 10.11

The term transistor tester (or analyser) used in this text is for instruments giving quantative measurements of transistor parameters. The tester should be able to provide direct readings for atleast two important measurements, such as:

1. A value for the forward gain in the common emitter configuration (h_{FE} for ac gain or h_{FE} for dc gain), that is β gain.
2. A value for collector to base leakage current, with emitter open I_{cbo}.

The latter measurement of C to B reverse current is generally regarded as most significant to test for the ageing of a transistor. It is an comparatively difficult measurement because of the small currents involved (in µA), and because of its extreme temperature sensitivity.

A typical service type transistor and diode tester examines transistors for the following characteristics.

1. Short circuits from C - E or base.
2. Direct measurement of I_{cbo}.
3. Direct reading of dc- β gain measurements (h_{FE})

10.11.1 Short-Circuit Test for C-E Breakdown

In the arrangement for the short-circuit test given in Fig. 10.18, the emitter and base terminals of the transistor under test are tied together and a reverse voltage of 4.5 V is applied between the collector and the two leads that are connected together. Figure 10.18(a) shows an arrangement for a PNP transistor and Fig. 10.18 (b) shows an arrangement for an NPN transistor.

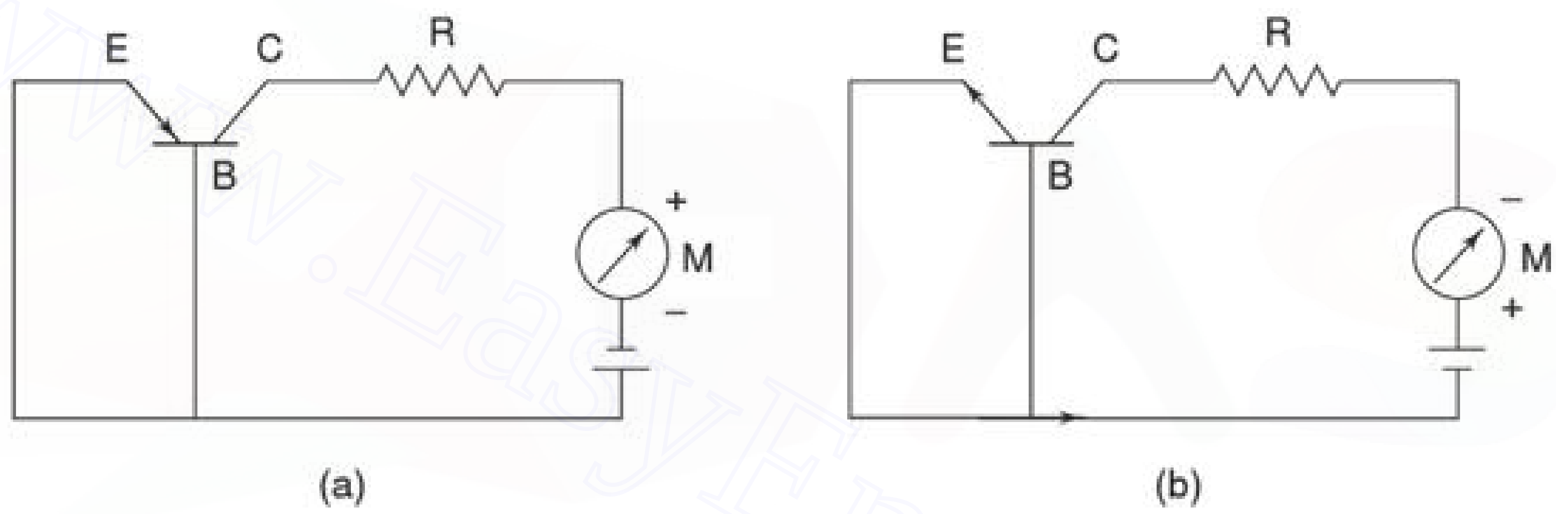


Fig. 10.18 Short circuit test

If there is a breakdown (usually from collector to emitter), the indicating meter tends to read full scale deflection. In that case, no further tests are performed on that transistor, thus avoiding possible damage to the meter circuit.

If the reading in the short position is less than the maximum allowable amount indicated on the chart, the next test for reverse current I_{cbo} is set up.

10.11.2 Direct Measurement of Collector-Leakage Current

Collector-leakage current is a function of the temperature and resistivity of the material of the transistor. Excessive leakage generally occurs when the conductor surface is contaminated. Other causes of this condition are overheating, or other types of damage. This is reverse current from the collector to the base, with the emitter open, denoted I_{cbo}. An excessive I_{cbo} indicates a faulty transistor. The tester circuit for this test is illustrated in Fig. 10.19(a). The collector-base junction is reverse biased and the emitter is open. The ammeter (in the micro range) indicates the reverse current.

Current from the collector to the emitter with an open base is denoted I_{ceo}. Figure 10.19(b) illustrates the circuit for this test. I_{ceo} should be expected to be much larger than I_{cbo}.

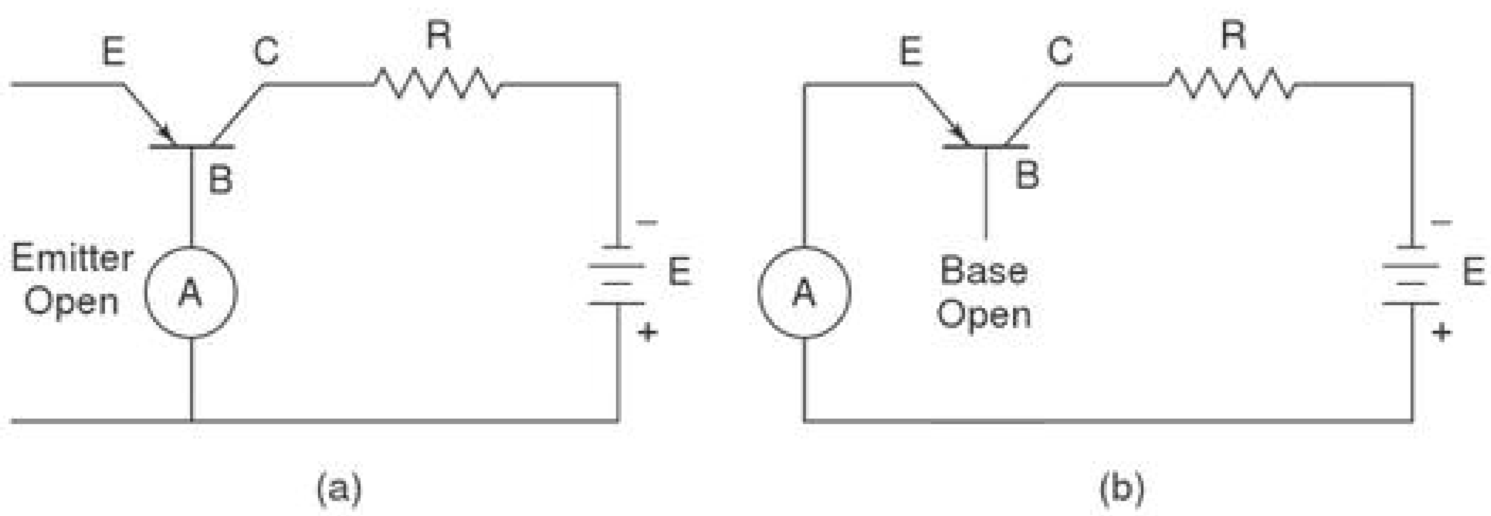


Fig. 10.19 (a) I_{cbo} test circuit (b) Tester circuit for I_{ceo} test

10.11.3 Direct Current Gain Test

Direct current gain is a measure of the effectiveness of the base in controlling collector current. It is a useful parameter for transistors used in low frequency power, amplification, switching, and control circuits. This test is useful only if the transistor is used in a common-emitter configuration.

Figure 10.20 illustrates the tester circuit used for test. R_1 is adjusted for a null on the voltmeter, at this point the dc gain is equal both to I_c/I_b, and R_x/R_2. R_1 usually has a calibrated dial to provide a direct reading of dc gain.

As a transistor ages, there is a tendency for the dc gain to decrease. This causes the amplification to decrease, which leads to distortion of the signal.

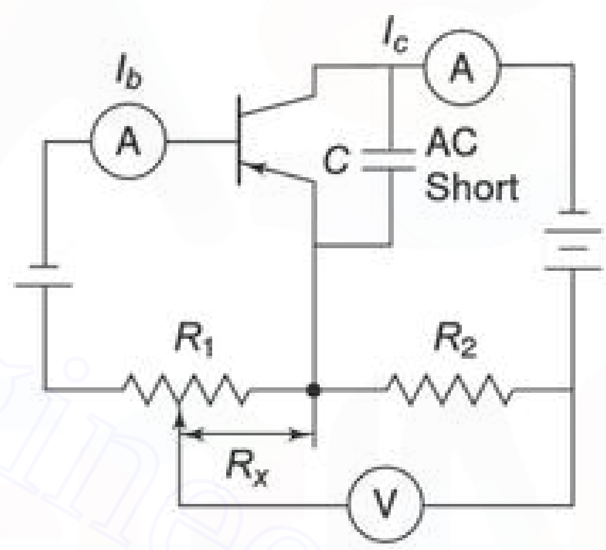


Fig. 10.20 Tester circuit for (gain) direct current test

10.11.4 Alternating Current Gain Test

Alternating current gain is expressed in two different ways, depending on the type of configuration the transistor is used in. For a common-base configuration, the amplification factor is alpha (α), which is the ratio of the change in the collector current to the change in the emitter current, with the collector voltage held constant. The collector has an ac short to the base during this test.

$$\alpha = \frac{\Delta I_c}{\Delta I_e}$$

If the transistor is in a common-emitter configuration, the amplification factor is beta β, which is the ratio of the change in collector current to the change in base current when the collector voltage is held constant. The collector has an ac short to the emitter during this test.

$$\beta = \frac{\Delta I_c}{\Delta I_b}$$

There is a definite relationship between alpha and beta, so that either may be calculated when the other is known.

$$\alpha = \frac{\beta}{1+\beta} \quad \text{and} \quad \beta = \frac{\alpha}{1-\alpha}$$

The test circuit for measuring beta is similar to that for measuring dc gain (see Fig. 10.20). The primary difference is that the beta measurement requires an ac signal at the transistor base. The proper values of either beta or alpha are given on the manufacturer's data sheet. The measured values should match these fairly closely, if the transistor is good.

10.11.5 Four Terminal Parameter Test (Hybrid Parameters)

A transistor may be considered as a four terminal network in order to determine the relationships between input and outputs. These relationships are referred to as hybrid (h) parameters, which are referred to in data sheets and on test instrument.

Hybrid parameters are very useful in determining the quality of a transistor. The four terminal network is shown in Fig. 10.21(a).

With this arrangement, there are two currents and two voltages to consider. If the two currents are considered as dependent variables, the resulting parameters are short-circuited parameters, and they are measured in mhos. When the two voltages are considered as dependent variables, the resulting parameters are open-circuit parameters, and they are measured in ohms. Hybrid (h) parameters are obtained by using one current and one voltage as dependent variables. The designations for the four h parameters are as follows.

h_i – input impedance with output shorted
h_r – reverse voltage ratio with input open
h_f – forward current gain with output shorted
h_o – output admittance with input open

The unit of measure for h_i is ohms, and for h_o is mhos. There are no units for h_f and h_r, since they are ratios.

The h parameters can be applied to any of the three basic amplifier configurations. An additional subscript letter is generally used to designate the type of configuration. Subscript b indicates common-base, e designates common-emitter and c denotes a common-collector.

The h parameter designations for a common emitter are h_{ie}, h_{re}, h_{fe}, and h_{oe}. Alpha for a common base circuit is equal to h_{fb} and beta in a common emitter is equal to h_{fe}.

The tester circuit for obtaining h parameters is illustrated in Fig. 10.21(b). G_1 is a calibrated current generator and G_2 is a calibrated voltage generator. The ac meter is used to indirectly measure current. The switches are four ganged sections of a five position rotary switch.

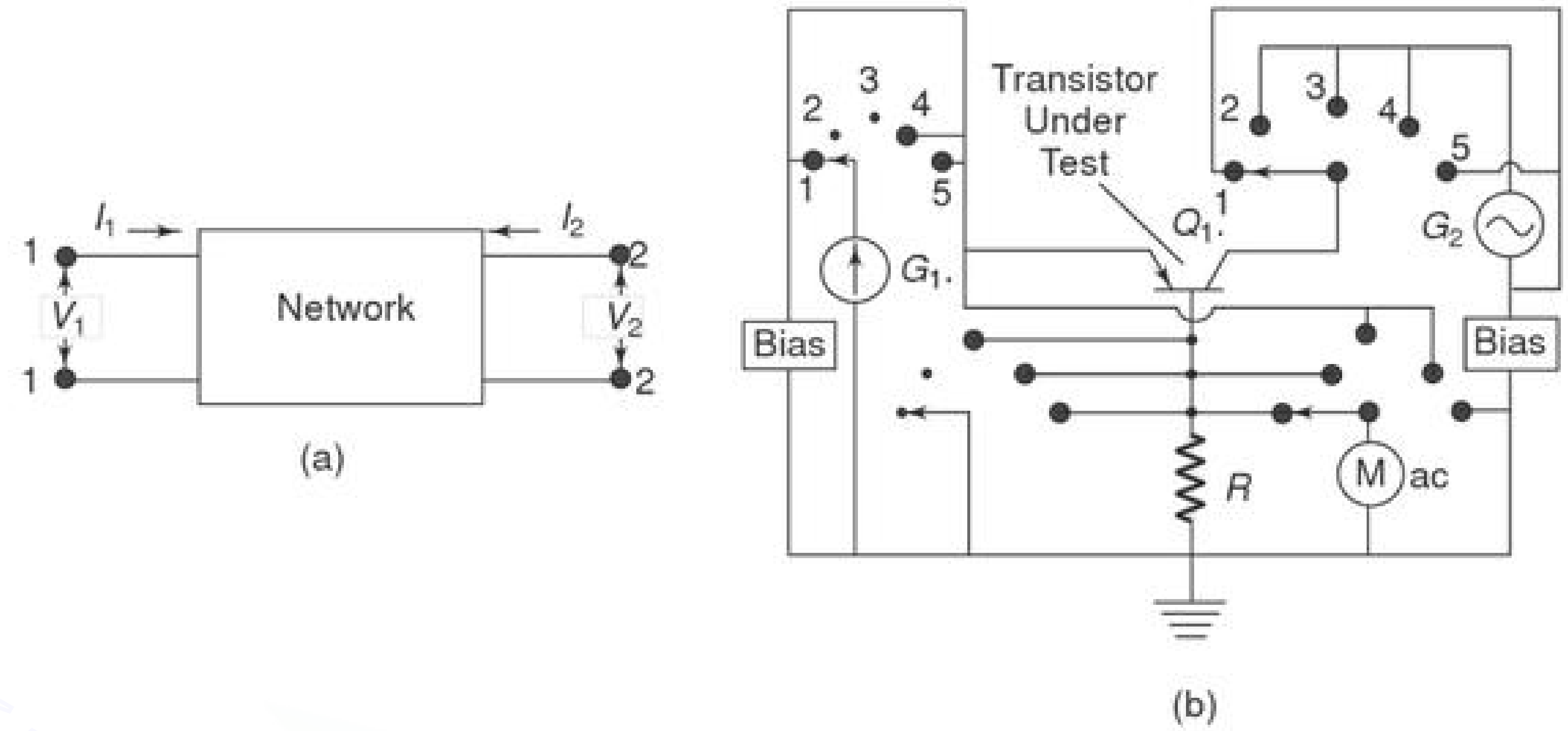


Fig. 10.21 (a) Basic four terminal network (b) Tester circuits for measuring hybrid parameters

Position 1 of the switch connects the calibrated current generator to the emitter of the transistor under test. The ac meter indicates $I + h_f$, which is the ratio of the ac base current (i_b) to the ac emitter current (i_e).

Position 2 of the switch connects the calibrated voltage generator to the collector, and the meter indicates the output admittance, h_o. The emitter is open during this measurement.

Position 3 measures h_r, position 4 measures h_i, and position 5 measures alpha.

10.11.6 Transistor Tester for Polarity

This tester checks the transistor for polarity (PNP or NPN). An audible signal gives an indication of gain. This tester is illustrated in Fig. 10.22.

The tester can also be used as a GO/NO GO tester to match unmarked devices.

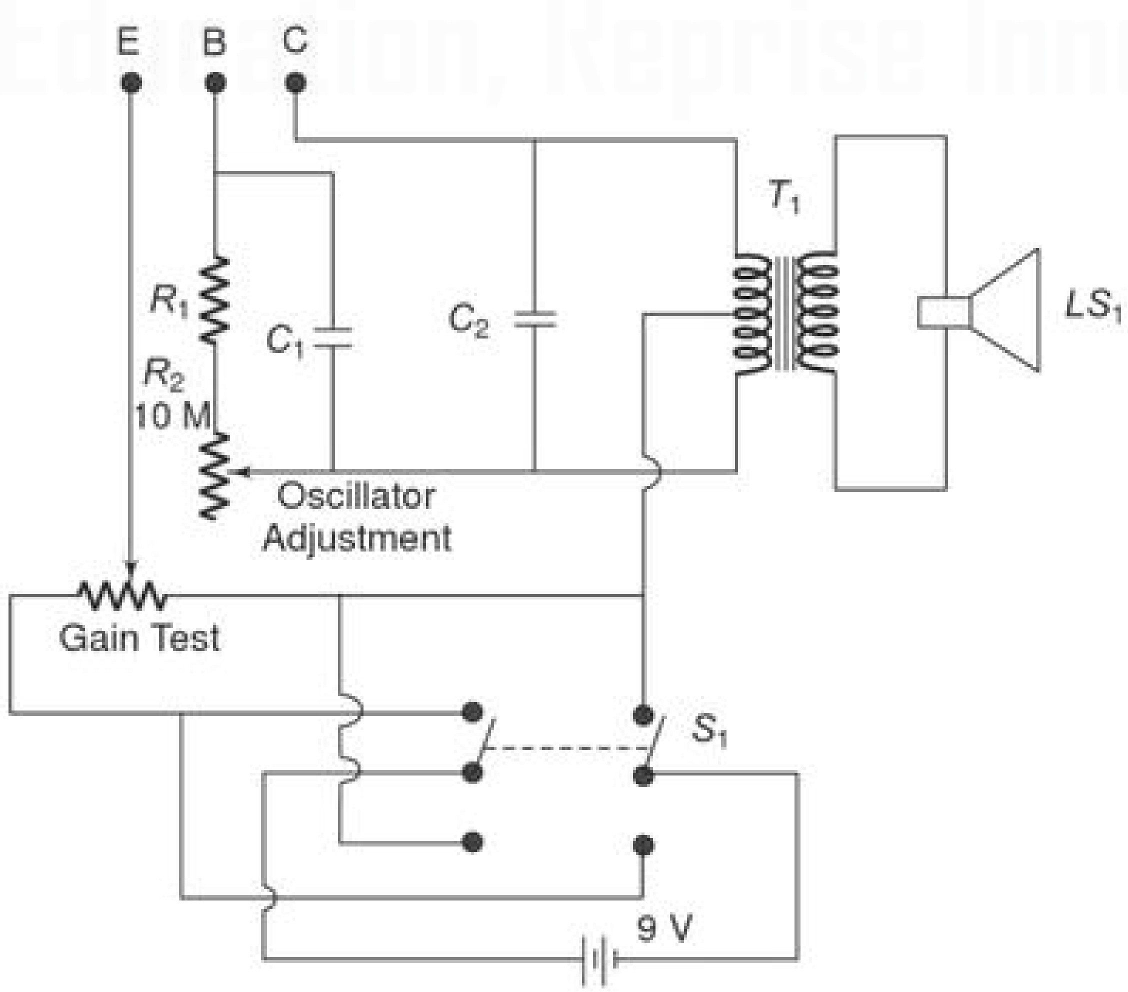


Fig. 10.22 Transistor tester for NPN/PNP

MEGGER 10.12

Another common method of measuring resistances above 50 M Ω is the Megger (megaohmmeter) shown in Fig. 10.23(a). This instrument is used to measure very high resistances, such as those found in cable insulations, between motor windings, in transformer windings, etc.

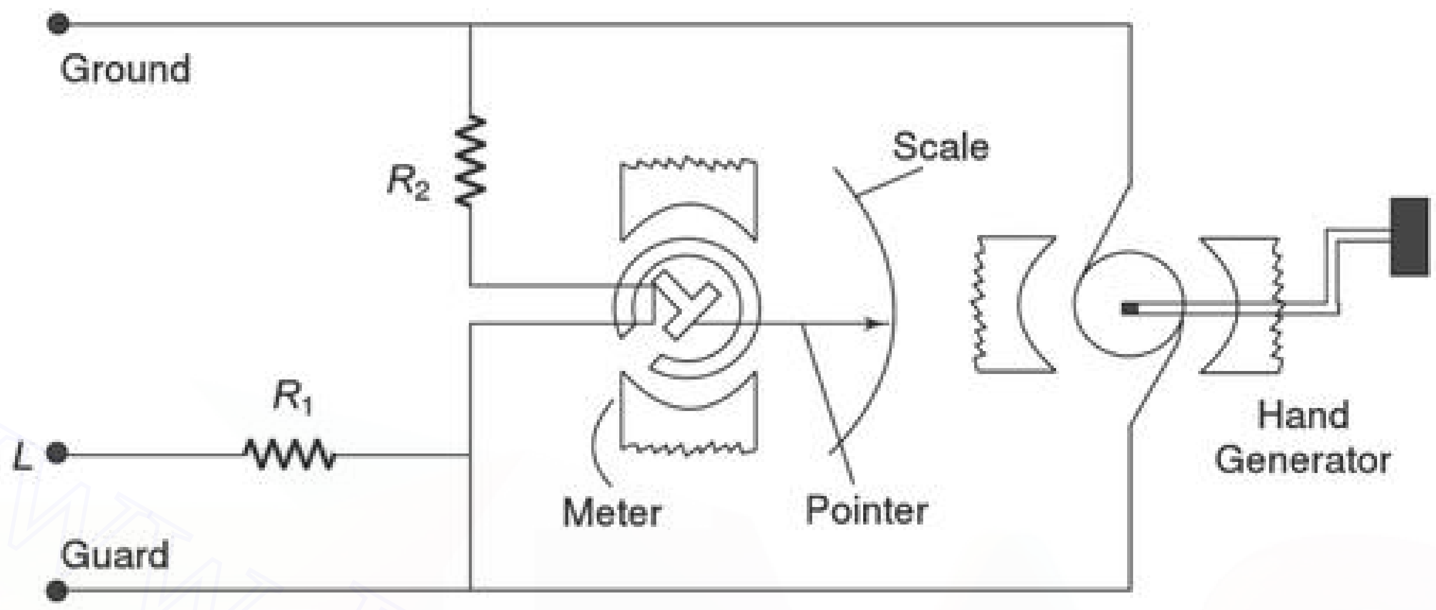


Fig. 10.23 (a) Basic megger circuit

Normal (shop) VOMs do not provide accurate indications above 10 MΩ because of the low voltage used in the ohmmeter circuit. Some laboratory test meters have a built-in ohmmeter with a high voltage power supply. The high voltage permits accurate high resistance measurement, but such meters are usually not portable. The Megger is essentially a portable ohmmeter with a built-in high voltage source. The Megger, shown in Fig. 10.23(b), has two main elements, a magnet-type dc generator to supply current for making measurements, and an ohmmeter which measures the resistance value. The generator armature is turned by a hand crank usually through step up gears, to produce an output voltage of 500 V. When the crank is turned, the gears turn the generator at high speed to generate an output voltage that may be 100, 500, 1000, 2500 or 5000 V, depending on the model.

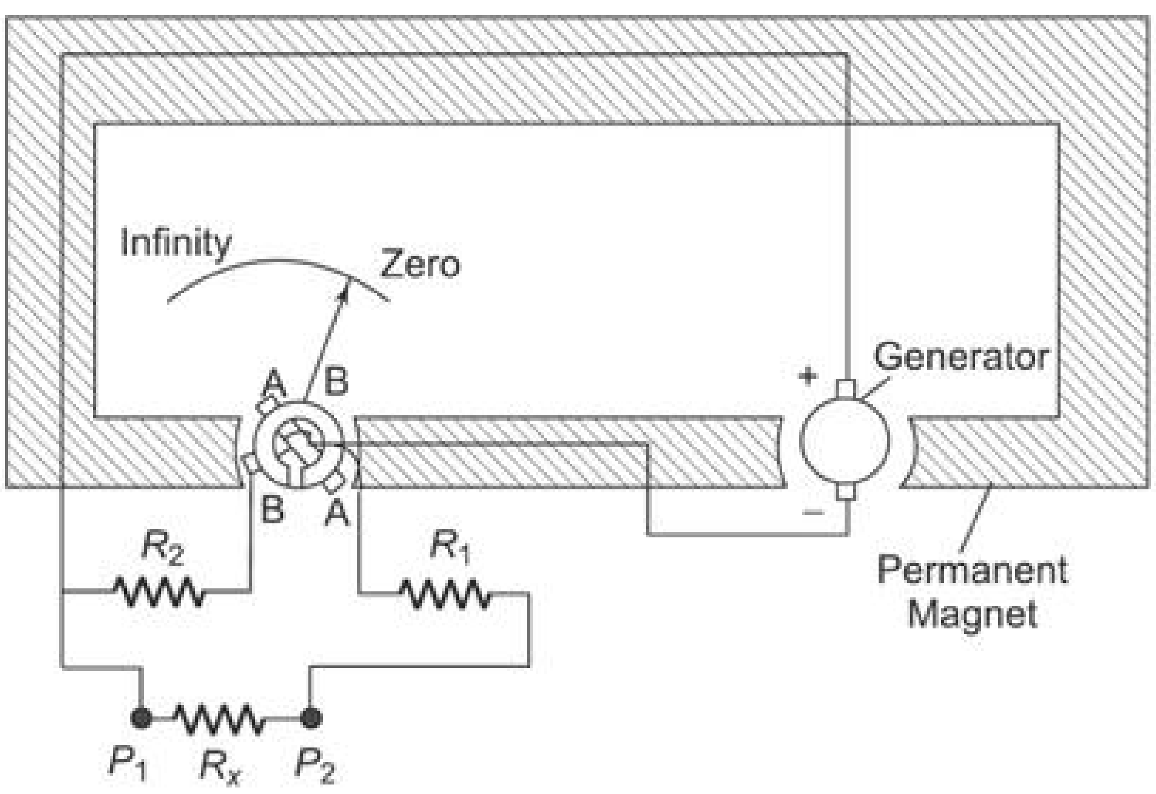


Fig. 10.23 (b) Megaohmmeter Circuit

The meter used differs slightly from the standard D'Arsonval movement, in that it has two windings. One windings is in series with the reference R_2 across the output of the generator, and is wound in such a way as to move the pointer towards the high resistance end of the scale when the generator is in operation. The other winding coil (A) and resistance R_1 are connected in series between the negative pole of the generator and the line terminal. This winding is so wound that when current flows through it from the generator, it tends to move the pointer towards the zero end of the scale. The two coils are mounted on the same shaft but at right angles to each other. Current is fed to both the coils by means of flexible connections that do not hinder the rotation of the element.

Coil A is the current coil with one terminal connected to the negative output and the other connected in series with R_1 to the test lead P_2. Test lead P_1 is connected to the generator positive output. When the unknown resistance R_x is connected across P_1 and P_2, current flows from the generator through coil A, resistances R_1 and R_x. The value of R_1 is so chosen so as to ensure that even if the line terminals are short-circuited, the current coil A is not damaged.

Coil B is the voltage coil and is connected across the generator output through the resistance R_2. If the test leads are left open, no current flows in coil A and coil B alone moves the pointer. Coil B take a position on the opposite side in the core, and the pointer indicates infinity or open.

When an extremely high resistance appears across the terminals, such as in an open circuit, the pointer reads infinity. On the other hand, when a resistance of relatively low value appears across the test points, such as when the cable insulation is wet, the current through the series winding causes the pointer to move towards zero (resistance short-circuited). However, the pointer stops at a point on the scale determined by the current through the series resistor, which in turn is governed by the value of the resistance being measured.

When an unknown resistance R_x is connected across the test leads, the current flows in coil A. The corresponding torque developed moves the pointer away from the infinity position, into a field of gradually increasing strength, until the torque fields between coils A and B are equal. Variations in the speed of the hand-cranked generator do not affect the Megaohmmeter readings, since charges in generator voltage affects both coils in the same manner.

Meggers may read resistances of several hundred or even thousands of megaohms. They have the advantage, as compared to an ordinary ohmmeter, of applying a high voltage to the circuit under test, and this voltage causes a current if any electrical leakage exists.

ANALOG pH METER 10.13

pH is defined as the negative logarithm of the active hydrogen ion. It is a measure of the acidity or alkalinity of an aqueous solution. The pH scale runs from 0 – 14, with pH 7, the neutral point, being the pH of pure water at 25°C. The lower the pH value, the more acidic the solution. Increasing pH values above 7.0, indicate increasing alkalinity.

Usually the pH is measured by immersing a special glass electrode and reference electrode into the solution. There are two types of methods used to measure the pH, the colorimetric method and the electrical method.

The colorimetric method is based on the assumption that if an indicator has the same colour in two solutions, then the pH of both solutions is the same. However, in practice this assumption does not hold good always, since the colour developed depends not only on the pH but also on other factors.

The electrical method is the most popular and is based upon a measurement of the electrode potential. The principle of this method is that when an electrode is immersed in the solution, a potential arises at the electrode solution boundary known as the electrode potential. This electrode potential, at a given temperature, depends upon the concentrations of ions of the electrolyte which exist in the solution. The electrode potential (in volts) of a metal immersed in a solution with ions of the same metal can be expressed by the following relation.

$$E = E_o + \frac{0.0001982\,(273 + t)}{n}\log_{10} a$$

where E_o = potential of the electrode, when its active-ion concentration in the solution is equal to unity.

t = temperature in degree centigrade

n = valency of the ion

a = active concentration of the ions of the metal in gram-equivalents per litre

In practice, only the potential difference can be measured and so the pH always has two elements; a measuring element, the potential of which depends on the concentration of the hydrogen ions, and a comparison element, the potential of which must remain constant. Two such elements connected electrically form a galvanic system, and by measuring the emf of this system we can drive the active concentration of the hydrogen ions in the solution under investigation.

The various electrodes used for pH measurements are as follows.

1. Hydrogen electrode
2. Calomel electrode
3. Quinhydrone and antimony electrodes
4. Glass electrodes

We now give some of the electrical methods used for measuring pH.

10.13.1 pH Measurement Using Hydrogen Electrode

The hydrogen electrode comprises a platinum plate covered with platinum black kept in a hydrogen element, where gaseous hydrogen at atmospheric pressure acts directly on this plate.

It consists of a hollow tube which is opened at the bottom end and immersed in the solution whose pH value is to be measured. The platinum plate is inserted into this hollow tube and joined to the platinum wire which is welded to the glass tube. This platinum wire is joined to a copper lead, as shown in Fig. 10.24.

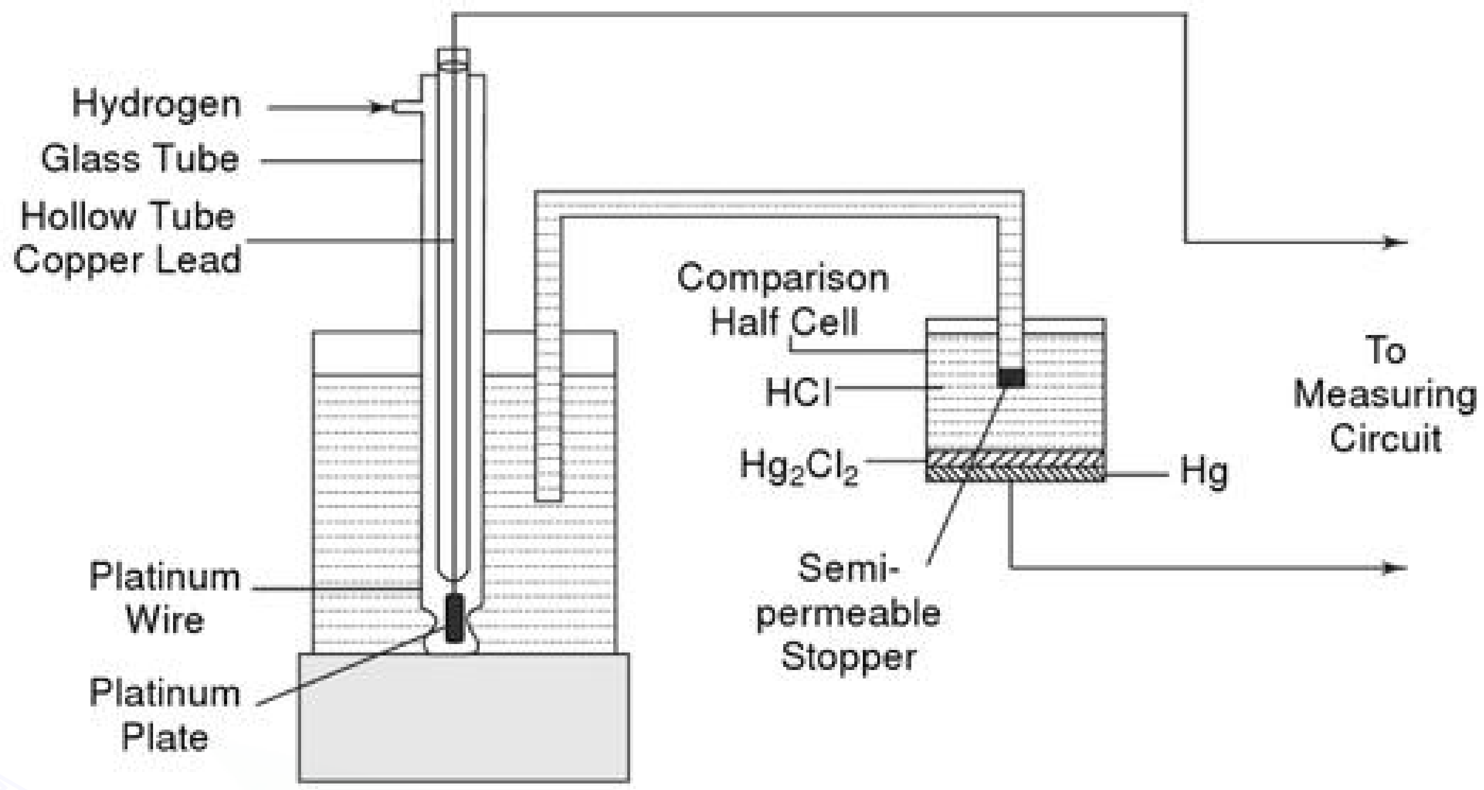


Fig. 10.24 pH measurement using hydrogen electrode

The hydrogen is fed to the outer tube from above and passes out through the lower apertures placed half way up the platinum plate. The hydrogen electrode is joined to the comparison half cell by an electrolytic solution. The cell is filled with an inert salt (for example, HCl) and closed by a semi-permeable stopper. This means of connecting the elements lowers the diffusion potential (up to 1– 2 mV), which arises at the boundary of the two solutions and introduces an error in the result of the measurement.

The electric potential developed on a hydrogen electrode dipped in a solution is caused by the concentration of hydrogen ions in the solution, or the pH of the solution. By measuring this electric potential, the pH of the solution can be determined. There is no method by which the absolute value of the potential developed on the hydrogen electrode can be determined. It is always the potential difference between two objects or the potential difference between two points on the same object which is determined. Therefore it is possible only to determine the relative potential of the hydrogen electrode compared to the known potential of some reference electrode.

10.13.2 pH Measurement Using a Thermocompensator

A thermocompensator is a temperature sensitive element (usually thermistor) installed in the solution with the electrodes. The glass electrode potential is influenced by changes in the temperature of the sample solution, and the thermocompensator corrects for this change. It should be noted that the thermo-compensator corrects for the voltage/temperature relationship of the glass electrode and does not correct for the actual changes in the pH of the solution with temperature variations. The use of a matched pair of thermistors can provide a linear temperature compensation response of 90% in less than one minute.

10.13.3 Differential Input pH Amplifier

Differential input techniques use integrated circuit operational amplifiers in conjunction with a difference amplifier. This device is so small that it can be mounted on a single circuit board and sealed on top of the electrode station (provided the temperature to which it is subjected is less than 70°C; otherwise it is mounted in separate junction box suitably located at the site).

As the pH glass electrode is a high impedance device with output at extremely low current levels, a high impedance precision amplifier with high stability is required for the accurate and reliable measurement of this signal. The very high resistance of the glass electrode demands that the measuring techniques does not require current when the reading is made. If any current is taken from the circuit, the portion of the emf used to force the current through the resistance subtracted from that originally available, and all values obtained are fictitiously low.

In a pH measurement system, any extraneous leakage current to the ground find a return path through the normally low resistance reference electrode. With a conventional single input amplifier, this extraneous voltage developed across the reference electrode adds to the measured pH potential, resulting in an error in the indicated pH. If the resistance of the reference electrode is relatively low, this error is usually insignificant. However, if this resistance increases due to coating or junction clogging, the extraneous voltage across it increases and can cause a significant error in the indicated pH.

In the differential input pH amplifier, the glass pH measuring electrode and the reference electrode are each inputted to separate high impedance constant gain integrated circuit operational amplifiers A_1 and A_2, with negligible current flowing through the electrodes. This arrangement is shown in Fig. 10.25.

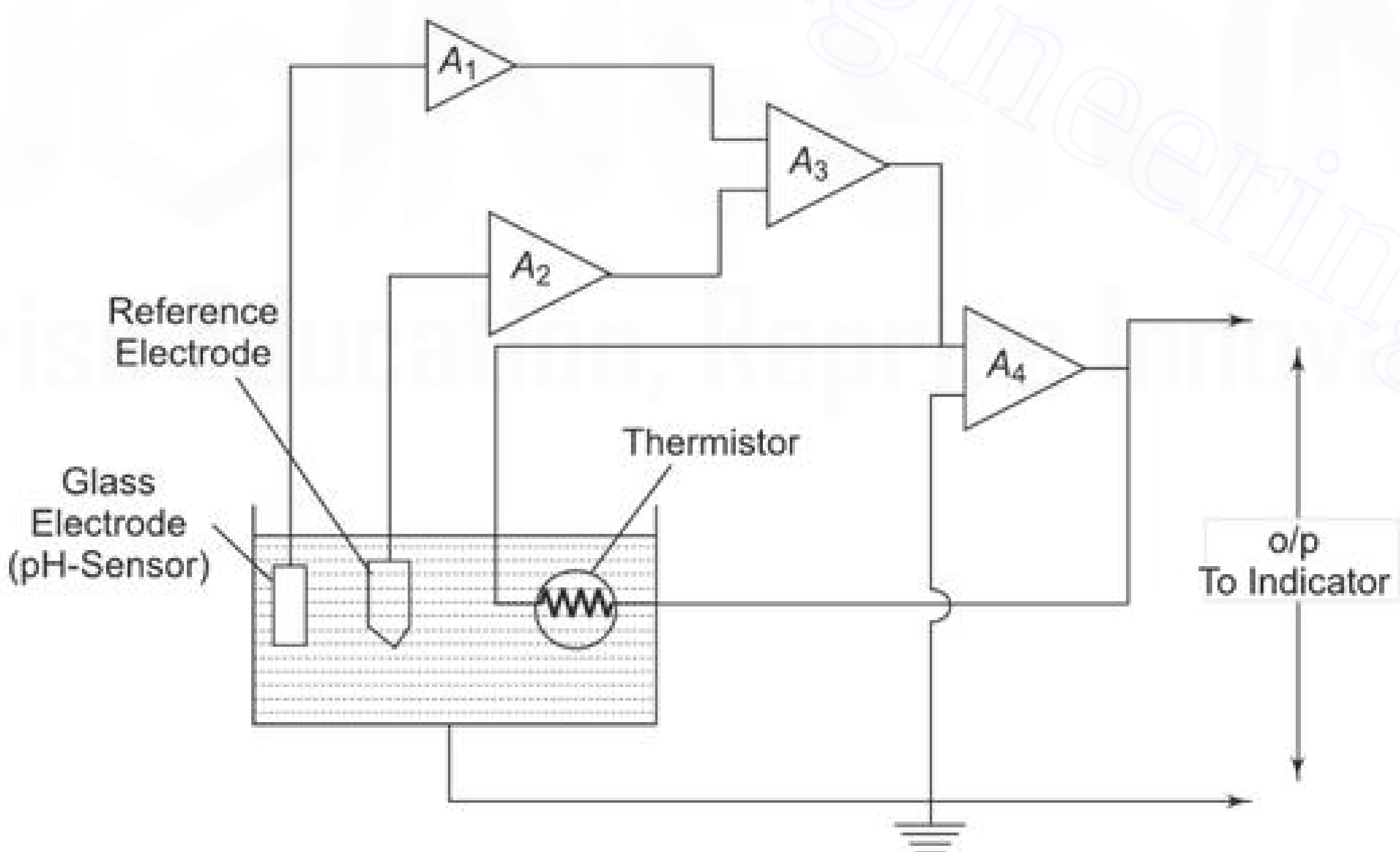


Fig. 10.25 Differential input pH meter

The glass electrode amplifier A_1 measures the pH potential as well as any potential through the solution to ground. The reference electrode amplifier A_2 measures the potential through the solution to ground. Amplifiers A_1 and A_2 are outputted to a difference amplifier A_3 which cancels out the solution potential and produces a signal equal only to the pH potential.

This method has the following advantages.

1. Virtually eliminates drift and noise
2. Has no stringent installation and maintenance requirements
3. Allows the pH indicator to be kept virtually any distance from the electrodes
4. Eliminates the need for costly coaxial cables between the measuring point and the pH indicator

10.13.4 Instruments for the Measurement of emf of Electrodes for pH Measurement

Indicating and automatic recording type instruments are used in industries for measuring the pH of different solutions. The pH is measured by measuring the difference of potential between the electrodes of the half cells. In order to eliminate distortions while measuring the emf of a sensor (e.g. the main sensing device of a pH meter, which consists of the appropriate electrode), the magnitude of the input resistance of the measuring instruments must be atleast two orders higher than the resistance of the electrodes. For example, if the resistance of glass electrodes is $1 - 2 \times 10^8\ \Omega$, the resistance of the instrument must be about $1 - 2 \times 10^{10}\ \Omega$. The dc voltage is transformed into ac voltage by frequency transformation circuits using either vibration converters or dynamic condensers.

TELEMETRY 10.14

Telemetry may be defined as measurement at a distance. According to ASA, *telemetering is the indicating, recording or integrating of a quantity at a distance by electrical means*.

There are several methods of classifying telemetering systems that are used.

IEEE bases its classification on the characteristics of the electrical signal. They are

(a) voltage (b) current (c) position (d) frequency, and (e) pulse.

Telemetering systems can also be classified as

(i) analog, and (ii) digital.

Telemetering can further be classified

(a) short-distance type, and (b) long-distance type.

The classification can also be based on whether the user has control over a transmission channel or not.

All of the IEEE's classifications can be used for shorter distance telemetring, but only the frequency and pulse types are suitable for long-distance telemetring.

The voltage, current, position and frequency can be used for analog telemetry, while only pulse type can be used for digital telemetring.

Voltage, current, position telemetring requires a physical connection between the transmitter and the receiver. The physical connection is called as a channel, which consists of one or two or more wires depending upon the system.

In case of RF, the telemetry channel is not a physical link

10.14.1 General Telemetring System

A general telemetring system is as shown in Fig 10.26. The primary detector and the final stage of the telemetring system have the same function as in a general measurement system.

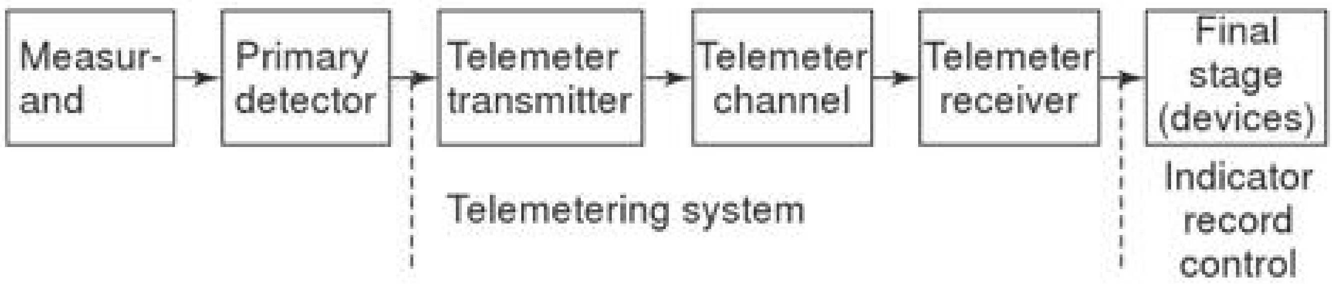


Fig 10.26 General telemetring system

The function of the telemeter transmitter is to convert output of a primary detector into a related quantity, which can be transmitted over the channel.

The function of the telemeter receiver, at the remote location, is to convert the transmitted signal into a related suitable quantity.

10.14.2 Electrical Telemetring System

The electrical telemetring system consists of a transmitter, which converts the input measured into an electrical signal, which is transmitted through a telemetring channel and is received at the other end by a receiver located at a distance in a remote location. This signal is then converted into a suitable usable form by the receiver and then can be indicated, recorded by the final stage device, which is calibrated in terms of the measurand.

The electrical telemetring systems can be broadly classified as

(i) dc systems, and (ii) ac systems.

10.14.3 DC Telemetring System

The dc telemetring system is categorized as

(i) Voltage Telemetring system
(ii) Current Telemetring system
(iii) Position Telemetring system

In a dc telemetring system the signal is transmitted through a channel, which utilizes direct transmission through cables in order to convey the information.

(i) Voltage Telemetring System

A voltage telemetring system transmits the measured variable as a function of an ac or dc voltage.

A simple voltage telemetring system is shown in Fig 10.27.

As seen from the diagram, a slide wire potentiometer is connected to a battery. The variable sliding contact of the potentiometer is moved by the pressure sensitive bourdon tube, which expands as the pressure is applied.

The telemetring channel consists of a pair of wires, which are connected to a voltage-measuring device such as a null balance dc indicator or recorder.

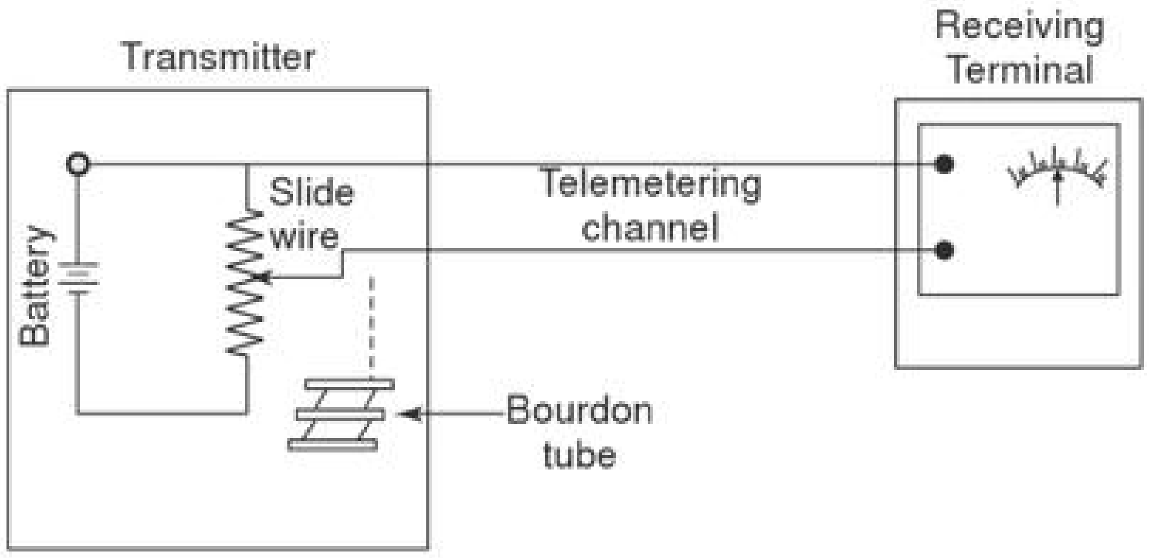


Fig. 10.27 Simple voltage telemetring system

As the measured pressure changes, the bourdon actuates the sliding contact, which in turn changes the voltage. The dc null balance potentiometer measures the voltage and positions the pointer on a scale calibrated to measure pressure.

The advantage of using a null balance dc potentiometer is, it reduces the current carried by the telemetring channel to a minimum.

The primary elements used by most of the systems produce a voltage signal. The primary elements can be thermocouples, tachometers, etc.

The application of voltage systems in the industry is limited to distances of up to about 300 metres.

Most of the receivers often use self-balancing potentiometers for such systems.

A voltage telemetring system requires high quality circuits than the current type. The signal-to-noise ratio must be comparatively high.

Since the power level is small for the voltage telemetring system, the transmission channel must be well protected from noise and interferences, which can be of the same order of the signal.

(ii) Current Telemetring System

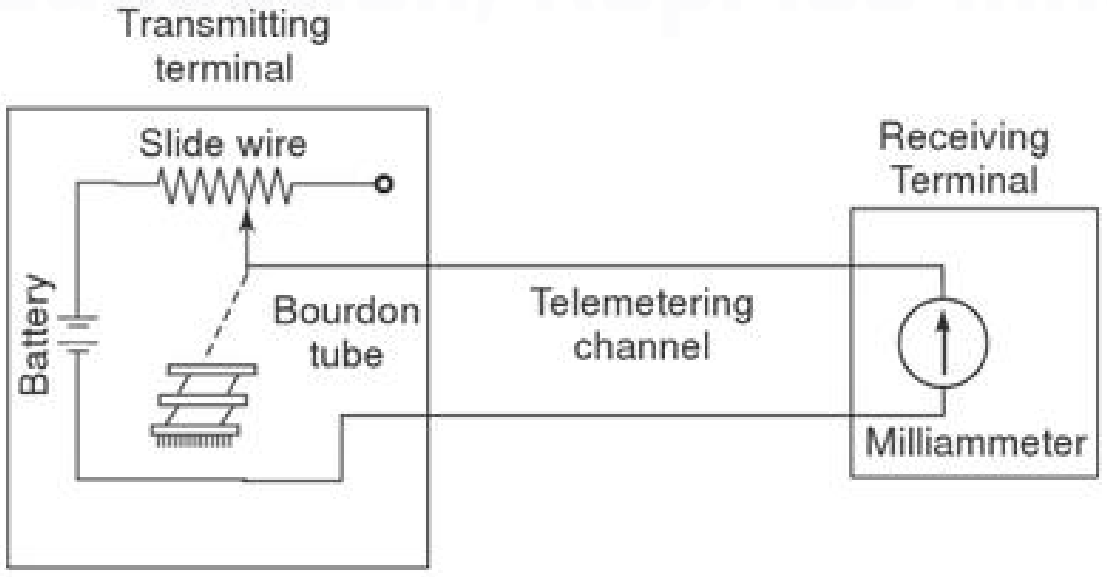


Fig 10.28 Basic current telemetering system

The basic version of a current telemetring system is shown in Fig 10.28.

This is similar to the voltage telemetring system except that the slide wire potentiometer is now connected in series with the battery.

The sliding contact of the potentiometer is connected to the pressure sensitive bourdon tube, which moves as the bourdon tube expands.

In this case, the telemetring channel consists of a pair of wires, which are connected to a current measuring device.

As the pressure changes, the bourdon tube expands, which in turn changes the position of the sliding contact on the (potentiometer) slide wire. This changes the current flow in the circuit. This current is measured by a milliammeter, whose scale has been calibrated to read pressure directly.

The most commonly used current telemetring systems are the (a) motion, and (b) force balance types which are improved version of the basic type.

(a) Motion Balance System In a motion balance system, the potentiometer or the slide wire is replaced by a position detector, such as LVDT as shown in Fig. 10.29.

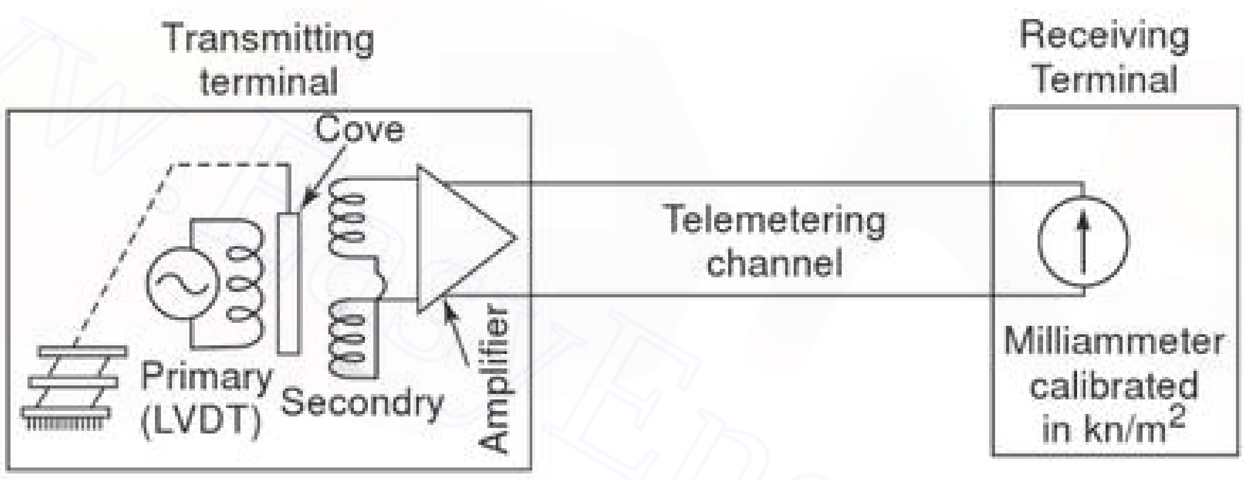


Fig 10.29 Motion current telemetering system

In this system, the bourdon tube is connected to the core of the LVDT. When pressure is applied to the bourdon tube, the bourdon tube expands causing a displacement. This moves the core of the LVDT, thereby producing an output voltage, which is then amplified and rectified. This voltage produces a dc current of the order of 4 mA to 20 mA in the telemetry channel and is measured by the milliammeter.

The scale of the milliammeter is directly calibrated in terms of pressure that is being measured.

(b) Force Balance Systems A force balance systems is as shown in Fig. 10.30, a part of the current output is fed back to oppose the motion (movement) of the input variable.

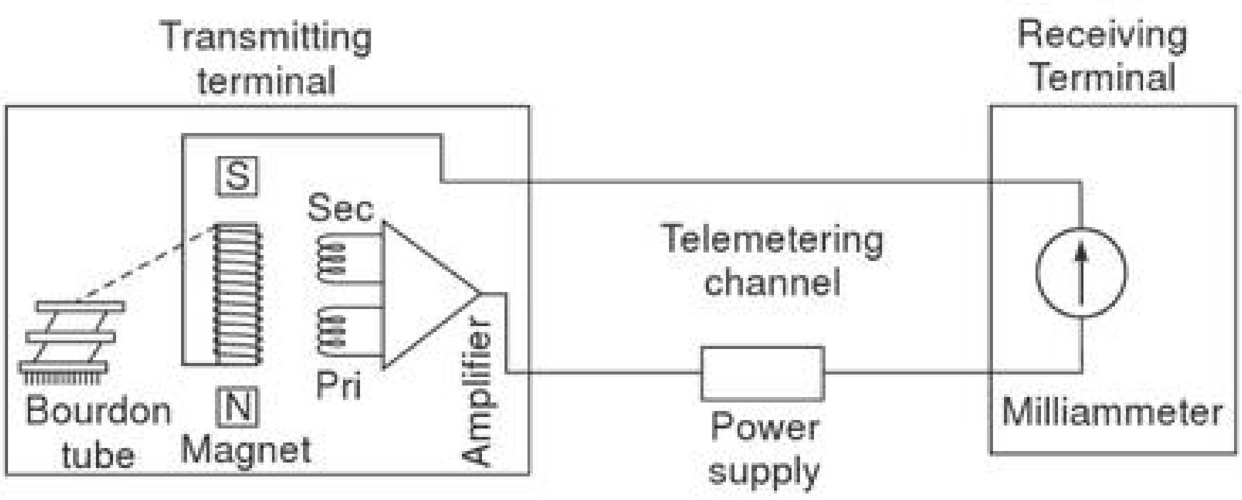


Fig 10.30 Force balance current telemetering system

The bourdon tube operates the system which rotates the feedback force coil.

This in turns changes the flux linkage between the primary and the secondary coils.

This change in flux linkages varies the amplitude of the amplifier. The output signal is then fed back to the feedback force coil, which in turn produces a force opposing the bourdon input.

A force balance system increases the accuracy, as smaller motions are required which results in better linearity.

Review Questions

1. State the working principle of an output power meter.
2. Explain with a diagram the working of an output power meter.
3. How is field strength measured? Explain the basic principle of a field strength meter.
4. Explain with a diagram the working of a basic field strength meter.
5. Explain with a diagram the working of a field strength meter using transistors.
6. State the basic principle on which the stroboscope operates.
7. Explain with a diagram the operation of a stroboscope.
8. Explain how speed of a motor can be measured using a stroboscope.
9. Explain the principle of a phase meter or a phase-sensitive detector.
10. Explain with a diagram the working of a phase-sensitive detector.
11. State the principle used in a basic vector impedance meter.
12. Explain with a diagram the working of a vector impedance meter.
13. Explain with a diagram how impedance can be measured using a commercial vector impedance meter. Explain with a diagram how phase angle can be measured using a commercial vector impedance meter.
14. Define *Q*-factor and resonance. Explain the working principle of a *Q*-meter.
15. Describe with a diagram the operation of a *Q*-meter. List the factors that causes error in a *Q*-meter.
16. Explain how *Q*-meter can be used to measure the following:
    (a) dc resistance of a coil
    (b) stray capacitance
    (c) impedance of a circuit
    (d) characteristics impedance of a transmission line.
17. Explain the operation of a *Q*-meter for measurement of stray capacitance.
18. Explain the operation of a *Q*-meter for measurement of HF resistance. Explain the operation of a *Q*-meter for measurement of low impedance value.
19. Explain the operation of a *Q*-meter for measurement of high impedance value
20. How can *Q* be measured using susceptance method?
21. What is a *LCR* bridge? How can *L*, *C* and *R* be measured using a skeleton *LCR* bridge?
22. State the features of a kit type *LCR* bridge.
23. Explain in brief the working of a kit type *LCR* bridge.
24. State the principle of *R-X* meters. Explain with a basic diagram the operation of an *R-X* meter.
25. Explain with a diagram the operation of an automatic bridge.

26. What is a transistor tester?
27. Explain with diagram how a transistor tester can be used for the measurement of the following:
    (i) Faulty transistor (ii) I_{cbo}
    (ii) I_{ceo} (iv) Beta gain
28. What is a megger? Explain with a diagram the working of a basic megger.
29. Explain with a diagram the working of a megaohmmeter circuit.
30. What do you understand by pH? Define pH.
31. How can pH be measured? State the different methods of pH measurement.
32. Explain with diagram pH measurement using hydrogen electrode.
33. Explain with diagram pH measurement using a thermocompensator.
34. Explain with diagram the operation of a differential input pH meter.
35. State the advantages of differential input pH meter.
36. Why is the necessity of using a thermocompensator for pH measurement?

Multiple Choice Questions

1. The output power meter is designed to measure the output power
   (a) inversely (b) directly
   (c) squared (d) indirectly
2. The field strength meter is used to measure
   (a) voltage
   (b) frequency
   (c) current
   (d) radiation intensity
3. The stroboscopic principle uses a
   (a) flashing light (b) inductance
   (c) capacitance (d) resistance
4. The stroboscope is used to measure
   (a) voltage (b) frequency
   (c) current (d) speed
5. The phase meter is measured by comparing
   (a) ac signal with reference signal
   (b) ac signal with dc signal
   (c) dc signal with reference signal
   (d) dc signal with ac signal
6. A vector impedance meter determines impedance in
   (a) magnitude form
   (b) polar form
   (c) exponential form
   (d) rectangular form
7. Q-factor is defined as
   (a) Reactance / Resistance
   (b) Resistance / Reactance
   (c) Resistance / Impedance
   (d) Impedance / Resistance
8. A Q meter is used to measure
   (a) voltage (b) inductance
   (c) capacitance (d) resistance
9. The shunt resistance R_{sh} used in Q meter has a value of
   (a) 0.02 Ω to 0.04 Ω
   (b) 2 Ω to 4 Ω
   (c) 0.2 Ω to 0.4 Ω
   (d) 2 kΩ to 4 kΩ.
10. The applied voltage to the resonant tank circuit has a
    (a) very low value 0.02 V
    (b) high value 4 V
    (c) medium value 0.04 V
    (d) very high value 400 V
11. A megger is used to measure
    (a) conductance (b) reactance
    (c) impedance (d) resistance
12. The pH scale runs from
    (a) 0–14 (b) 10–14
    (c) 7–14 (d) 0–7
13. The neutral point of pH is
    (a) 0 (b) 14
    (c) 7 (d) 10
14. A thermocompensator is a
    (a) thermocouple (b) RTD
    (c) thermometer (d) thermistor

Practice Problems

1. Determine the distributed stray capacitances for the following data
   First measurement f_1 = 4 MHz and C_1 = 3.3 kpf
   Second measurement $f_2 = 3f_1$ = 12 MHz and C_2 = 1000 pf
   Also calculate the value of inductance.
2. The distributed capacitance was found to be 20 pf by use of a Q meter. The first resonance occurred at C_1 = 300 pf and f_1 was half the second resonance frequency. Determine the value of C_2 and f_2 at the second resonance (given L = 40 µH).

Further Reading

1. *Handbook of Electronic Measurements*, Vols. I & II, Polytechnic Institute of Brooklyn, 1956. (Microwave Research Institute)
2. John D. Lenk, *Handbook of Electronic Meters, Theory and Applications*, Prentice-Hall, 1980.
3. Rugus, D. Turner, *Basic Electronics Test Instruments*, Rinehart Books, 1953.
4. Vestor Robinson, *Handbook of Electronic Instrumentation, Testing and Troubleshooting*, D.B. Taraporevala Sons & Co, 1979.
5. Miles, Retter Sander (jr), *Electronic Meters Techniques and Troubleshooting*, Reston Publishing Co, 1977.
6. John D. Lenk, *Handbook of Electronic Test Equipment, Prentice-Hall, 1971.*

Chapter **11**

Bridges

INTRODUCTION 11.1

A bridge circuit in its simplest form consists of a network of four resistance arms forming a closed circuit, with a dc source of current applied to two opposite junctions and a current detector connected to the other two junctions, as shown in Fig. 11.1.

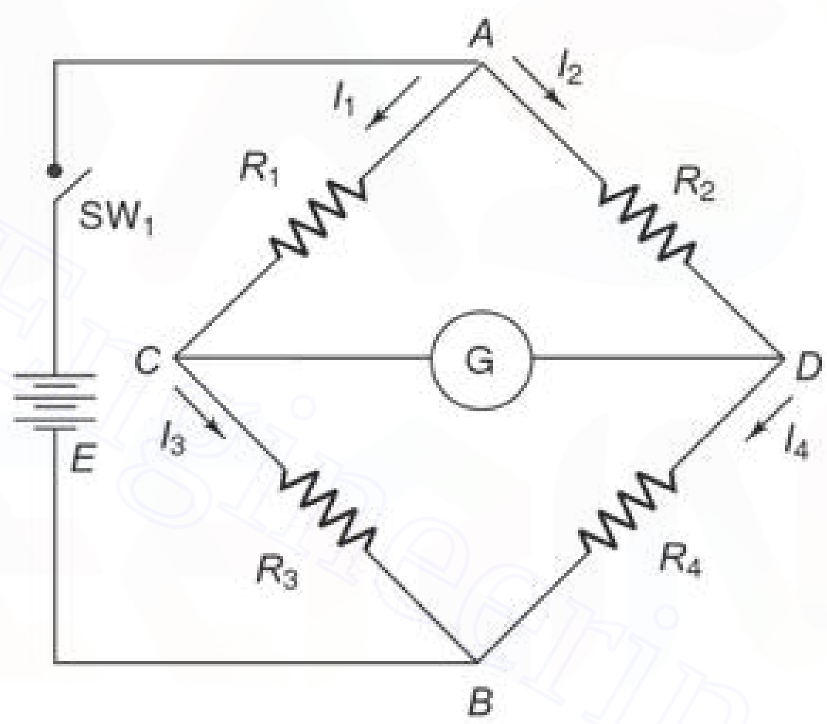


Fig. 11.1 Wheatstone's bridge

Bridge circuits are extensively used for measuring component values such as *R*, *L* and *C*. Since the bridge circuit merely compares the value of an unknown component with that of an accurately known component (a standard), its measurement accuracy can be very high. This is because the readout of this comparison is based on the null indication at bridge balance, and is essentially independent of the characteristics of the null detector. The measurement accuracy is therefore directly related to the accuracy of the bridge component and not to that of the null indicator used.

The basic dc bridge is used for accurate measurement of resistance and is called Wheatstone's bridge.

WHEATSTONE'S BRIDGE (MEASUREMENT OF RESISTANCE) 11.2

Wheatstone's bridge is the most accurate method available for measuring resistances and is popular for laboratory use. The circuit diagram of a typical Wheatstone bridge is given in Fig. 11.1. The source of emf and switch is connected to points *A* and *B*, while a sensitive current indicating meter, the galvanometer, is connected to points *C* and *D*. The galvanometer is a sensitive microammeter, with a zero center scale. When there is no current through the meter, the galvanometer pointer rests at 0, i.e. mid scale. Current in one direction causes the pointer to deflect on one side and current in the opposite direction to the other side.

When SW_1 is closed, current flows and divides into the two arms at point A, i.e. I_1 and I_2. The bridge is balanced when there is no current through the galvanometer, or when the potential difference at points C and D is equal, i.e. the potential across the galvanometer is zero.

To obtain the bridge balance equation, we have from the Fig. 11.1.

$$I_1 R_1 = I_2 R_2 \tag{11.1}$$

For the galvanometer current to be zero, the following conditions should be satisfied.

$$I_1 = I_3 = \frac{E}{R_1 + R_3} \tag{11.2}$$

$$I_2 = I_4 = \frac{E}{R_2 + R_4} \tag{11.3}$$

Substituting in Eq. (11.1)

$$\frac{E \times R_1}{R_1 + R_3} = \frac{E \times R_2}{R_2 + R_4}$$

$$R_1 \times (R_2 + R_4) = (R_1 + R_3) \times R_2$$

$$R_1 R_2 + R_1 R_4 = R_1 R_2 + R_3 R_2$$

$$R_4 = \frac{R_2 R_3}{R_1}$$

This is the equation for the bridge to be balanced.

In a practical Wheatstone's bridge, at least one of the resistance is made adjustable, to permit balancing. When the bridge is balanced, the unknown resistance (normally connected at R_4) may be determined from the setting of the adjustable resistor, which is called a standard resistor because it is a precision device having very small tolerance.

Hence $$R_x = \frac{R_2 R_3}{R_1} \tag{11.4}$$

Example 11.1 *Figure 11.1 consists of the following parameters. $R_1 = 10$ k, $R_2 = 15$ k and $R_3 = 40$ k. Find the unknown resistance R_x.*

Solution From the equation for bridge balance we have

$$R_1 R_4 = R_2 R_3, \text{ i.e. } R_1 R_x = R_2 R_3$$

Therefore $$R_x = \frac{R_2 R_3}{R_1} = \frac{15\text{ k} \times 40\text{ k}}{10\text{ k}} = 60\text{ k}\Omega$$

11.2.1 Sensitivity of a Wheatstone Bridge

When the bridge is in an unbalanced condition, current flows through the galvanometer, causing a deflection of its pointer. The amount of deflection is a function of the sensitivity of the galvanometer. Sensitivity can be thought of as deflection per unit current. A more sensitive galvanometer deflects by a greater amount for the same current. Deflection may be expressed in linear or angular units of measure, and sensitivity can be expressed in units of S = mm/μA or degree/μA or radians/μA.

Therefore it follows that the total deflection D is $D = S \times I$, where S is defined above and I is the current in microamperes.

11.2.2 Unbalanced Wheatstone's Bridge

To determine the amount of deflection that would result for a particular degree of unbalance, general circuit analysis can be applied, but we shall use Thevenin's theorem.

Since we are interested in determining the current through the galvanometer, we wish to find the Thévenin's equivalent, as seen by the galvanometer.

Thévenin's equivalent voltage is found by disconnecting the galvanometer from the bridge circuit, as shown in Fig. 11.2, and determining the open-circuit voltage between terminals a and b.

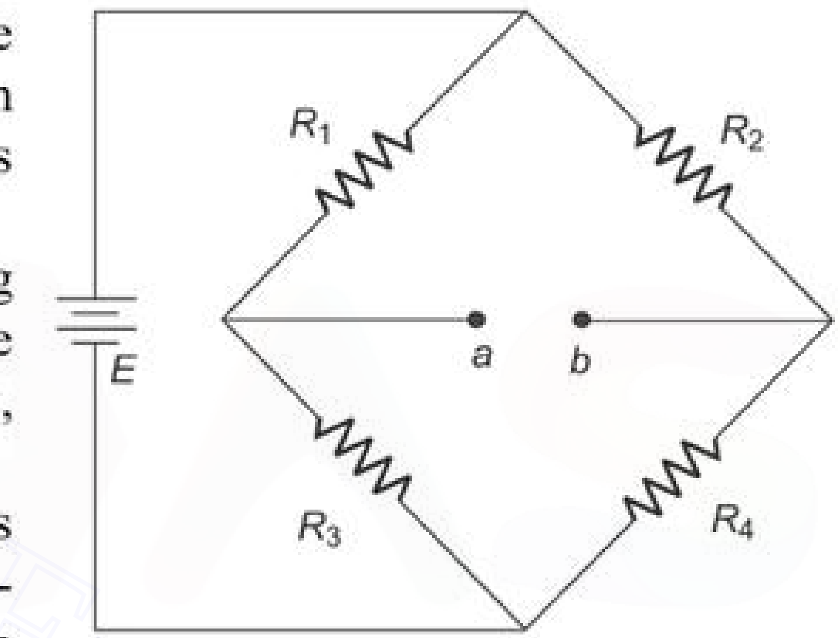


Fig. 11.2 Unbalanced wheatstone's bridge

Applying the voltage divider equation, the voltage at point a can be determined as follows

$$E_a = \frac{E \times R_3}{R_1 + R_3} \quad \text{and at point } b, \quad E_b = \frac{E \times R_4}{R_2 + R_4}$$

Therefore, the voltage between a and b is the difference between E_a and E_b, which represents Thévenin's equivalent voltage.

$$E_{th} = E_{ab} = E_a - E_b = \frac{E \times R_3}{R_1 + R_3} - \frac{E \times R_4}{R_2 + R_4}$$

Therefore $$E_{ab} = E\left(\frac{R_3}{R_1 + R_3} - \frac{R_4}{R_2 + R_4}\right)$$

Thévenin's equivalent resistance can be determined by replacing the voltage source E with its internal impedance or otherwise short-circuited and calculating the resistance looking into terminals a and b. Since the internal resistance is assumed to be very low, we treat it as 0 Ω. Thévenin's equivalent resistance circuit is shown in Fig. 11.3.

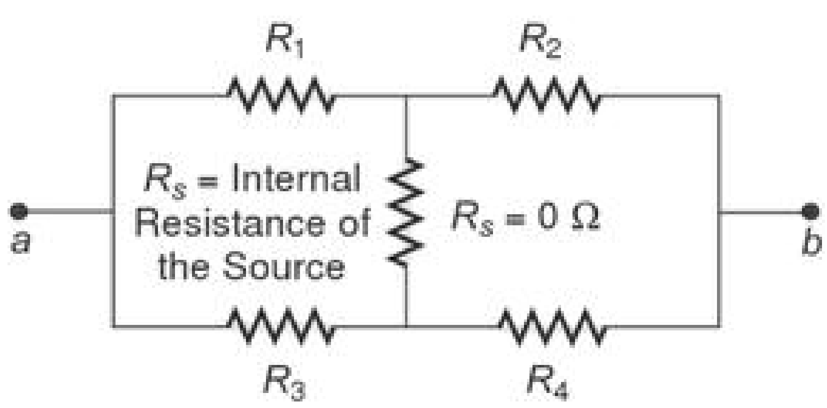


Fig. 11.3 Thévenin's resistance

The equivalent resistance of the circuit is $R_1//R_3$ in series with $R_2//R_4$ i.e. $R_1//R_3 + R_2//R_4$.

$$\therefore \qquad R_{th} = \frac{R_1\,R_3}{R_1 + R_3} + \frac{R_2\,R_4}{R_2 + R_4}$$

Therefore, Thévenin's equivalent circuit is given in Fig. 11.4. Thévenin's equivalent circuit for the bridge, as seen looking back at terminals a and b in Fig. 11.2, is shown in Fig. 11.4.

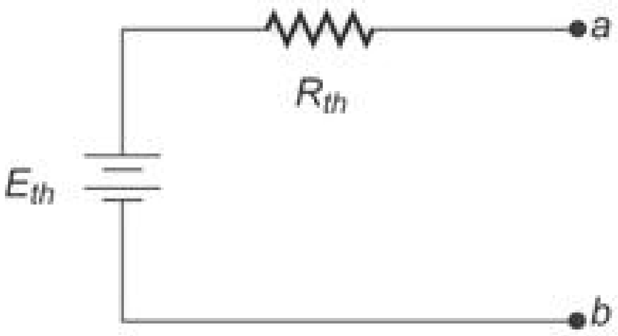


Fig. 11.4 Thévenin's equivalent

If a galvanometer is connected across the terminals a and b of Fig. 11.2, or its Thévenin equivalent Fig. 11.4 it will experience the same deflection at the output of the bridge. The magnitude of current is limited by both Thévenin's equivalent resistance and any resistance connected between a and b. The resistance between a and b consists only of the galvanometer resistance R_g. The deflection current in the galvanometer is therefore given by

$$I_g = \frac{E_{th}}{R_{th} + R_g} \tag{11.5}$$

Example 11.2 *An unbalanced Wheatstone bridge is given in Fig. 11.5. Calculate the current through the galvanometer.*

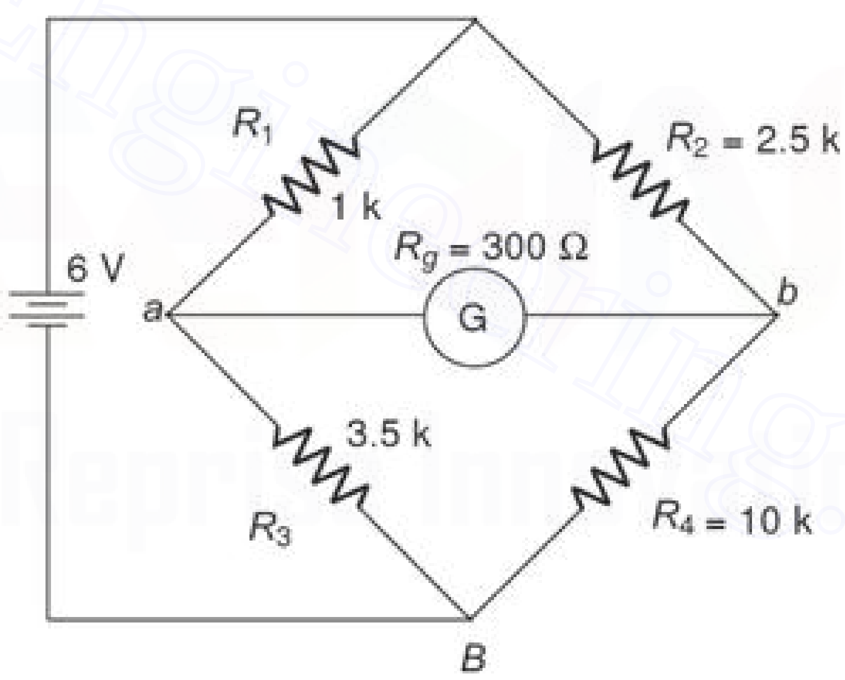


Fig. 11.5

Solution The Thévenin's equivalent voltage between a and b is the difference of voltages at these points i.e.

$$E_{th} = E_a - E_b = E_b - E_a.$$

$$\therefore \quad E_{th} = E\left(\frac{R_4}{R_2 + R_4} - \frac{R_3}{R_1 + R_3}\right)$$

$$E_{th} = 6\left(\frac{10\text{ k}}{2.5\text{ k} + 10\text{ k}} - \frac{3.5\text{ k}}{1\text{ k} + 3.5\text{ k}}\right)$$

$$E_{th} = 6\,(0.800 - 0.778)$$

$$E_{th} = 0.132\text{ V}$$

Thévenin's equivalent resistance is

$$R_{th} = \frac{R_1\,R_3}{R_1 + R_3} + \frac{R_2\,R_4}{R_2 + R_4}$$

$$R_{th} = \frac{1\text{ k} \times 3.5\text{ k}}{1\text{ k} + 3.5\text{ k}} + \frac{2.5\text{ k} \times 10\text{ k}}{2.5\text{ k} + 10\text{ k}}$$

$$= 0.778\text{ k} + 2\text{ k}$$
$$= 2.778\text{ k}$$

The equivalent circuit connected along with the galvanometer is as shown in Fig. 11.6.

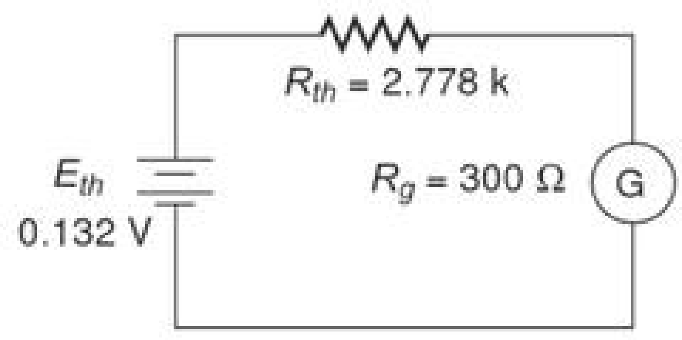


Fig. 11.6 Equivalent circuit

The current through the galvanometer is given by

$$I_g = \frac{E_{th}}{R_{th} + R_g} = \frac{0.132\text{ V}}{2.778\text{ k} + 0.3\text{ k}} = 42.88\ \mu\text{A}$$

11.2.3 Slightly Unbalanced Wheatstone's Bridge

If three of the four resistor in a bridge are equal to R and the fourth differs by 5% or less, we can develop an approximate but accurate expression for Thévenin's equivalent voltage and resistance.

Consider the circuit in Fig. 11.7.

The voltage at point a is

$$E_a = \frac{E \times R}{R + R} = \frac{E \times R}{2R} = \frac{E}{2}$$

The voltage at point b is

$$E_b = \frac{R + \Delta r \times E}{R + R + \Delta r} = \frac{E(R + \Delta r)}{2R + \Delta r}$$

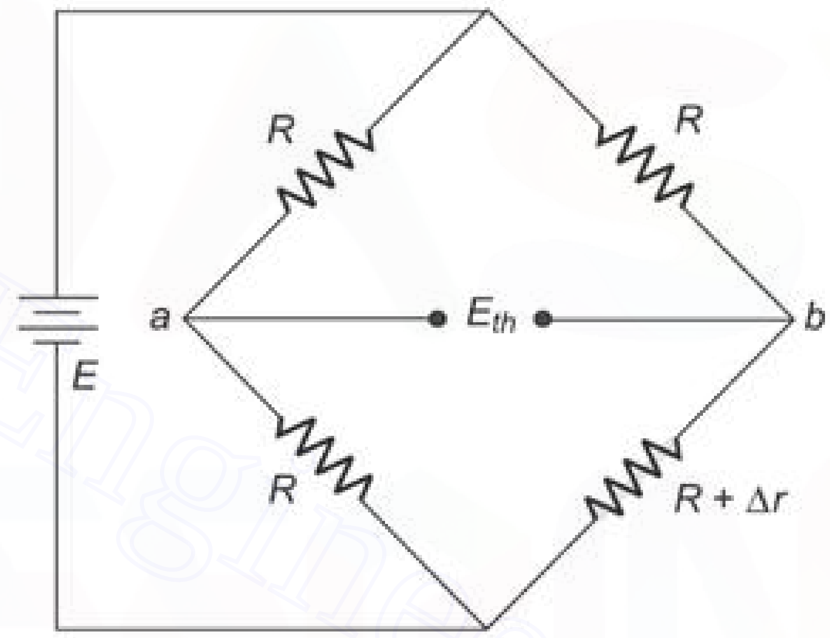


Fig. 11.7 Slightly unbalanced Wheatstone's bridge

Thévenin's equivalent voltage between a and b is the difference between these voltages.

Therefore $$E_{th} = E_a - E_b = E\left(\frac{(R + \Delta r)}{2R + \Delta r} - \frac{1}{2}\right)$$

$$= E\left(\frac{2(R + \Delta r) - (2R + \Delta r)}{2(2R + \Delta r)}\right)$$

$$= E\left(\frac{2R + 2\Delta r - 2R - \Delta r}{4R + 2\Delta r}\right)$$

$$= E\left(\frac{\Delta r}{4R + 2\Delta r}\right)$$

If Δr is 5% of R or less, Δr in the denominator can be neglected without introducing appreciable error. Therefore, Thévenin's voltage is

$$E_{th} = \frac{E \times \Delta r}{4R} = E\left(\frac{\Delta r}{4R}\right)$$

The equivalent resistance can be calculated by replacing the voltage source with its internal impedance (for all practical purpose short-circuit). The Thévenin's equivalent resistance is given by

$$R_{th} = \frac{R \times R}{R + R} + \frac{R(R + \Delta r)}{R + R + \Delta r}$$

$$= \frac{R}{2} + \frac{R(R + \Delta r)}{2R + \Delta r}$$

Again, if Δr is small compared to R, Δr can be neglected. Therefore,

$$R_{th} = \frac{R}{2} + \frac{R}{2} = R$$

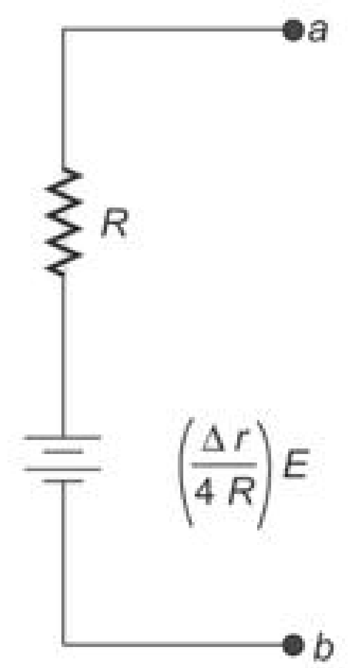


Fig. 11.8 Thévenin's equivalent of a slightly unbalanced Wheatstone's bridge

Using these approximations, the Thévenin's equivalent circuit is as shown in Fig. 11.8. These approximate equations are about 98% accurate if $\Delta r \leq 0.05\ R$.

Example 11.3 *Given a centre zero 200 – 0 – 200 μA movement having an internal resistance of 125 Ω. Calculate the current through the galvanometer given in Fig. 11.9 by the approximation method.*

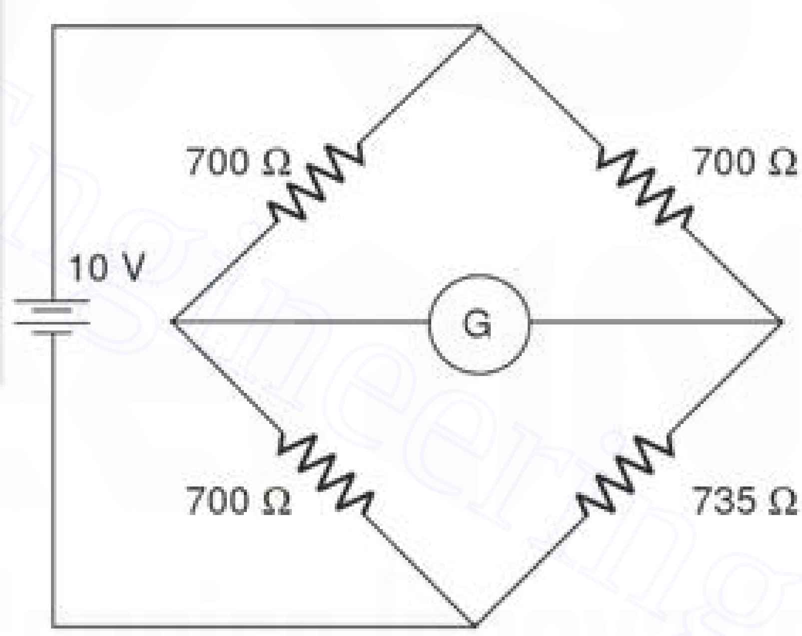


Fig. 11.9

Solution The Thévenin's equivalent voltage is

$$E_{th} = \frac{E(\Delta r)}{4R}$$

$$= \frac{10 \times 35}{4 \times 700} = 0.125 \text{ V}$$

Thévenin's equivalent resistance is

$$R_{th} = R = 700\ \Omega$$

The current through the galvanometer is

$$I_g = \frac{E_{th}}{R_{th} + R_g} = \frac{0.125 \text{ V}}{700 + 125} = \frac{0.125}{825} = 151.5\ \mu\text{A}$$

If the detector is a 200 – 0 – 200 μA galvanometer, we see that the pointer is full scale for a 5% change in resistance.

11.2.4 Application of Wheatstone's Bridge

A Wheatstone bridge may be used to measure the dc resistance of various types of wire, either for the purpose of quality control of the wire itself, or of some assembly in which it is used. For example, the resistance of motor windings, transformers, solenoids, and relay coils can be measured.

Wheatstone's bridge is also used extensively by telephone companies and others to locate cable faults. The fault may be two lines shorted together, or a single line shorted to ground.

11.2.5 Limitations of Wheatstone's Bridge

For low resistance measurement, the resistance of the leads and contacts becomes significant and introduces an error. This can be eliminated by Kelvin's Double bridge.

For high resistance measurements, the resistance presented by the bridge becomes so large that the galvanometer is insensitive to imbalance. Therefore, a power supply has to replace the battery and a dc VTVM replaces the galvanometer. In the case of high resistance measurements in mega ohms, the Wheatstones bridge cannot be used.

Another difficulty in Wheatstone's bridge is the change in resistance of the bridge arms due to the heating effect of current through the resistance. The rise in temperature causes a change in the value of the resistance, and excessive current may cause a permanent change in value.

KELVIN'S BRIDGE 11.3

When the resistance to be measured is of the order of magnitude of bridge contact and lead resistance, a modified form of Wheatstone's bridge, the Kelvin bridge is employed.

Kelvin's bridge is a modification of Wheatstone's bridge and is used to measure values of resistance below 1 Ω. In low resistance measurement, the resistance of the leads connecting the unknown resistance to the terminal of the bridge circuit may affect the measurement.

Consider the circuit in Fig. 11.10, where R_y represents the resistance of the connecting leads from R_3 to R_x (unknown resistance). The galvanometer can be connected either to point c or to point a. When it is connected to point a, the resistance R_y, of the connecting lead is added to the unknown resistance R_x, resulting in too high indication for R_x. When the connection is made to point c, R_y is added to the bridge arm R_3 and resulting measurement of R_x is lower than the actual value, because now the actual value of R_3 is higher than its nominal value by the resistance R_y. If the galvanometer is connected to point b, in between points c and a, in such a way that the ratio of the resistance from c to b and that from a to b equals the ratio of resistances R_1 and R_2, then

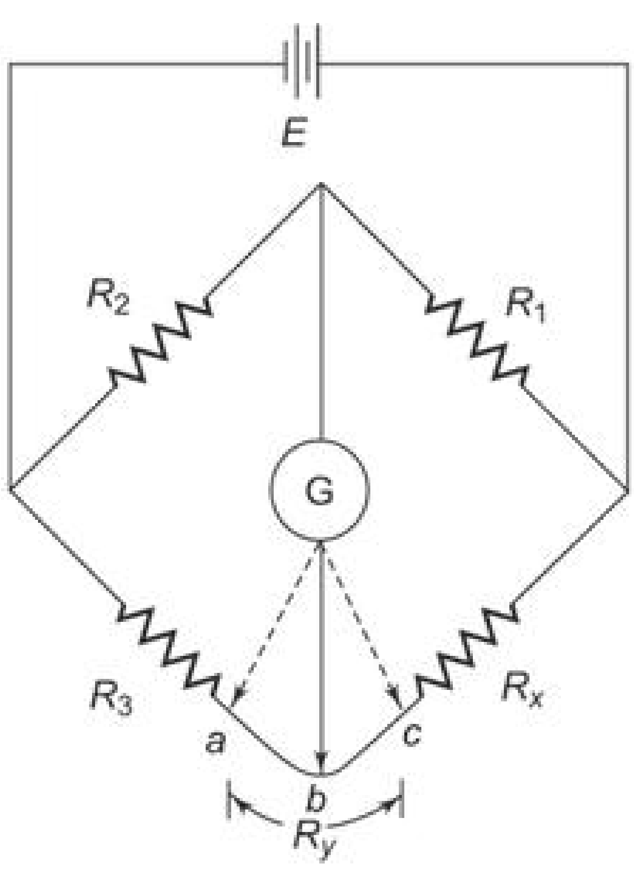


Fig. 11.10 Kelvin's bridge

$$\frac{R_{cb}}{R_{ab}} = \frac{R_1}{R_2} \tag{11.6}$$

and the usual balance equations for the bridge give the relationship

$$(R_x + R_{cb}) = \frac{R_1}{R_2}(R_3 + R_{ab}) \tag{11.7}$$

but $$R_{ab} + R_{cb} = R_y \text{ and } \frac{R_{cb}}{R_{ab}} = \frac{R_1}{R_2}$$

$$\frac{R_{cb}}{R_{ab}} + 1 = \frac{R_1}{R_2} + 1$$

$$\frac{R_{cb} + R_{ab}}{R_{ab}} = \frac{R_1 + R_2}{R_2}$$

i.e. $$\frac{R_y}{R_{ab}} = \frac{R_1 + R_2}{R_2}$$

Therefore $$R_{ab} = \frac{R_2 R_y}{R_1 + R_2} \quad \text{and as} \quad R_{ab} + R_{cb} = R_y$$

$\therefore$ $$R_{cb} = R_y - R_{ab} = R_y - \frac{R_2 R_y}{R_1 + R_2}$$

$\therefore$ $$R_{cb} = \frac{R_1 R_y + R_2 R_y - R_2 R_y}{R_1 + R_2} = \frac{R_1 R_y}{R_1 + R_2}$$

Substituting for R_{ab} and R_{cb} in Eq. (11.7), we have

$$R_x + \frac{R_1 R_y}{R_1 + R_2} = \frac{R_1}{R_2}\left(R_3 + \frac{R_2 R_y}{R_1 + R_2}\right)$$

$$R_x + \frac{R_1 R_y}{R_1 + R_2} = \frac{R_1 R_3}{R_2} + \frac{R_1 R_2 R_y}{R_2 (R_1 + R_2)}$$

Hence $$R_x = \frac{R_1 R_3}{R_2} \tag{11.8}$$

Equation (11.8) is the usual Wheatstone's balance equation and it indicates that the effect of the resistance of the connecting leads from point a to point c has been eliminated by connecting the galvanometer to an intermediate position, b.

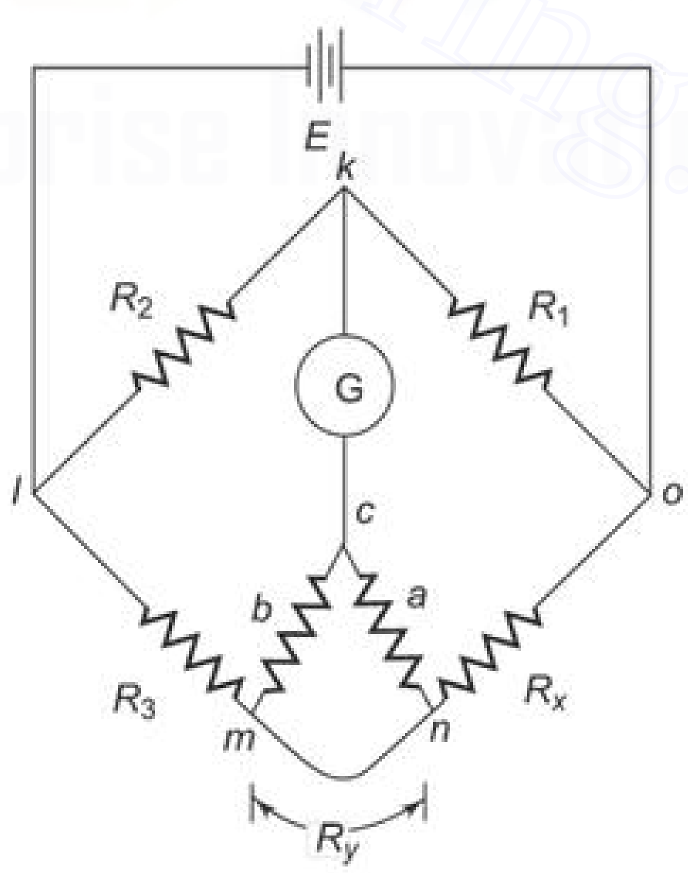


Fig. 11.11 Kelvin's double bridge

The above principle forms the basis of the construction of Kelvin's Double Bridge, popularly known as Kelvin's Bridge. It is a Double bridge because it incorporates a second set of ratio arms. Figure 11.11 shows a schematic diagram of Kelvin's double bridge.

The second set of arms, a and b, connects the galvanometer to a point c at the appropriate potential between m and n connection, i.e. R_y. The ratio of the resistances of arms a and b is the same as the ratio of R_1 and R_2. The galvanometer indication is zero when the potentials at k and c are equal.

$$\therefore \quad E_{lk} = E_{lmc}$$

But
$$E_{lk} = \frac{R_2}{R_1 + R_2} \times E \tag{11.9}$$

and
$$E = I\left(R_3 + R_x + \frac{(a+b)R_y}{a+b+R_y}\right)$$

Substituting for E in Eq.(11.9),

we get
$$E_{lk} = \frac{R_2}{R_1 + R_2} \times I\left(R_3 + R_x + \frac{(a+b)R_y}{a+b+R_y}\right) \tag{11.10}$$

Similarly,
$$E_{lmc} = I\left(R_3 + \frac{b}{a+b}\left[\frac{(a+b)R_y}{a+b+R_y}\right]\right) \tag{11.11}$$

But
$$E_{lk} = E_{lmc}$$

i.e.
$$\frac{IR_2}{R_1 + R_2}\left(R_3 + R_x + \frac{(a+b)R_y}{a+b+R_y}\right) = I\left[R_3 + \frac{b}{a+b}\left\{\frac{(a+b)R_y}{a+b+R_y}\right\}\right]$$

$$\therefore \quad R_3 + R_x + \frac{(a+b)R_y}{a+b+R_y} = \frac{R_1 + R_2}{R_2}\left(R_3 + \frac{bR_y}{a+b+R_y}\right)$$

$$\therefore \quad R_3 + R_x + \frac{(a+b)R_y}{a+b+R_y} = \left(\frac{R_1}{R_2} + 1\right)\left(R_3 + \frac{bR_y}{a+b+R_y}\right)$$

$$R_x + \frac{(a+b)R_y}{a+b+R_y} + R_3 = \frac{R_1 R_3}{R_2} + R_3 + \frac{bR_1 R_y}{R_2(a+b+R_y)} + \frac{bR_y}{a+b+R_y}$$

$$R_x = \frac{R_1 R_3}{R_2} + \frac{bR_1 R_y}{R_2(a+b+R_y)} + \frac{bR_y}{a+b+R_y} - \frac{(a+b)R_y}{a+b+R_y}$$

$$R_x = \frac{R_1 R_3}{R_2} + \frac{bR_1 R_y}{R_2(a+b+R_y)} + \frac{bR_y - aR_y - bR_y}{a+b+R_y}$$

$$R_x = \frac{R_1 R_3}{R_2} + \frac{bR_1 R_y}{R_2(a+b+R_y)} - \frac{aR_y}{a+b+R_y}$$

$$R_x = \frac{R_1 R_3}{R_2} + \frac{bR_y}{(a+b+R_y)}\left(\frac{R_1}{R_2} - \frac{a}{b}\right)$$

But
$$\frac{R_1}{R_2} = \frac{a}{b}$$

Therefore, $$R_x = \frac{R_1 R_3}{R_2}$$

This is the usual equation for Kelvin's bridge. It indicates that the resistance of the connecting lead R_y, has no effect on the measurement, provided that the ratios of the resistances of the two sets of ratio arms are equal. In a typical Kelvin's bridge the range of a resistance covered is 1 – 0.00001 Ω (10 μohm) with an accuracy of ± 0.05% to ± 0.2%.

Example 11.4 *If in Fig. 11.12 the ratio of R_a to R_b is 1000 Ω, R_1 is 5 Ω and R_1 = 0.5 R_2. What is the value of R_x.*

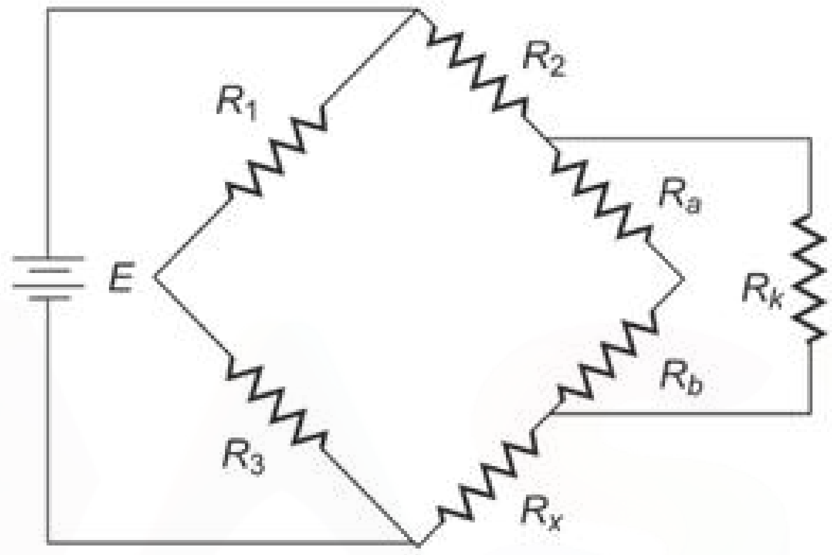


Fig. 11.12 Kelvin's bridge

Solution Resistance R_x can be calculated as follows.

$$\frac{R_x}{R_2} = \frac{R_b}{R_a}$$

Therefore,

$$\frac{R_x}{R_2} = \frac{R_b}{R_a} = \frac{1}{1000}$$

Since

$$R_1 = 0.5\,R_2,\ R_2 = 5/0.5 = 10\ \Omega.$$

Therefore $$R_x/10 = 1/1000 = 10 \times 1/1000 = 1/100 = 0.01\ \Omega.$$

PRACTICAL KELVIN'S DOUBLE BRIDGE 11.4

Figure 11.13 shows a commercial Kelvin's bridge capable of measuring resistances from 10 – 0.00001 Ω.

Contact potential drops in the circuit may cause large errors. This effect is reduced by varying a standard resistance consisting of nine steps of 0.001 Ω each, plus a calibrated manganin bar of 0.0011 Ω with a sliding contact. When both contacts are switched to select the suitable value of standard resistance, the voltage drop between the ratio arm connection points is changed, but the total resistance around the battery circuit is unchanged.

This arrangement places any contact resistance in series with the relatively high resistance value of the ratio arms, rendering the contact resistance effect negligible. The ratio R_1/R_2 is selected (as given in Fig. 11.13) such that a relatively large part of the standard resistance is used and hence R_x is determined to the largest possible number of significant figures. Therefore, measurement accuracy improves.

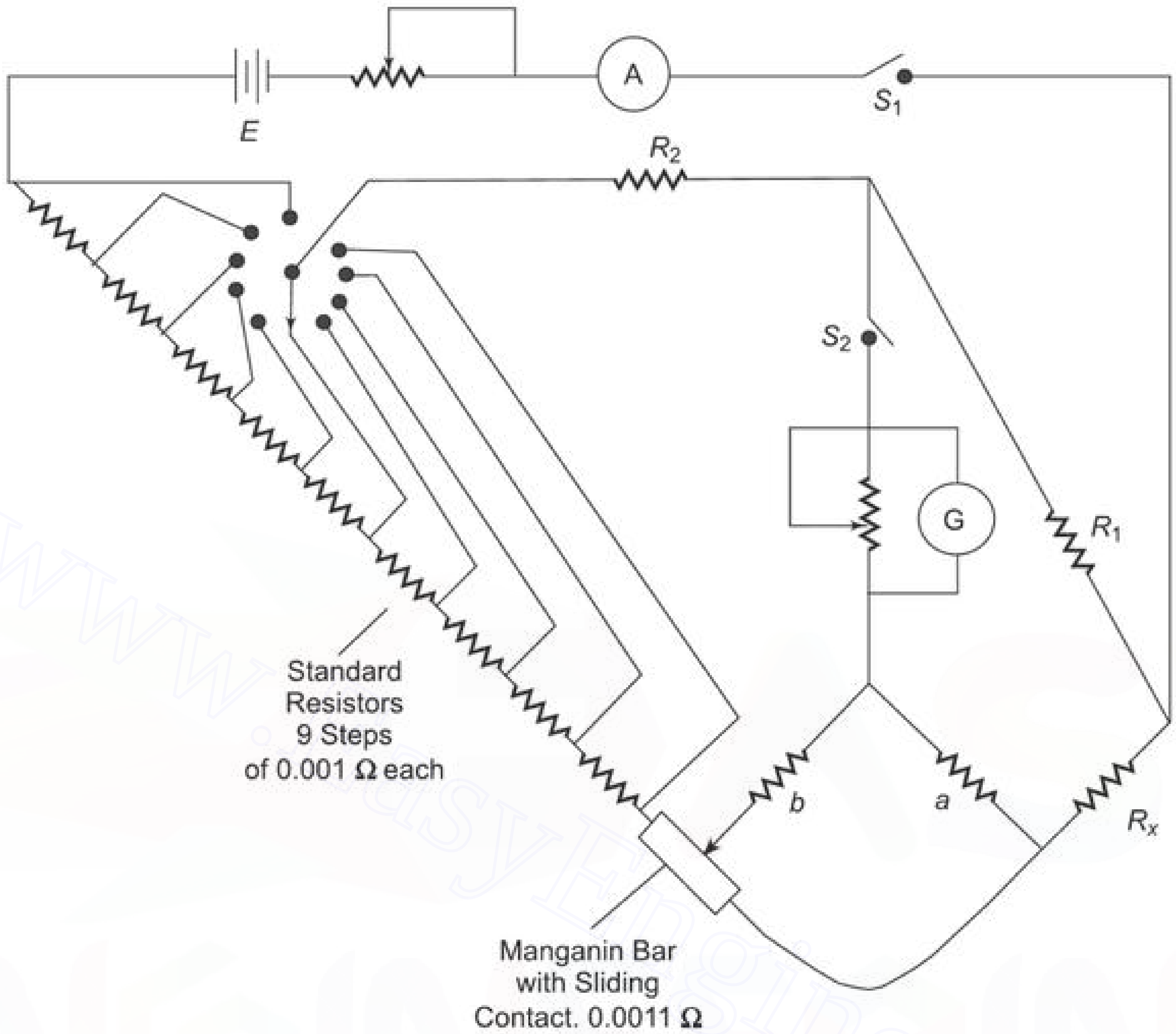


Fig. 11.13 Practical kelvin's bridge

BRIDGE CONTROLLED CIRCUITS 11.5

Whenever a bridge is unbalanced, a potential difference exists at its output terminal. The potential difference causes current to flow through the detector (say, a galvanometer) when the bridge is used as part of a measuring instrument. When the bridge is used as an error detector in a control circuit, the potential difference at the output of the bridge is called an error signal, as in Fig. 11.14.

Passive circuit elements such as strain gauges, temperature sensitive resistors (thermistors) and photo resistors, produce no output voltage. However, when used as one arm of Wheatstones bridge, a change in their sensitive parameter (heat, light, pressure) produces a change in their resistances. This causes the bridge to be unbalanced, thereby producing an output voltage or an error signal.

Resistor R_v in Fig. 11.14 may be sensitive to one of many different physical parameters, such as heat or light. If the particular parameter to which the resistor is sensitive, is of a magnitude such that the ratio R_2/R_v equals R_1/R_3, then the error signal is zero. If the physical parameters changes, R_v also changes. The bridge then becomes unbalanced and an error signal occurs. In most control applications the measured and controlled parameter is corrected, restoring R_v to the value that creates a null condition at the output of the bridge.

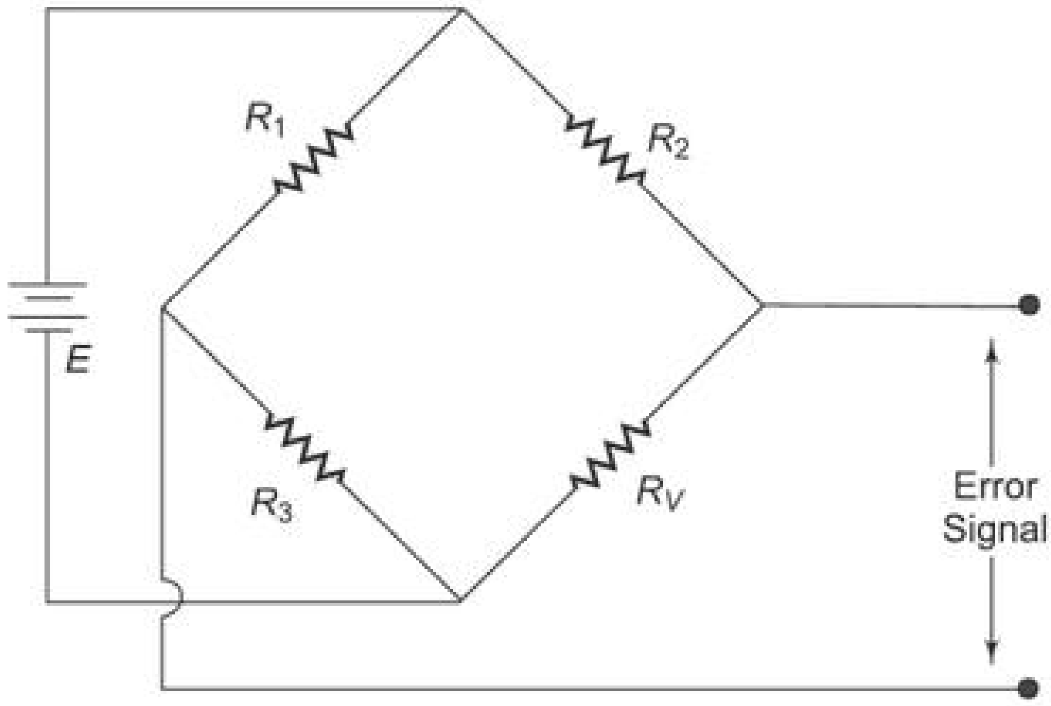


Fig. 11.14 Wheatstone's bridge error detector with resistance R_v sensitive to some physical parameters

Since R_v varies by only a small amount, the amplitude of the error signal is normally quite low. It is therefore amplified before being used for control purposes.

Example 11.5 *Resistor R_v in Fig. 11.15(a) is temperature sensitive, with a relation between resistance and temperature as shown in Fig. 11.15(b). Calculate (i) at what temperature the bridge is balanced, and (ii) The amplitude of the error signal at 60°C.*

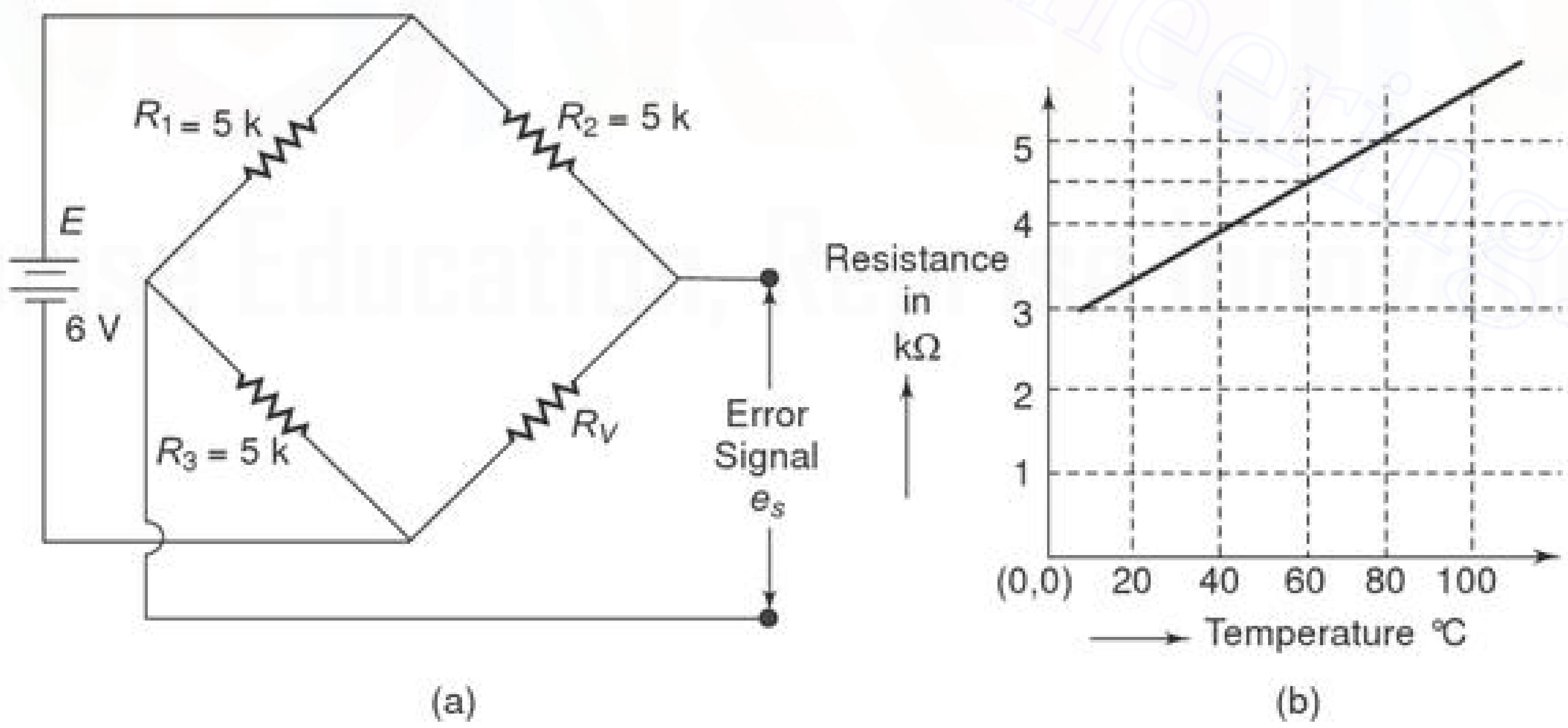


Fig. 11.15

Solution

(i) The value of R_v when the bridge is balance is calculated as

$$R_v = \frac{R_2\,R_3}{R_1} = \frac{5\text{ k} \times 5\text{ k}}{5\text{ k}} = 5\text{ k}\Omega$$

The bridge is balanced when the temperature is 80°C. This is read directly from the graph of Fig. 11.15(b).

(ii) We can also determine the resistance of R_v at 60°C directly from the graph. This values of 4.5 kΩ. Therefore the error signal is given by

$$e_s = E\left(\frac{R_3}{R_1 + R_3} - \frac{R_v}{R_2 + R_v}\right)$$

$$= 6\left(\frac{5\text{ k}}{5\text{ k} + 5\text{ k}} - \frac{4.5\text{ k}}{5\text{ k} + 4.5\text{ k}}\right)$$

$$= 6\,(0.5 - 0.4736)$$

$$= 6\,(0.0263)$$

$$= 0.158\text{ V}$$

The error signal can also be determined by using the following equation.

$$e_s = E_{th} = E\left(\frac{\Delta r}{4R}\right) = 6\left(\frac{500}{4 \times 5\text{ k}}\right)$$

$$e_s = 0.150\text{ V}$$

DIGITAL READOUT BRIDGES 11.6

The tremendous increase in the use of digital circuitry has had a marked effect on electronic test instruments. The early use of digital circuits in bridges was to provide a digital readout. The actual measuring circuitry of the bridge remained the same, but operator error in observing the reading was eliminated. The block diagram for a Wheatstone bridge with digital readout is shown in Fig. 11.16. Note that a logic circuit is used to provide a signal to R_3, sense the null, and provide a digital readout representing the value of R_x.

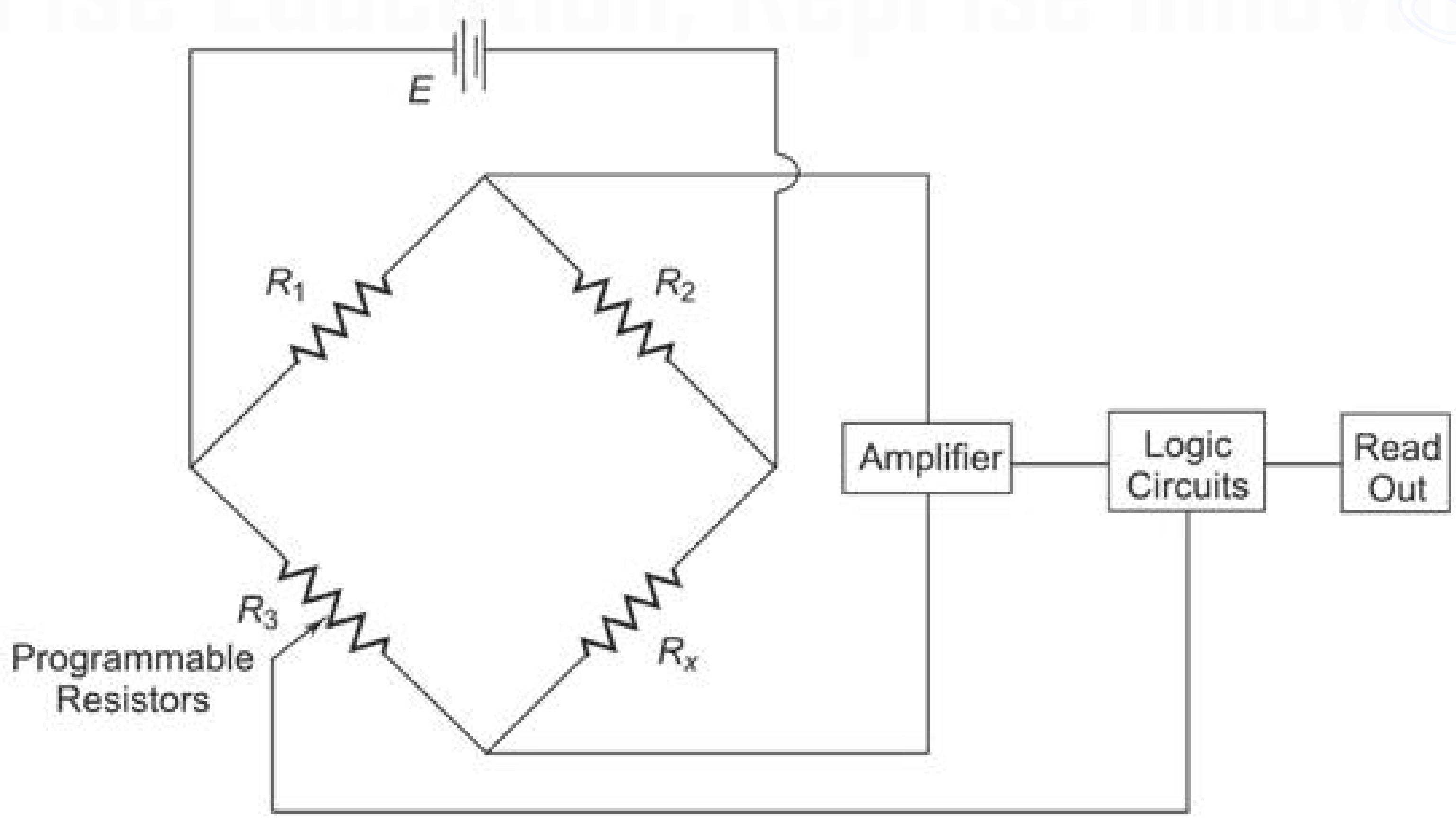


Fig. 11.16 Block diagram of wheatstone's bridge with digital readout

MICROPROCESSOR CONTROLLED BRIDGES 11.7

Digital computers have been used in conjunction with test systems, bridges, and process controllers for several years. In these applications, computers were used to give instructions and perform operations on the data measured. When microprocessors were first developed they were used in much the same way as digital computers. However, real improvements in performance occurred when the microprocessor was truly integrated into the instrument. With this accomplished, microprocessors cannot only give instructions about measurement, but also they can change the way the measurements are taken. This innovation has given rise to a whole new class of instruments, called Intelligent Instruments.

The complexity and cost of making analog measurements can be reduced using a microprocessor. This reduction of analog circuitry is important, even if additional digital circuitry must be added, because precision analog components are expensive. Also, adjusting, testing and troubleshooting analog circuits is time consuming and often expensive. Digital circuits can often replace analog circuits because various functions can be done either way.

The following are some of the ways in which microprocessors are reducing the cost and complexity of analog measurements.

1. Replacing sequential control logic with stored control programs.
2. Eliminating some auxiliary equipment by handling interfacing, programming and other system functions.
3. Providing greater flexibility in the selection of measurement circuits, thereby making it possible to measure one parameter and calculate another parameter of interest.
4. Reducing accuracy requirements by storing and applying correction factors.

Instruments in which microprocessors are an integral part can take the results of a measurement that is easiest to make in a given circuit, then calculate and display the value of some other desired parameter, which may be much more difficult to measure directly.

For example, conventional counters can measure the period of a low frequency waveform. This is then converted to frequency either manually, or using extensive circuitry. On the other hand, such calculations are done very easily by a microprocessor. Measurements of resistance and conductance, which are reciprocals of each other offer another example. Some hybrid digital/analog bridges are designed to measure conductance by measuring current. This measurement is then converted to a resistance value by rather elaborate circuitry. With a microprocessor based instrument, a resistance value is easily obtained from the conductance measurement.

Many other similar examples could be presented. However, the important thing to remember is that the microprocessor is an integral part of the measuring instrument. This results in an intelligent instrument that allows us to choose the easiest method of measurement and requires only one measurement circuit to obtain various results. Specifically, one quantity can be measured in terms of another, or several others with completely different dimensions, and the desired results calculated with the microprocessor.

(One such microprocessor-based instrument is the General Radio model 1658RLC digibridge.)

Such intelligent instruments represent a new era in impedance measuring instruments. The following are some features of these instruments.

1. Automatically measures *R*, inductance *L*, capacitance *C*, dissipation factor *D* and storage factors for inductors *Q*.
2. 0.1% basic accuracy
3. Series or parallel measurement mode
4. Autoranging
5. No calibration required
6. Ten bins for component sorting/binning (equivalent, binary number)
7. Three test speeds
8. Three types of display-programmed bin limits, measured values or bin number.

Most of these features are available because of the use of a microprocessor, e.g. the component sorting/binning feature is achieved by programming the microprocessor.

When using the instrument in this mode, bins are assigned a tolerance range. When a component is measured, a digital readout (bin number) indicating the proper bin for that component is displayed on the keyboard control panel.

AC BRIDGES 11.8

Impedances at AF or RF are commonly determined by means of an ac Wheatstone bridge. The diagram of an ac bridge is given in Fig. 11.17. This bridge is similar to a dc bridge, except that the bridge arms are impedances. The bridge is excited by an ac source rather than dc and the galvanometer is replaced by a detector, such as a pair of headphones, for detecting ac. When the bridge is balanced,

$$\frac{Z_1}{Z_3} = \frac{Z_2}{Z_4}$$

where Z_1, Z_2, Z_3 and Z_4 are the impedances of the arms, and are vector complex quantities that possess phase angles. It is thus necessary to adjust both the magnitude and phase angles of the impedance arms to achieve balance, i.e. the bridge must be balanced for both the reactance and the resistive component.

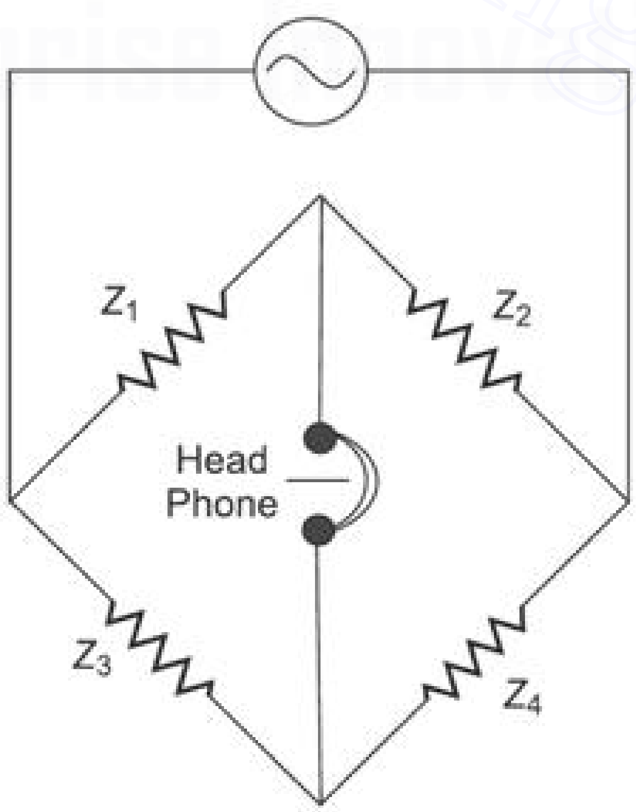


Fig. 11.17 ac Wheatstone's bridge

CAPACITANCE COMPARISON BRIDGE 11.9

Figure 11.18 shows the circuit of a capacitance comparison bridge. The ratio arms R_1, R_2 are resistive. The known standard capacitor C_3 is in series with R_3. R_3 may also include an added variable resistance needed to balance the bridge. C_x is the unknown capacitor and R_x is the small leakage resistance of the capacitor. In this case an unknown capacitor is compared with a standard capacitor and the value of the former, along with its leakage resistance, is obtained. Hence.

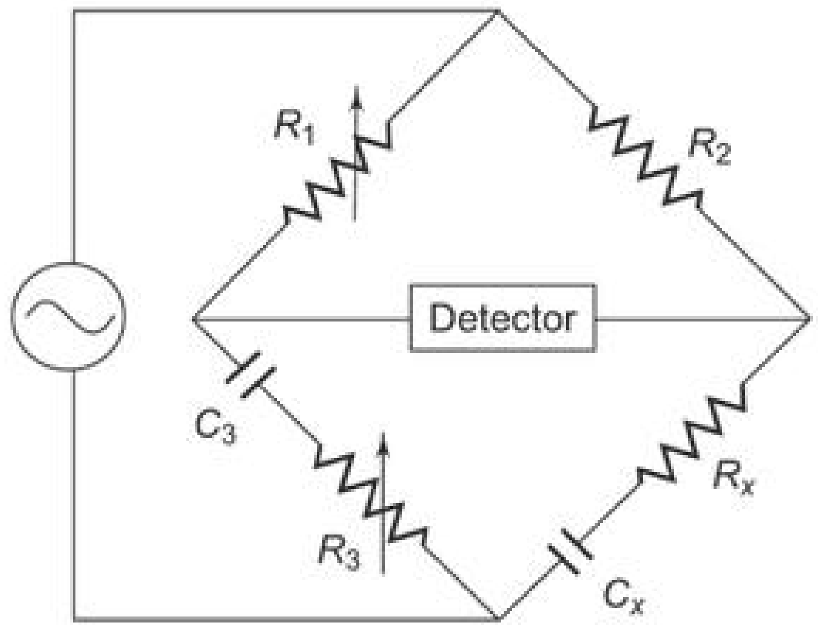


Fig. 11.18 Capacitance comparison bridge

$$Z_1 = R_1$$
$$Z_2 = R_2$$
$$Z_3 = R_3 \text{ in series with } C_3 = R_3 - j/\omega C_3$$
$$Z_x = R_x \text{ in series with } C_x = R_x - j/\omega C_x$$

The condition for balance of the bridge is

$$Z_1 Z_x = Z_2 Z_3$$

i.e. $$R_1\left(R_x - \frac{j}{\omega C_x}\right) = R_2\left(R_3 - \frac{j}{\omega C_3}\right)$$

$\therefore$ $$R_1 R_x - \frac{jR_1}{\omega C_x} = R_2 R_3 - \frac{jR_2}{\omega C_3}$$

Two complex quantities are equal when both their real and their imaginary terms are equal. Therefore,

i.e. $$R_1 R_x = R_2 R_3 \qquad \therefore R_x = \frac{R_2 R_3}{R_1} \qquad [11.12(a)]$$

and $$\frac{R_1}{\omega C_x} = \frac{R_2}{\omega C_3} \qquad C_x = \frac{C_3 R_1}{R_2} \qquad [11.12(b)]$$

Since R_3 does not appear in the expression for C_x, as a variable element it is an obvious choice to eliminate any interaction between the two balance controls.

Example 11.6 (a) *A capacitance comparison bridge (similar angle bridge) is used to measure a capacitive impedance at a frequency of 2 kHz. The bridge constants at balance are $C_3 = 100\ \mu F$, $R_1 = 10\ k\Omega$, $R_2 = 50\ k\Omega$, $R_3 = 100\ k\Omega$. Find the equivalent series circuit of the unknown impedance.*

Solution Finding R_x using the equation

$$R_x = \frac{R_2 R_3}{R_1}$$

$$= \frac{100 \text{ k} \times 50 \text{ k}}{10 \text{ k}} = 500 \text{ k}\Omega$$

Then finding C_x using the equation

$$C_x = \frac{R_1}{R_2} C_3$$

$$= \frac{10 \text{ k}}{50 \text{ k}} \times 100 \times 10^{-6} = 20 \ \mu\text{F}$$

The equivalent series circuit is shown in Fig. 11.19.

Fig. 11.19

Example 11.6 (b) *In the measurement of capacitance using capacitance bridge comparison bridge.*

R_1 in branch BC = 2000 Ω

R_2 in branch CD = 2850 Ω

R_4 in branch DA = 52 Ω in series with C_4 = 0.5µF

R_x in series with C_x in branch AB (unknowns)

f = 400 Hz.

Solution

Step 1: $$R_x = \frac{R_1 R_4}{R_2} = \frac{2000}{2850} \times 52 = 36.5 \ \Omega$$

Step 2: $$C_x = \frac{R_2}{R_1} \times C_4 = \frac{2850}{2000} \times 0.5 \ \mu\text{F} = 0.7125 \ \mu\text{F}$$

Step 3: Loss angle of the capacitor (a series *RC* circuit) is defined as the angle by which current departs an exact quadrature from the applied voltage. 'δ' is the loss angle of the capacitor and is given by tan δ.

$$\tan \delta = \frac{R_x}{X_x} = \omega C_x R_x = 2\pi f C_x R_x$$

$$= 2 \times 3.14 \times 400 \times 36.5 \times 0.7125 \ \mu\text{F} = 0.06533$$

Hence $\delta = 3^\circ \ 74'$

INDUCTANCE COMPARISON BRIDGE 11.10

Figure 11.20 gives a schematic diagram of an inductance comparison bridge. In this, values of the unknown inductance L_x and its internal resistance R_x are obtained by comparison with the standard inductor and resistance, i.e. L_3 and R_3.

The equation for balance condition is

$$Z_1 Z_x = Z_2 Z_3.$$

The inductive balance equation yields

$$L_x = \frac{L_3 R_2}{R_1} \qquad [11.13(a)]$$

and resistive balance equations yields

$$R_x = \frac{R_2 R_3}{R_1} \qquad [(11.13(b)]$$

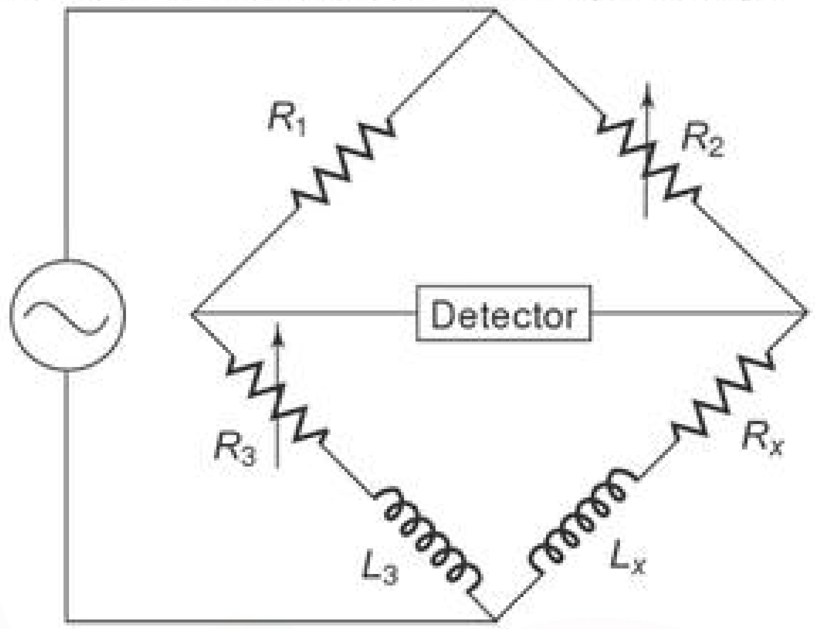


Fig. 11.20 Inductance comparison bridge

In this bridge R_2 is chosen as the inductive balance control and R_3 as the resistance balance control. (It is advisable to use a fixed resistance ratio and variable standards). Balance is obtained by alternately varying L_3 or R_3. If the Q of the unknown reactance is greater than the standard Q, it is necessary to place a variable resistance in series with the unknown reactance to obtain balance.

If the unknown inductance has a high Q, it is permissible to vary the resistance ratio when a variable standard inductor is not available.

Example 11.7 *An inductance comparison bridge is used to measure inductive impedance at a frequency of 5 KHz.The bridge constants at balance are L_3 = 10 mH, R_1 = 10 kΩ, R_2 = 40 KΩ, R_3 = 100 KΩ. Find the equivalent series circuit of the unknown impedance.*

Solution Given L_3 = 10 mH, R_1 = 10 kΩ, R_2 = 40 kΩ, R_3 = 100 kΩ. To find R_x and L_x.

From balance equation,

Step 1: $$R_x = \frac{R_2 R_3}{R_1} = \frac{40\text{ K} \times 100\text{ K}}{10\text{ K}} = 400\text{ k}\Omega$$

Step 2: $$L_x = \frac{R_2 L_3}{R_1} = \frac{10\text{ mH} \times 40\text{ K}}{10\text{ K}} = 40\text{ mH}$$

The equivalent series circuit is shown in Fig. 11.21.

Fig. 11.21

MAXWELL'S BRIDGE 11.11

Maxwell's bridge, shown in Fig. 11.22, measures an unknown inductance in terms of a known capacitor. The use of standard arm offers the advantage of compactness and easy shielding. The capacitor is almost a loss-less component. One arm has a resistance R_1 in parallel with C_1, and hence it is easier to write the balance equation using the admittance of arm 1 instead of the impedance.

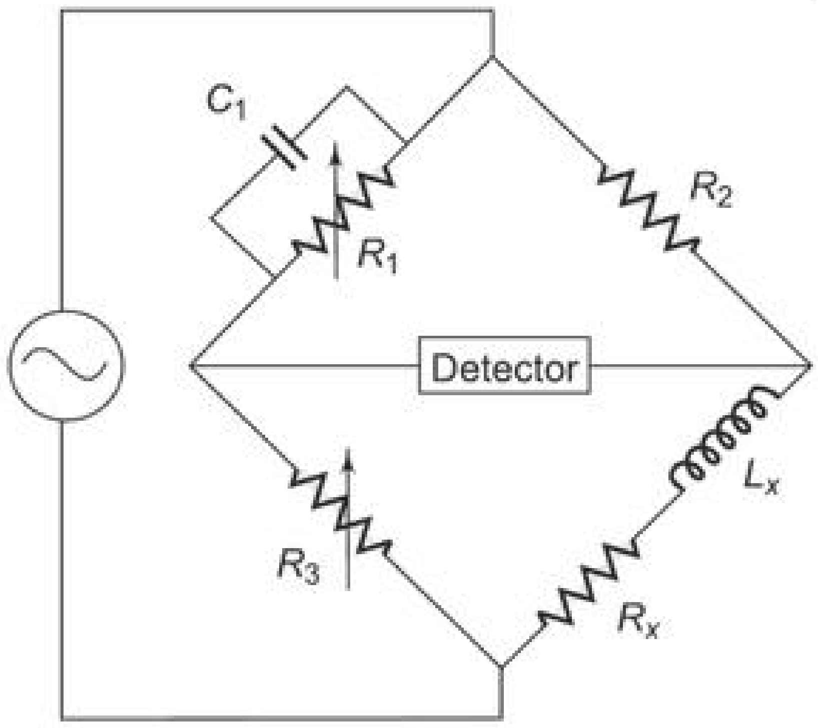


Fig. 11.22 Maxwell's bridge

The general equation for bridge balance is

$$Z_1 Z_x = Z_2 Z_3$$

i.e.
$$Z_x = \frac{Z_2 Z_3}{Z_1} = Z_2 Z_3 Y_1 \tag{11.14}$$

Where $Z_1 = R_1$ in parallel with C_1 i.e. $Y_1 = \frac{1}{Z_1}$

$$Y_1 = \frac{1}{R_1} + j\omega C_1$$

$$Z_2 = R_2$$

$$Z_3 = R_3$$

$Z_x = R_x$ in series with $L_x = R_x + j\omega L_x$

From Eq. (11.14) we have

$$R_x + j\omega L_x = R_2 R_3 \left(\frac{1}{R_1} + j\omega C_1\right)$$

$$R_x + j\omega L_x = \frac{R_2 R_3}{R_1} + j\omega C_1 R_2 R_3$$

Equating real terms and imaginary terms we have

$$R_x = \frac{R_2 R_3}{R_1} \text{ and } L_x = C_1 R_2 R_3 \tag{11.15}$$

Also
$$Q = \frac{\omega L_x}{R_x} = \frac{\omega C_1 R_2 R_3 \times R_1}{R_2 R_3} = \omega C_1 R_1$$

Maxwell's bridge is limited to the measurement of low Q values (1 – 10). The measurement is independent of the excitation frequency. The scale of the resistance can be calibrated to read inductance directly.

The Maxwell bridge using a fixed capacitor has the disadvantage that there is an interaction between the resistance and reactance balances. This can be avoided by varying the capacitances, instead of R_2 and R_3, to obtain a reactance balance. However, the bridge can be made to read directly in Q.

The bridge is particularly suited for inductances measurements, since comparison with a capacitor is more ideal than with another inductance. Commercial bridges measure from 1 – 1000 H, with ± 2% error. (If the Q is very large, R_1 becomes excessively large and it is impractical to obtain a satisfactory variable standard resistance in the range of values required).

Example 11.8 (a) *A Maxwell bridge is used to measure an inductive impedance. The bridge constants at balance are*
$C_1 = 0.01\ \mu F$, $R_1 = 470\ k\Omega$, $R_2 = 5.1\ k\Omega$, and $R_3 = 100\ k\Omega$.
Find the series equivalent of the unknown impedance.

Solution We need to find R_x and L_x.

$$R_x = \frac{R_2\,R_3}{R_1} = \frac{100\text{ k} \times 5.1\text{ k}}{470\text{ k}} = 1.09\text{ k}\Omega$$

$$\begin{aligned} L_x &= R_2\,R_3\,C_1 \\ &= 5.1\text{ k} \times 100\text{ k} \times 0.01\ \mu\text{f} \\ &= 5.1\text{ H} \end{aligned}$$

The equivalent series circuit is shown in Fig. 11.23.

Fig. 11.23

Example 11.8 (b) *The arms of an ac Maxwell's bridge are arranged as follows:*
AB and BC are non-reactive resistors of 100 Ω each, DA a standard variable reactor L_1 of resistance 32.7 Ω and CD consists of a standard variable resistor R in series with a coil of unknown impedance Z, balance was found with L_1 = 50 mH and Z = 1.36R. Find the R and L of coil.

Solution Given: $R_1 = 32.7\ \Omega$, $L_1 = 50$ mH
$R_2 = 1.36\ \Omega$, $R_3 = 100\ \Omega$, $R_4 = 100\ \Omega$

Step 1: To find 'r' and L_2 where r is the resistance of the coil

Given that $R_4R_1 = R_3(R_2 + r)$

$\therefore$ $32.7 \times 100 = 100\,(1.36 + r)$

$\therefore$ $100(32.7 - 1.36) = 100\,r$

$\therefore$ $r = 32.7 - 1.36$

$r = 31.34\ \Omega$

Step 2: To find L_2, $L_2 = L_1 \times \dfrac{R_4}{R_3} = 50\text{ mH} \times \dfrac{100}{100}$

$\therefore$ $L_2 = 50$ mH

HAY'S BRIDGE 11.12

The Hay bridge, shown in Fig. 11.24, differs from Maxwell's bridge by having a resistance R_1 in series with a standard capacitor C_1 instead of a parallel. For large phase angles, R_1 needs to be low; therefore, this bridge is more convenient for measuring high-Q coils. For $Q = 10$, the error is $\pm$ 1%, and for $Q = 30$, the error is $\pm$ 0.1%. Hence Hay's bridge is preferred for coils with a high Q, and Maxwell's bridge for coils with a low Q.

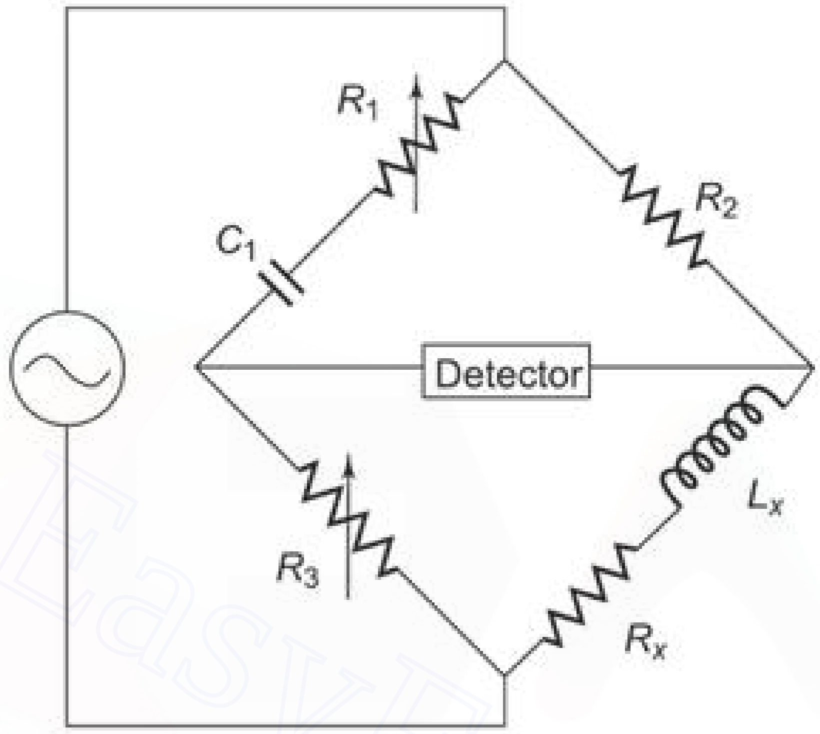


Fig. 11.24 Hay's Bridge

At balance

$$Z_1 Z_x = Z_2 Z_3, \text{ where}$$
$$Z_1 = R_1 - j/\omega C_1$$
$$Z_2 = R_2$$
$$Z_3 = R_3$$
$$Z_x = R_x + j\omega L_x$$

Substituting these values in the balance equation we get

$$\left(R_1 - \frac{j}{\omega c_1}\right)(R_x + j\omega L_x) = R_2 R_3$$

$$R_1 R_x + \frac{L_x}{C_1} - \frac{j R_x}{\omega C_1} + j\omega L_x R_1 = R_2 R_3$$

Equating the real and imaginary terms we have

$$R_1 R_x + \frac{L_x}{C_1} = R_2 R_3 \tag{11.16}$$

and

$$\frac{R_x}{\omega C_1} = \omega L_x R_1 \tag{11.17}$$

Solving for L_x and R_x we have, $R_x = \omega^2 L_x C_1 R_1$.

Substituting for R_x in Eq. (11.16)

$$R_1 (\omega^2 R_1 C_1 L_x) + \frac{L_x}{C_1} = R_2 R_3$$

$$\omega^2 R_1^2 C_1 L_x + \frac{L_x}{C_1} = R_2 R_3$$

Multiplying both sides by C_1 we get

$$\omega^2 R_1^2 C_1^2 L_x + L_x = R_2 R_3 C_1$$

Therefore,
$$L_x = \frac{R_2 R_3 C_1}{1 + \omega^2 R_1^2 C_1^2} \tag{11.18}$$

Substituting for L_x in Eq. (11.17)

$$R_x = \frac{\omega^2 C_1^2 R_1 R_2 R_3}{1 + \omega^2 R_1^2 C_1^2} \tag{11.19}$$

The term ω appears in the expression for both L_x and R_x. This indicates that the bridge is frequency sensitive.

The Hay bridge is also used in the measurement of incremental inductance. The inductance balance equation depends on the losses of the inductor (or Q) and also on the operating frequency.

An inconvenient feature of this bridge is that the equation giving the balance condition for inductance, contains the multiplier $1/(1 + 1/Q^2)$. The inductance balance thus depends on its Q and frequency.

Therefore,
$$L_x = \frac{R_2 R_3 C_1}{1 + (1/Q)^2}$$

For a value of Q greater than 10, the term $1/Q^2$ will be smaller than 1/100 and can be therefore neglected.

Therefore $L_x = R_2 R_3 C_1$, which is the same as Maxwell's equation. But for inductors with a Q less than 10, the $1/Q^2$ term cannot be neglected. Hence this bridge is not suited for measurements of coils having Q less than 10.

A commercial bridge measure from 1 μ H – 100 H with ± 2% error.

Example 11.9 (a) *Find the series equivalent inductance and resistance of the network that causes an opposite angle (Hay bridge) to null with the following bridges arms. (See Fig. 11.25.)*

ω = 3000 rad/s, R_2 = 10 kΩ,
R_1 = 2 kΩ, C_1 = 1 μF
R_3 = 1 kΩ

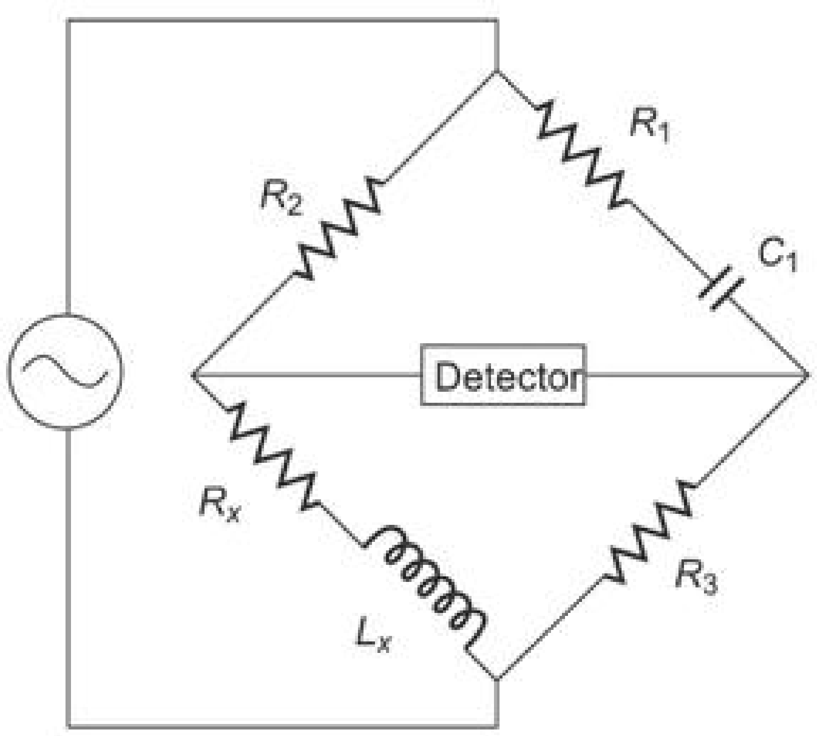


Fig. 11.25

Solution We need to find R_x and L_x.

From Eq. (11.19) we have

$$R_x = \frac{\omega^2 R_1 R_2 R_3 C_1^2}{1 + \omega^2 R_1^2 C_1^2}$$

$$= \frac{(3000)^2 \times 10\text{ k} \times 2\text{ k} \times 1\text{ k} \times (1 \times 10^{-6})^2}{1 + (3000)^2 \times (2\text{ k})^2 \times (1 \times 10^{-6})^2}$$

$$= \frac{180 \times 10^3}{1 + 36} = \frac{180}{37} \times 10^3$$

$$= 4.86\text{ k}\Omega$$

and from Eq. (11.18) we have,

$$L_x = \frac{R_2 R_3 C_1}{1 + \omega^2 R_1^2 C_1^2}$$

$$= \frac{10\text{ k} \times 1\text{ k} \times (1 \times 10^{-6})}{1 + (3000)^2 \times (2\text{ k})^2 \times (1 \times 10^{-6})^2}$$

$$= \frac{10}{1 + 36} = \frac{10}{37} = 0.27 = 270\text{ mH}$$

Therefore $R_x = 4.86$ k and $L_x = 270$ mH

Example 11.9 (b) *Four arms of a Hay Bridge are arranged as follows: AD is coil of unknown impedance Z, DC is a non-inductive resistance of 1 kΩ, CB is a non-inductive resistance of 800 Ω in series with a standard capacitor of 2 μF, BA is a non-inductive resistance of 16500 Ω, if the supply frequency is 50 Hz. Calculate the value of L and R of coil When the bridge is balanced.*

Solution Given $R_2 = 1000\ \Omega$, $R_3 = 16500\ \Omega$, $R_4 = 800\ \Omega$, $C_4 = 2\ \mu\text{F}$, $f = 50$ Hz

Step 1:

$\therefore \quad \omega = 2\pi f = 2 \times 3.14 \times 50 = 314$ and $\omega^2 = (314)^2 = 98596$

Step 2:

$$L_x = \frac{R_2 R_3 C_4}{1 + \omega^2 C_4^2 R_4^2},\ R_x = \frac{\omega^2 C_4^2 R_4 R_2 R_3}{1 + \omega^2 C_4^2 R_4^2}$$

$$\therefore \quad L_1 = \frac{(1000) \times 16500 \times 2 \times 10^{-6}}{1 + 98596 \times (2\mu\text{F})^2 \times (800)^2} = 26.4\text{ H}$$

Step 3: $$R_x = \frac{\omega^2 C_4^2 R_4 R_2 R_3}{1 + \omega^2 C_4^2 R_4^2}$$

$$R_1 = \frac{(314)^2 \times (2\mu\text{F})^2 \times 16500 \times 800 \times 1000}{1 + (314)^2 \times (2\mu\text{F})^2 \times (800)^2} = 4.18\text{ k}\Omega$$

Example 11.9 (c) *Find the unknown resistance and inductance having the following bridge arms*

$C_4 = 1\ \mu F$, $R_2 = R_3 = R_4 = 1000\ \Omega$, $\omega = 314$ rad/s

Solution To find R_1 and L_1

Step 1: Given

$$L_1 = \frac{R_2 R_3 C_4}{1+\omega^2 C_4^2 R_4^2}, R_1 = \frac{\omega^2 C_4^2 R_4 R_2 R_3}{1+\omega^2 C_4^2 R_4^2}$$

$$\therefore \quad L_1 = \frac{1000 \times 1000 \times 1 \times 10^{-6}}{1+(314)^2 \times (1\ \mu F)^2 \times (1000)^2} = 0.91\ H$$

Step 2: $$R_x = \frac{\omega^2 C_4^2 R_4 R_2 R_3}{1+\omega^2 C_4^2 R_4^2}$$

$$R_1 = \frac{(314)^2 \times (1\mu F)^2 \times 1000 \times 1000 \times 1000}{1+(314)^2 \times (1\ \mu F)^2 \times (1000)^2} \approx 89.79\ \Omega$$

SCHERING'S BRIDGE 11.13

A very important bridge used for the precision measurement of capacitors and their insulating properties is the Schering bridge. Its basic circuit arrangement is given in Fig. 11.26. The standard capacitor C_3 is a high quality mica capacitor (low-loss) for general measurements, or an air capacitor (having a very stable value and a very small electric field) for insulation measurement.

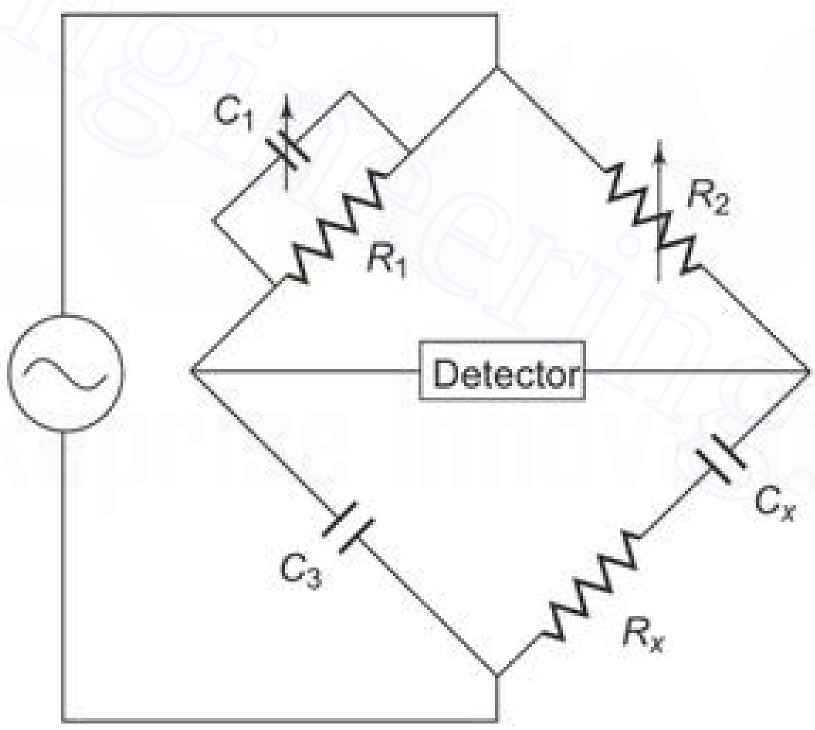


Fig. 11.26 Schering's bridge

For balance, the general equation is

$$Z_1 Z_x = Z_2 Z_3$$

$$\therefore \quad Z_x = \frac{Z_2 Z_3}{Z_1}, Z_x = Z_2 Z_3 Y_1$$

where
$$Z_x = R_x - j/\omega C_x$$
$$Z_2 = R_2$$
$$Z_3 = -j/\omega C_3$$
$$Y_1 = 1/R_1 + j\,\omega C_1$$

as $$Z_x = Z_2 Z_3 Y_1$$

$$\therefore \quad \left(R_x - \frac{j}{\omega C_x}\right) = R_2\left(\frac{-j}{\omega C_3}\right) \times \left(\frac{1}{R_1} + j\omega C_1\right)$$

$$\left(R_x - \frac{j}{\omega C_x}\right) = \frac{R_2(-j)}{R_1(\omega C_3)} + \frac{R_2 C_1}{C_3}$$

Equating the real and imaginary terms, we get

$$R_x = \frac{R_2 C_1}{C_3} \quad [11.20(a)]$$

and

$$C_x = \frac{R_1}{R_2} C_3 \quad [11.20(b)]$$

The dial of capacitor C_1 can be calibrated directly to give the dissipation factor at a particular frequency.

The dissipation factor D of a series RC circuit is defined as the cotangent of the phase angle.

$$D = \frac{R_x}{X_x} = \omega C_x R_x$$

Also, D is the reciprocal of the quality factor Q, i.e. $D = 1/Q$. D indicates the quality of the capacitor.

Commercial units measure from 100 pf – 1 µf, with ± 2% accuracy. The dial of C_3 is graduated in terms of direct readings for C_x, if the resistance ratio is maintained at a fixed value.

This bridge is widely used for testing small capacitors at low voltages with very high precision.

The lower junction of the bridge is grounded. At the frequency normally used on this bridge, the reactances of capacitor C_3 and C_x are much higher than the resistances of R_1 and R_2. Hence, most of the voltage drops across C_3 and C_x, and very little across R_1 and R_2. Hence if the junction of R_1 and R_2 is grounded, the detector is effectively at ground potential. This reduces any stray-capacitance effect, and makes the bridge more stable.

Example 11.10 (a) *An ac bridge has the following constants (refer Fig. 11.27).*

Arm AB — capacitor of 0.5 µF in parallel with 1 kΩ resistance

Arm AD — resistance of 2 kΩ

Arm BC — capacitor of 0.5 µF

Arm CD — unknown capacitor C_x and R_x in series

Frequency — 1 kHz

Determine the unknown capacitance and dissipation factor.

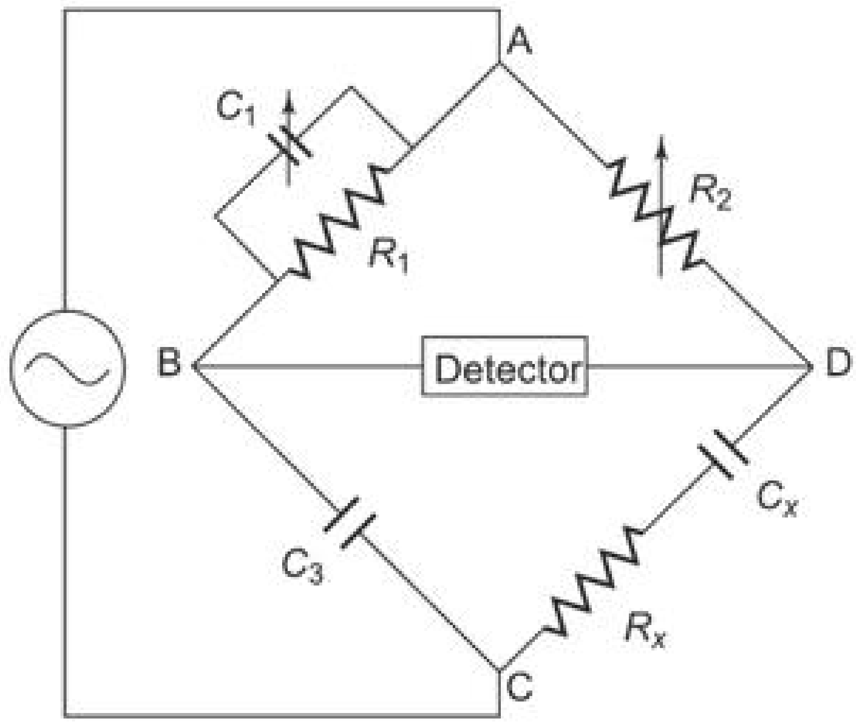


Fig. 11.27

Solution From Eqs 11.20(a) and 11.20(b), we have

$$R_x = \frac{C_1}{C_3} R_2 = \frac{0.5\ \mu F}{0.5\ \mu F} \times 2\ k = 2\ k\Omega$$

$$C_x = \frac{R_1}{R_2} \times C_3 = \frac{1\ k}{2\ k} \times 0.5\ \mu F = 0.25\ \mu F$$

The dissipation factor is given by

$$\begin{aligned} D &= \omega C_x R_x \\ &= 2 \times 3.142 \times 1000 \times 2\ k \times 0.25\ \mu F \\ &= 4 \times 3.142 \times 0.25 \\ &= 3.1416 \end{aligned}$$

Example 11.10 (b) *A sample of insulation was placed in arm AB of a Schering bridge, when the bridge was balanced at a frequency of 50 Hz, the other arms of the bridge were as follows*

Arm BC – a non-inductive R of 100 Ω

Arm CD – a non-inductive R of 300 Ω in parallel with a capacitor of 0.5 μF

Arm DA – a loss free capacitor of 100 pf

Determine the capacitance, equivalent series resistance and PF of the insulation in test arm AB

Solution Given $R_3 = 100\ \Omega$

$R_4 = 300\ \Omega$, $C_4 = 0.5\ \mu F$

$C_2 = 100\ pf$, $f = 50$ Hz

Step 1:

$\therefore \quad \omega = 2\pi f = 2 \times 3.14 \times 50 = 314$

Step 2 : From the balance condition, we have

$$C_1 = \frac{R_4}{R_3} \times C_2 = \frac{300\ \Omega}{100\ \Omega} \times 100\ pf = 300\ pf$$

Step 3:

$$R_1 = \frac{C_4}{C_2} \times R_3 = \frac{0.5\ \mu F}{100\ pf} \times 100$$

$$= \frac{0.5 \times 10^{-6}}{100 \times 100^{-12}} \times 100 = 0.5 \times 10^6\ \Omega = 0.5\ M\Omega$$

Step 4: Power factor

$$\begin{aligned} &= \omega R_4 C_4 \\ &= 314 \times 300 \times 0.5 \times 10^{-6} \\ &= 314 \times 30\cancel{0} \times \frac{5}{1\cancel{0}} \times 10^{-6} \\ &= 4710 \times 10^{-6} = 0.0471 \end{aligned}$$

Example 11.10 (c) *A condenser bushing forms arm BC of a Schering Bridge and a standard capacitor of 500 pf and negligible loss forms an arm AB. Arm CD consists of a non-inductive resistance of 300 Ω. When this bridge is balanced, arm AD has a resistance and capacitor in parallel of 100 Ω and 0.1 μF respectively. The supply frequency is 50 Hz. Calculate the capacitance and dielectric loss of angle of the bushing.*

Solution Given $R_4 = 100\ \Omega$, $C_4 = 0.1\ \mu F$

$C_2 = 500$ pF, $R_3 = 300\ \Omega$

$f = 50$ Hz

Step 1:

$\therefore \quad \omega = 2\pi f = 2 \times 3.14 \times 50 = 314$

Step 2: $C_1 = \dfrac{R_4}{R_3} \times C_2 = \dfrac{100}{300} \times 500 \times 10^{-12} = 166.6$ pF

Step 3: Dielectric loss angle is given by

$$\tan \delta = \omega C_4 R_4$$
$$= 3.14 \times 0.1 \times 10^{-6} \times 100$$
$$= 3.14 \times 10 \times 10^{-6}$$
$$\tan \delta = 0.03140$$

Hence $\delta = 1.8^{o}$

Example 11.10 (d) *A sheet of 4.5-mm thick Bakelite is tested at 50 Hz between 12 cm in diameter. The Schering bridge uses a standard air capacitor C_2 of 105 pF capacitor, a non–reactive, R_4 of 1000/π in parallel with a variable capacitor and is obtained with $C_4 = 0.5\ \mu F$ and $R_3 = 260\ \Omega$. Calculate the capacitance, PF and relative permittivity of the sheet.*

Solution It is given that

d = thickness of sheet in metre = 4.5×10^{-3}

$f = 50$ Hz,

$\therefore \quad \omega = 2\pi f = 2 \times 3.14 \times 50 = 314$

A = area of the electrodes in m^2 = $\pi (6 \times 10^{-2})^2$

$$C_2 = 105 \times 10^{-12},\ R_4 = \frac{1000}{\pi},\ C_4 = 0.5\ \mu F,\ R_3 = 260\ \Omega$$

Step 1: $C_1 = \dfrac{R_4}{R_3} \times C_2 = \dfrac{1000}{\pi \times 260} \times 105 \text{ pF} = \dfrac{1000}{8164} \times 105 \text{ pf}$

$C_1 = 128.7$ pf

Step 2: PF is given by

$$\omega R_4 C_4 = 2 \times 3.14 \times 50 \times \frac{1000}{\pi} \times 0.5 \times 10^{-6}$$

$$= 2 \times \cancel{3.14} \times 50 \times \frac{1000}{\cancel{\pi}} \times 0.5 \times 10^{-6}$$

$$= 10^{-1} \times 0.5 = 0.05$$

Step 3: Given that the capacitance is given by $C_1 = K_r K_o \dfrac{A}{d}$

$\therefore$ Relative permittivity is given by

$$K_r = \frac{C_1 d}{K_o A}$$

$$= \frac{128.7\,\text{pF} \times 4.5 \times 10^{-3}}{8.854 \times 10^{-12} \times \pi (6 \times 10^{-2})^2}$$

$$= \frac{128.7 \times 4.5 \times 10^{-15}}{8.854 \times 10^{-12} \times 3.14 \times 36 \times 10^{-4}}$$

$$= \frac{579.15 \times 10^{-15}}{1000.85 \times 10^{-16}}$$

$$= 5.786$$

Example 11.10 (e) *A capacitor is tested by a Schering bridge which forms one arm AB of the bridge. The other arms are*

AD – a non-inductive resistance of 100 Ω,

DC – a non-reactive resistance of 300 Ω in parallel with a capacitor of 0.5 μF,

BC – a standard loss free capacitor of 100 pF,

The supply frequency is 50 Hz. The bridge is balanced.

Calculate the capacitor value and the power factor of the capacitor under test.

Solution Given $R_3 = 100\ \Omega$, $R_4 = 300\ \Omega$, $C_2 = 100$ pF, $C_4 = 0.5\ \mu$F

Let the desired capacitance of the capacitor to be tested be C_1 and r_1 is the resistance representing the loss.

Step 1: From the given equation for C_1 we have

$$C_1 = \frac{R_4}{R_3} \times C_2 = \frac{300}{100} \times 100\ \text{pF}$$

$$C_1 = 300\ \text{pf}$$

Step 2: $$r_1 = R_3 \times \frac{C_4}{C_2} = 100 \times \frac{0.5\ \mu\text{F}}{100\ \text{pF}} \times 500\ \text{k}\Omega$$

Step 3: The power factor can be as follows:

$$\text{PF} = \omega C_4 R_4 = 2\pi f \times C_4 R_4$$

$$= 2 \times 3.14 \times 50 \times 300 \times 0.5 \times 10^{-6}$$

$$= 0.0471$$

Example 11.10 (f) *A sample Bakelite was tested by the bridge method (Schering) at 11 kV,50 Hz. Balance was obtained at the followings values*
AB – dielectric material under test in the form of a capacitor
BC – a standard air capacitor of 100 pf
CD – capacitor of 0.6 μF in parallel with a non-reactive resistance of 300 Ω
DA – non–reactive resistance of 100 Ω
Calculate the capacitance and equivalent series resistance of the sample.

Solution The given bridge is of a Schering bridge. To find R_x and C_x
Given $R_1 = 300\ \Omega$, $R_2 = 100\ \Omega$, $C_1 = 0.6\ \mu F$, $C_3 = 100$ pf

Step 1: $R_x = R_2 \times \dfrac{C_1}{C_3} = 100 \times \dfrac{0.6 \times 10^{-6}}{100 \times 10^{-12}} = 6\ M\Omega$

Step 2: $C_x = \dfrac{R_1}{R_2} \times C_3 = \dfrac{300}{100} \times 100 \times 10^{-12} = 300\ pF$

Example 11.10(g) *An ac bridge has the following constants:*
Arm AB – capacitor of 0.1 μF in parallel with 2 kΩ resistor
Arm AD – resistance of 5 kΩ
Arm BC – capacitor of 0.25 μF
Arm AB – unknown capacitor C_x and R_x in series
f = 2 kHz
Determine the unknown capacitance and dissipation factor.

Solution From the balance equation for a Schering bridge, we have

Step 1: $R_x = \dfrac{C_1}{C_2} \times R_2 = \dfrac{0.1\ \mu F}{0.25\ \mu F} \times 5\ k\Omega$

$$= \frac{10}{25} \times 5\ k\Omega = 2\ k\Omega$$

Step 2: $C_x = \dfrac{R_1}{R_2} \times C_3 = \dfrac{2\ k\Omega}{5\ k\Omega} \times 0.25\ \mu F$

$$= \frac{2}{5} \times \frac{25\ \mu F}{100} = 0.1\ \mu F$$

Step 3 : Dissipation factor $(D) = \omega C_x R_x$

$$= 2 \times 3.142 \times 2000 \times 0.1\ \mu F \times 2\ k\Omega$$
$$= 2 \times 3.142 \times 4 \times 0.1$$
$$= 8 \times 3.142 \times 0.1$$
$$D = 2.5136$$

WIEN'S BRIDGE 11.14

The Wien bridge shown in Fig. 11.28 has a series RC combination in one arm and a parallel combination in the adjoining arm. Wien's bridge in its basic form, is designed to measure frequency. It can also be used for the measurement of an unknown capacitor with great accuracy.

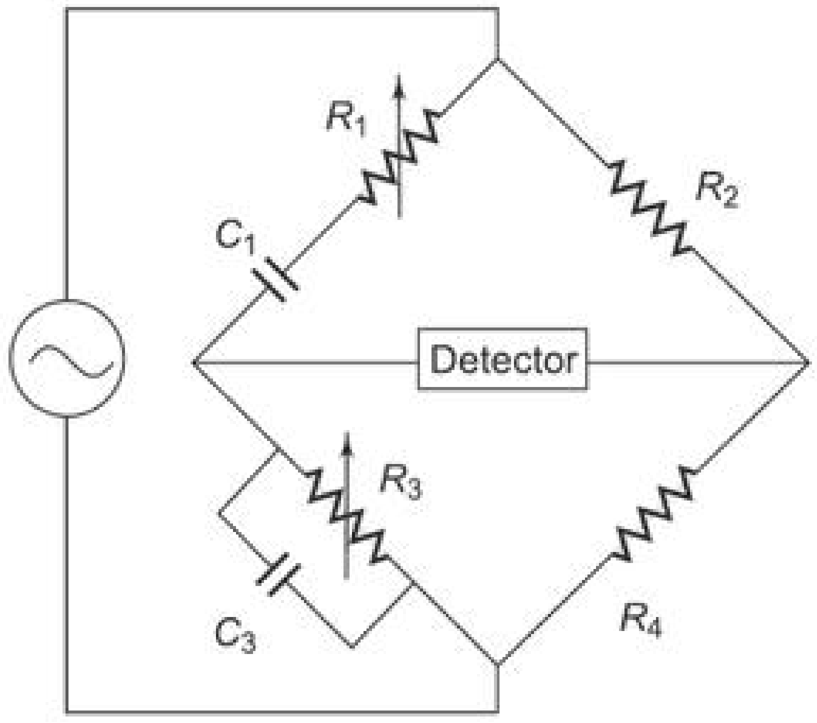


Fig. 11.28 Wein's bridge

The impedance of one arm is

$$Z_1 = R_1 - j/\omega C_1.$$

The admittance of the parallel arm is

$$Y_3 = 1/R_3 + j\,\omega\,C_3.$$

Using the bridge balance equation, we have $Z_1 Z_4 = Z_2 Z_3$.

Therefore, $Z_1 Z_4 = Z_2/Y_3$, i.e. $Z_2 = Z_1 Z_4 Y_3$.

$$\therefore \quad R_2 = R_4\left(R_1 - \frac{j}{\omega C_1}\right)\left(\frac{1}{R_3} + j\omega C_3\right)$$

$$R_2 = \frac{R_1 R_4}{R_3} - \frac{j R_4}{\omega C_1 R_3} + j\,\omega\,C_3 R_1 R_4 + \frac{C_3 R_4}{C_1}$$

$$R_2 = \left(\frac{R_1 R_4}{R_3} + \frac{C_3 R_4}{C_1}\right) - j\left(\frac{R_4}{\omega C_1 R_3} - \omega\,C_3 R_1 R_4\right)$$

Equating the real and imaginary terms we have

$$R_2 = \frac{R_1 R_4}{R_3} + \frac{C_3 R_4}{C_1} \quad \text{and} \quad \frac{R_4}{\omega C_1 R_3} - \omega\,C_3 R_1 R_4 = 0$$

Therefore $$\frac{R_2}{R_4} = \frac{R_1}{R_3} + \frac{C_3}{C_1} \qquad (11.21)$$

and $$\frac{1}{\omega C_1 R_3} = \omega\,C_3 R_1 \qquad (11.22)$$

$$\therefore \quad \omega^2 = \frac{1}{C_1 R_1 R_3 C_3}$$

$$\omega = \frac{1}{\sqrt{C_1 R_1 C_3 R_3}}$$

as $\omega = 2\,\pi f$

$$\therefore \quad f = \frac{1}{2\pi\sqrt{C_1 R_1 C_3 R_3}} \qquad (11.23)$$

The two conditions for bridge balance, (11.21) and (11.23), result in an expression determining the required resistance ratio R_2/R_4 and another expression determining the frequency of the applied voltage. If we satisfy Eq. (11.21) and also excite the bridge with the frequency of Eq. (11.23), the bridge will be balanced.

In most Wien bridge circuits, the components are chosen such that $R_1 = R_3 = R$ and $C_1 = C_3 = C$. Equation (11.21) therefore reduces to $R_2/R_4 = 2$ and Eq. (11.23) to $f = 1/2\pi RC$, which is the general equation for the frequency of the bridge circuit.

The bridge is used for measuring frequency in the audio range. Resistances R_1 and R_3 can be ganged together to have identical values. Capacitors C_1 and C_3 are normally of fixed values.

The audio range is normally divided into 20 – 200 – 2 k – 20 kHz ranges. In this case, the resistances can be used for range changing and capacitors C_1 and C_3 for fine frequency control within the range. The bridge can also be used for measuring capacitances. In that case, the frequency of operation must be known.

The bridge is also used in a harmonic distortion analyzer, as a Notch filter, and in audio frequency and radio frequency oscillators as a frequency determining element.

An accuracy of 0.5% – 1% can be readily obtained using this bridge. Because it is frequency sensitive, it is difficult to balance unless the waveform of the applied voltage is purely sinusoidal.

Example 11.11 *A Wien bridge circuit consists of the following:*

$R_1 = 4.7\ k\Omega$, $C_1 = 5\ nf$

$R_2 = 20\ k\ \Omega$, $C_3 = 10\ nf$

$R_3 = 10\ k\ \Omega$

$R_4 = 100\ k\ \Omega$.

Determine the frequency of the circuit.

Solution The frequency is given by the equation

$$f = \frac{1}{2\pi\sqrt{C_1\ R_1\ R_3\ C_3}}$$

$$f = \frac{1}{2\pi\sqrt{5\times10^{-9}\times4.7\times10^{3}\times10\times10^{-9}\times10\times10^{3}}}$$

$$f = \frac{1}{2\pi\sqrt{5\times10^{-10}\times4.7}}$$

$$f = \frac{10^{5}}{2\pi\sqrt{5\times4.7}} = 3.283\ \text{kHz}$$

Example 11.12 *Find the equivalent parallel resistance and capacitance that causes a Wien bridge to null with the following component values.*

$R_1 = 3.1\ k\Omega$
$C_1 = 5.2\ \mu F$
$R_2 = 25\ k\Omega$
$f = 2.5\ kHz$
$R_4 = 100\ k\Omega$

Solution Given $\omega = 2\pi f = 2 \times 3.14 \times 2500 = 15.71$ k rad/s.

Substituting the value of C_3 from Eq. (11.22) in Eq. (11.21) we get,

$$R_3 = \frac{R_4}{R_2}\left(R_1 + \frac{1}{\omega^2 R_1 C_1^2}\right)$$

$$= \frac{100\text{ k}}{25\text{ k}}\left(3.1\text{ k} + \frac{1}{(15.71\text{ k})^2 \times 3.1\text{ k} \times (5.2 \times 10^{-6})^2}\right)$$

$$= 12.4\text{ k}\Omega$$

$$C_3 = \frac{R_2}{R_4}\left(\frac{C_1}{1 + \omega^2 R_1^2 C_1^2}\right)$$

$$= \frac{25\text{ k}}{100\text{ k}}\left(\frac{5.2 \times 10^{-6}}{1 + (15.71\text{ k})^2 \times (3.1\text{ k})^2 \times (5.2 \times 10^{-6})^2}\right)$$

$$= 1.3 \times 10^{-6}\left(\frac{1}{1 + 64133.07}\right)$$

$$= 20.3\text{ pf}$$

The value of C_3 can also be found out by using equation $C_3 = \dfrac{1}{\omega^2 C_1 R_1 R_3}$.

Example 11.13 *An ac bridge with terminals ABCD has in*
Arm AB a resistance of 800 Ω in parallel with a capacitor of 0.5 μF,
Arm BC – a resistance of 400 Ω in series with a capacitor of 1 μF,
Arm CD – a resistance of 1000 Ω, Arm DA – a pure resistance R.
(a) Determine the value of frequency for which the bridge is balanced
(b) Calculate the value of R required to produce balance.

Solution The bridge configuration is of Wien Bridge.

Given : $C_1 = 0.5\ \mu F$, $R_1 = 800\ \Omega$
$C_2 = 1.0\ \mu F$, $R_2 = 400\ \Omega$
$R_4 = 1000\ \Omega$, $R_3 = R = ?$

Step 1 : Frequency calculated by

$$f = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}}$$

$$= \frac{1}{2\pi\sqrt{800 \times 0.5\,\mu\text{F} \times 400 \times 1\,\mu\text{F}}}$$

$$= \frac{1}{2\pi\sqrt{800 \times 400 \times 0.5 \times 10^{-12}}}$$

$$= \frac{10^6}{2\pi\sqrt{800 \times 200}}$$

$$= \frac{10^6}{2\pi \times 400} = \frac{1000\text{ kHz}}{2 \times 3.14 \times 400} = \frac{1000}{314 \times 8} = 0.398\text{ kHz}$$

Step 2 : Also given,

$$\frac{R_2}{R_1} + \frac{C_1}{C_2} = \frac{R_4}{R_3}$$

$$\therefore \quad \frac{400}{800} + \frac{0.5\,\mu\text{F}}{1\,\mu\text{F}} = \frac{1000}{R}$$

$$\therefore \quad 0.5 + 0.5 = \frac{1000}{R}$$

$$\therefore \quad R = 1000\,\Omega$$

WAGNER'S EARTH (GROUND) CONNECTION 11.15

When performing measurements at high frequency, stray capacitances between the various bridge elements and ground, and between the bridge arms themselves, becomes significant. This introduces an error in the measurement, when small values of capacitance and large values of inductance are measured.

An effective method of controlling these capacitances, is to enclose the elements by a shield and to ground the shield. This does not eliminate the capacitance, but makes it constant in value.

Another effective and popular method of eliminating these stray capacitances and the capacitances between the bridge arms is to use a Wagner's ground connection. Figure 11.29 shows a circuit of a capacitance bridge. C_1 and C_2 are the stray capacitances. In Wagner's ground connection, another arm, consisting of R_w and C_w forming a potential divider, is used. The junction of R_w and C_w is grounded and is called Wagner's ground connection. The procedure for adjustment is as follows.

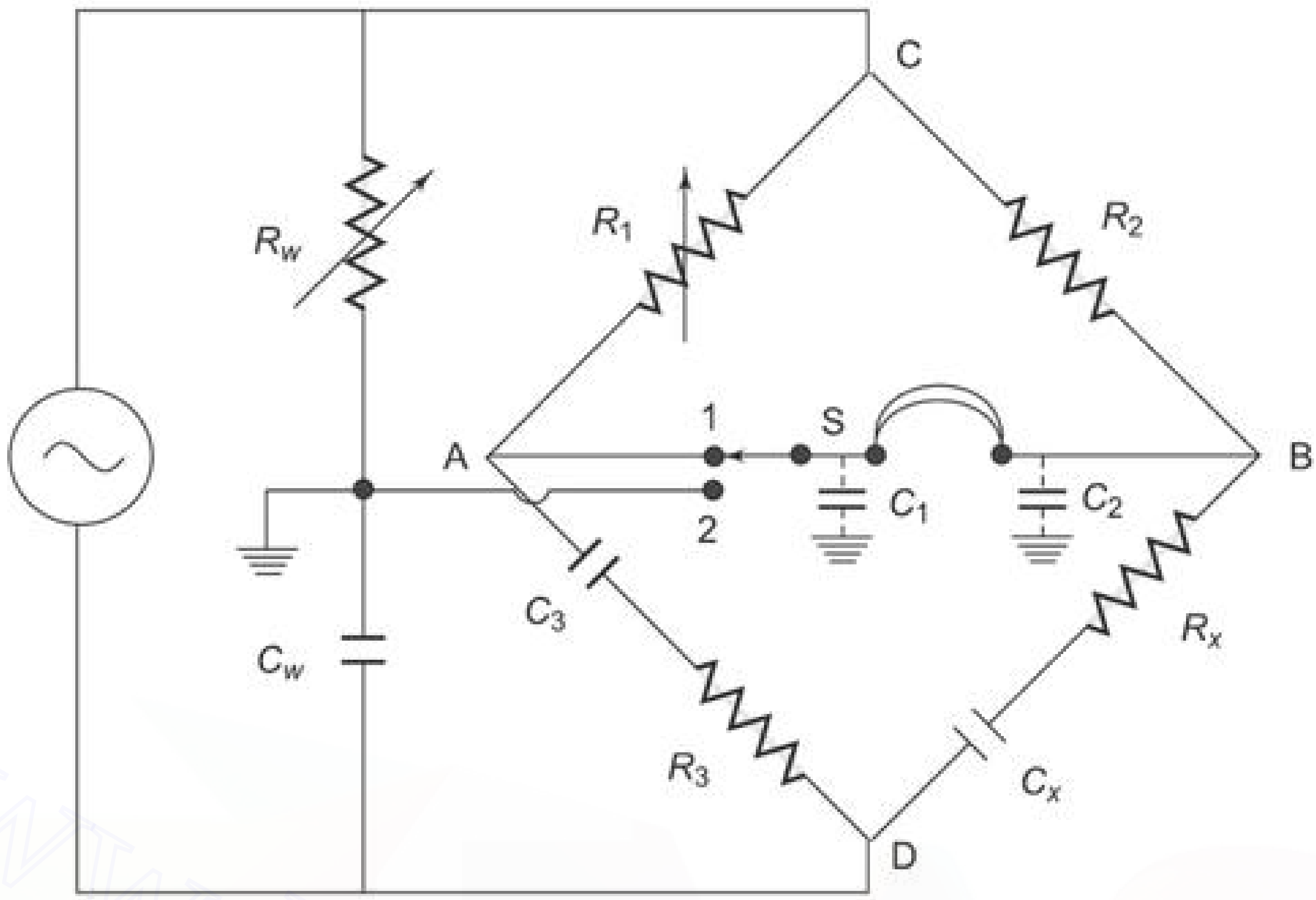


Fig. 11.29 Wagner's earth connection

The detector is connected to point 1 and R_1 is adjusted for null or minimum sound in the headphones. The switch S is then connected to point 2, which connects the detector to the Wagner ground point. Resistor R_w is now adjusted for minimum sound. When the switch 'S' is connected to point 1, again there will be some imbalance. Resistors R_1 and R_3 are then adjusted for minimum sound and this procedure is repeated until a null is obtained on both switch positions 1 and 2. This is the ground potential. Stray capacitances C_1 and C_2 are then effectively short-circuited and have no effect on the normal bridge balance.

The capacitances from point C to D to ground are also eliminated by the addition of Wagner's ground connection, since the current through these capacitors enters Wagner's ground connection.

The addition of the Wagner ground connection does not affect the balance conditions, since the procedure for measurement remains unaltered.

RESONANCE BRIDGE 11.16

One arm of this bridge, shown in Fig. 11.30, consists of a series resonance circuit. The series resonance circuit is formed by R_d, C_d and L_d in series. All the other arms consists of resistors only.

Using the equation for balance, we have $Z_1 Z_4 = Z_2 Z_3$,
where $Z_1 = R_b$, $Z_2 = R_c$, $Z_3 = R_a$, and $Z_4 = R_d + j\omega L_d - j/\omega C_d$.

Therefore $$R_b\left(R_d + j\omega L_d - \frac{j}{\omega C_d}\right) = R_a R_c$$

$$\therefore \quad R_b R_d + j\,\omega L_d R_b - \frac{j R_b}{\omega C_d} = R_a R_c$$

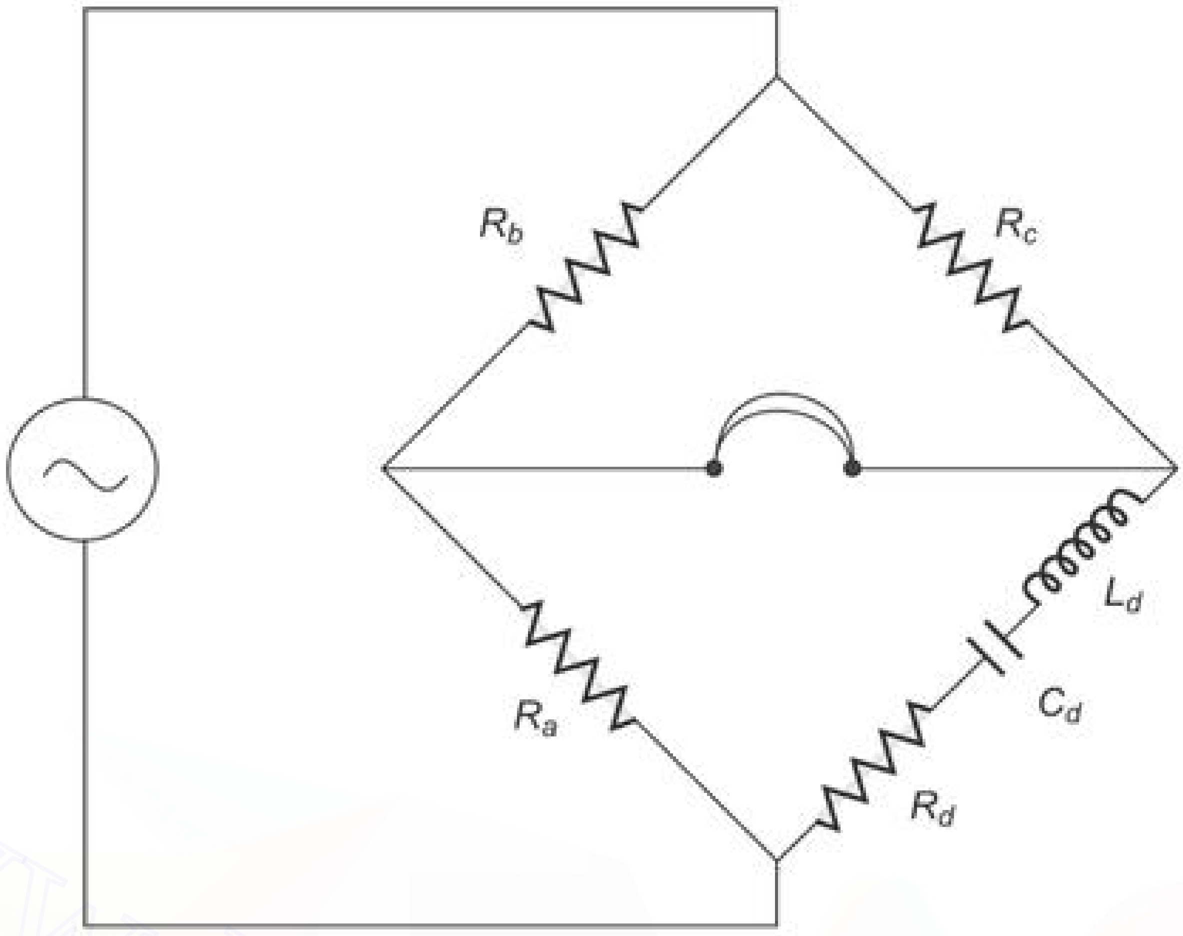


Fig. 11.30 Resonance bridge

Equating the real and imaginary terms

we get $R_b R_d = R_a R_c$ and $j\,\omega L_d - \dfrac{j}{\omega C_d} = 0$

Therefore $R_d = \dfrac{R_a R_c}{R_b}$ and $\omega L_d = \dfrac{1}{\omega C_d}$ i.e. $\omega^2 = \dfrac{1}{L_d C_d}$

Therefore $$f = \frac{1}{2\pi\sqrt{L_d C_d}} \tag{11.24}$$

The bridge can be used to measure unknown inductances or capacitances. The losses R_d can be determined by keeping a fixed ratio R_a/R_b and using a standard variable resistance to obtain balance. If an inductance is being measured, a standard capacitor is varied until balance is obtained. If a capacitance is being measured, a standard inductor is varied until balance is obtained.The operating frequency of the generator must be known in order to calculate the unknown quantity. Balance is indicated by the minimisation of sound in the headphones.

MAXWELL–WIEN BRIDGE 11.17

As seen before, a positive phase angle of inductive impedance can be compensated by the negative phase angle of capacitive impedance, which is placed in the opposite arms *CD*. As shown in Fig. 11.31, the unknown inductance can be determined in terms of capacitance.

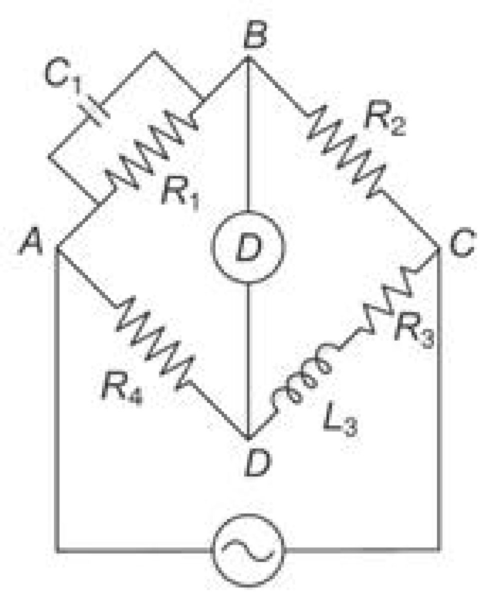


Fig 11.31 Maxwell's–Wein bridge

Balance condition is obtained when

$$Z_1Z_3 = Z_2Z_4$$

But

$$Z_1 = R_1 // jXc_1,\ \frac{1}{Z_1} = \frac{1}{R_1} + \frac{1}{jXc_1} = \frac{1}{R_1} + j\omega C_1 = \frac{1 + j\omega C_1 R_1}{R_1}$$

Therefore, $Z_1 = \dfrac{R_1}{1 + j\omega\, C_1\, R_1}$

$$Z_2 = R_2,\ Z_4 = R_4 \text{ and } Z_3 = R_3 + j\omega L_3$$

Using balance condition, $Z_1Z_3 = Z_2Z_4$

Therefore, $\left(\dfrac{R_1}{1 + j\omega\, C_1\, R_1}\right)(R_3 + j\omega L_3) = R_2R_4$

Therefore, $R_1R_3 + j\omega L_3R_1 = R_2R_4\,(1 + j\omega C_1R_1)$

$$R_1R_3 + j\omega L_3R_1 = R_2R_4 + j\omega C_1R_1\, R_2R_4$$

Equating the real and imaginary terms, we have

$R_1R_3 = R_2R_4$ therefore $R_3 = \dfrac{R_2R_4}{R_1}$

and $j\omega L_3R_1 = j\omega C_1R_1\, R_2R_4$

Therefore, $L_3 = C_1R_2R_4$

Hence the unknown resistance R_3 and unknown inductance L_3 can be determined

Example 11.11

From Fig. 11.31,

$R_1R_3 = R_2R_4$, therefore $R_3 = \dfrac{R_2R_4}{R_1} = \dfrac{600 \times 400}{1000} = 240\ \Omega$

$L_3 = C_1R_2R_4 = 0.5 \times 10^{-6} \times 600 \times 400 = 12 \times 10^{-2}\, H = 0.12$ mH.

Hence $R_3 = 240\ \Omega$ and $L_3 = 0.12$ mH

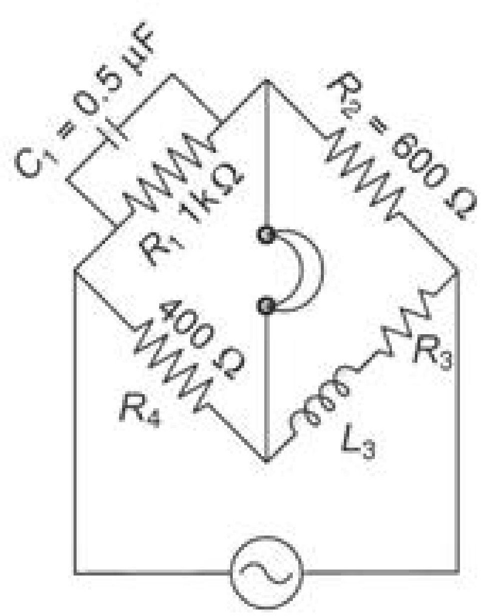


Fig. 11.31(a)

ANDERSON BRIDGE 11.18

The Anderson Bridge is a very important and useful modification of the Maxwell–Wien Bridge as shown in Fig 11.32.

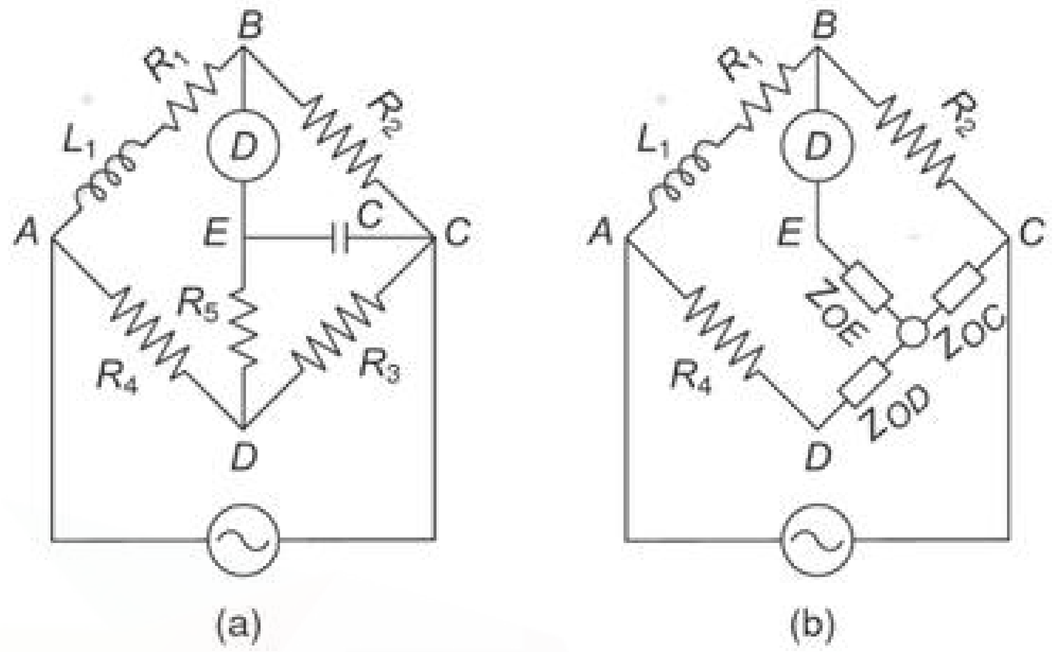


Fig 11.32 Anderson's bridge

The balance condition for this bridge can be easily obtained by converting the mesh impedances C, R_3, R_5 to an equivalent star with the star point 0 as shown in Fig 11.32(b) by using star/delta transformation.

As per delta to star transformation

$$Z_{OD} = \frac{R_3\, R_5}{(R_3 + R_5 + 1/j\omega C)} \qquad Z_{OC} = \frac{R_3 / j\omega C}{(R_3 + R_5 + 1/j\omega C)} = Z_3$$

Hence with reference to Fig. 11.32 (b) it can be seen that

$$Z_1 = (R_1 + j\omega L_1),\ Z_2 = R_2,\ Z_3 = Z_{OC} = \frac{R_3 / j\omega C}{(R_3 + R_5 + 1/ j\omega C)} \text{ and } Z_4 = R_4 + Z_{OD}$$

For balance condition,

$$Z_1 Z_3 = Z_2\, Z_4$$

Therefore, $(R_1 + j\omega L_1) \times Z_{OC} = Z_2 \times (Z_4 + Z_{OD})$

$$(R_1 + j\omega L_1) \times \left(\frac{R_3 / j\omega C}{(R_3 + R_5 + 1/j\omega C} \right) = R_2 \left(R_4 + \frac{R_3 R_5}{(R_3 + R_5 + 1\, j\omega C} \right)$$

Simplifying,

$$(R_1 + j\omega L_1) \times \frac{R_3 / j\omega C}{(R_3 + \cancel{R_5 + 1} / j\omega C} = R_2 \left(R_4\, (R_3 + R_5 + 1/j\omega C) + \frac{R_3 R_5}{(R_3 + \cancel{R_5 + 1} / j\omega C} \right)$$

$$(R_1 + j\omega L_1) \times \frac{R_3}{j\omega C} = R_2\, R_4\, (R_3 + R_5 + 1/j\omega C) + R_2 R_3 R_5$$

$$\frac{R_1\, R_3}{j\omega C} + \frac{j\omega L_1 R_3}{j\omega C} = R_2 R_3 R_4 + R_2 R_4 R_5 + \frac{R_2 R_4}{j\omega C} + R_2 R_3 R_5$$

$$\frac{-j R_1 R_3}{\omega C} + \frac{L_1 R_3}{C} = R_2 R_3 R_4 + R_2 R_4 R_5 - \frac{j R_2 R_4}{\omega C} + R_2 R_3 R_5$$

Equating the real terms and imaginary terms

$$\frac{L_1 R_3}{C} = R_2 R_3 R_4 + R_2 R_4 R_5 + R_2 R_3 R_5$$

$$L_1 = \frac{C}{R_3}(R_2 R_3 R_4 + R_2 R_4 R_5 + R_2 R_3 R_5)$$

$$L_1 = CR_2\left[R_4 + \frac{R_4 R_5}{R_3} + R_5\right]; \quad L_1 = CR_2\left[R_4 + R_5 + \frac{R_4 R_5}{R_3}\right]$$

$$\frac{-j R_1 R_3}{\omega C} = \frac{-j R_2 R_4}{\omega C}; \quad R_1 R_3 = R_2 R_4, \text{ therefore, } R_1 = \frac{R_2 R_4}{R_3}$$

This method is capable of precise measurement of inductances and a wide range of values from a few μH to several Henries.

Example 11.14 *An inductive coil was tested by an Anderson bridge. The following were the values on balance.*
Arm AB unknown inductance having resistance R_1 and inductance L_1
Arm BC, CD, DA are resistors having 1000 Ω, 1000 Ω and 2000 Ω respectively
A capacitor of 10 μF and resistance 400 Ω are connected between CE and ED respectively, Source between A and C, r = 496. Determine L_1 and R_1.

Solution Given : $R_2 = 200\ \Omega$, $R_3 = 1000\ \Omega$, $R_4 = 1000\ \Omega$, $C = 10\ \mu F$, $r = 496$

Step 1: To calculate

$$R_1 = \frac{R_2 R_3}{R_4} = \frac{200 \times 1000}{1000} = 200\ \Omega$$

Step 2: Similarly to calculate

$$L_1 = \frac{CR_3}{R_4}(rR_4 + R_2 R_4 + rR_2)$$

$$= \frac{10 \times 10^{-6} \times 1000}{1000} \times (496 \times 10^3 + 200 \times 10^3 + 496 \times 200)$$

$$= 10^{-5} \times 10^3 \times (496 + 200 + 0.496 \times 200)$$

$$= 10^{-2}(496 + 200 + 99.2)$$

$$= 795.2 \times 10^{-2}$$

$$= 7.952 \text{ H}$$

THE OWEN BRIDGE 11.19

In the arrangement shown in Fig 11.33, the unknown inductance is measured in terms of resistance and capacitance. This method has the advantage of being useful over a very wide range of inductances with capacitors of reasonable dimensions.

As per the balance condition,

$$Z_1 Z_3 = Z_2 Z_4$$

$$Z_1 = \frac{-j}{\omega C_1}, Z_2 = R_2, Z_4 = R_4 - \frac{j}{\omega C_4}, Z_3 = R_3 + j\omega L_3$$

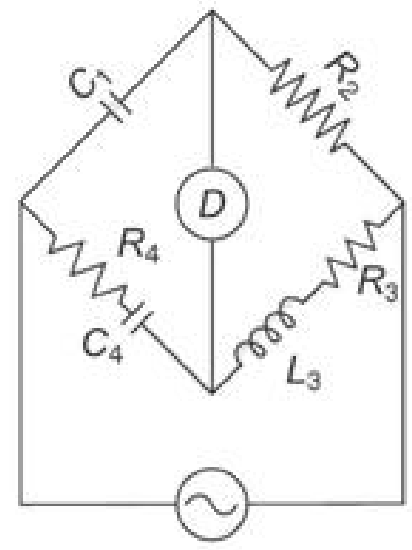


Fig 11.33 Owen's bridge

Hence substituting in the balance equation, we get

$$\left(\frac{-j}{\omega C_1}\right) \times (R_3 + j\omega L_3) = R_2 \times \left(R_4 - \frac{j}{\omega C_4}\right)$$

$$\frac{-j R_3}{\omega C_1} + \frac{-j \times j\omega L_3}{\omega C_1} = R_2 R_4 - \frac{j R_2}{\omega C_4}$$

$$\frac{-j R_3}{\omega C_1} + \frac{L_3}{C_1} = R_2 R_4 - \frac{j R_2}{\omega C_4}$$

Equating the real and the imaginary terms,

$$\frac{L_3}{C_1} = R_2 R_4 \text{ therefore, } L_3 = C_1 R_2 R_4$$

$$\frac{-j R_3}{\omega C_1} = \frac{-j R_2}{\omega C_4} \text{ Therefore, } \frac{R_3}{C_1} = \frac{R_2}{C_4} \text{ hence } R_3 = \frac{C_1 R_2}{C_4}$$

As seen from the values of R_3 and L_3 the term 'ω' does not appear in both the final equations. Hence the bridge is unaffected by frequency variations.

DE SAUTY BRIDGE 11.20

As seen from Fig. 11.34,

Let

C_2 be the capacitor whose capacitance is to be measured,

C_3 be a standard capacitor

R_1, R_2 be non-inductive resistors

Balance is obtained by varying either R_1 or R_2

For balance conditions, point B and D are at same potential.

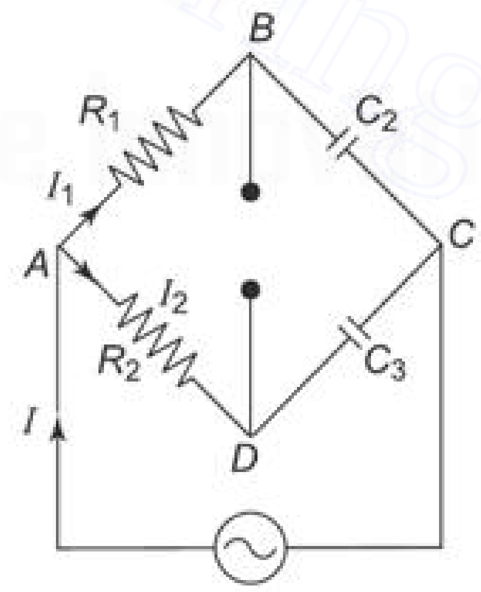


Fig 11.34 De Sauty bridge

Therefore, $V_B = V_D$

$$I_1 R_1 = I_2 R_2 \quad (11.25)$$

$$\frac{-j}{\omega C_2} \times I_1 = \frac{-j}{\omega C_3} \times I_2 \quad (11.26)$$

Dividing equation (11.25) and (11.26) we have

$$\frac{I_1 R_1}{\frac{-j}{\omega C_2} \times I_1} = \frac{I_2 R_2}{\frac{-j}{\omega C_3} \times I_2}$$

$$\frac{R_1 \times \omega C_2}{-j} = \frac{R_2 \times \omega C_3}{-j} \text{ therefore, } R_1 \times C_2 = R_2 \times C_3$$

Hence $R_1\, C_2 = R_2\, C_3$ therefore, $C_2 = \dfrac{R_2}{R_1} \cdot C_3$

The bridge has maximum sensitivity when $C_2 = C_3$.

If both the capacitors are not free from dielectric loss, to obtain perfect balance is difficult.

A perfect balance can only be obtained if air capacitors are used.

CAREY FOSTER / HEYDWEILLER BRIDGE 11.21

This bridge was basically designed and used by Carey Foster and was later on modified by Heydweiller for use in ac. Hence this bridge has both their names associated.

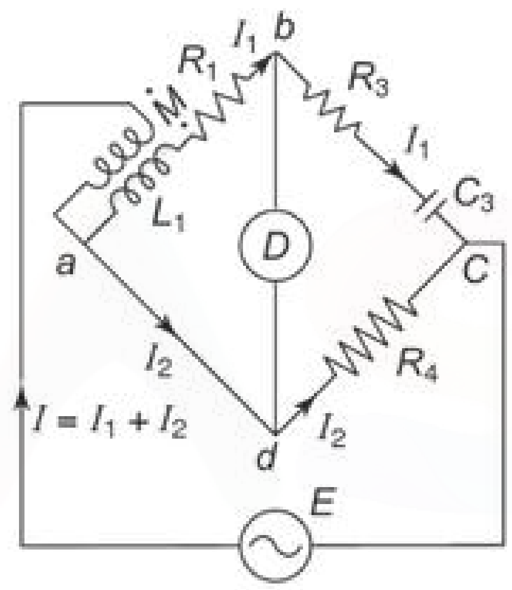


Fig 11.35 Carey Foster/Heydweiller bridge

The two bridges are used for opposite purposes.

(i) If it is used for measurement of capacitance in terms of a standard mutual inductance, the bridge is known as Carey Foster's bridge.

(ii) It can also be used for measurement of mutual inductance in terms of a standard capacitance. Then the bridge is known as Heydweiller's bridge.

The bridge circuit is as shown in Fig 11.35. The bridge has a special feature, that one of its arms '*ad*' is short circuited and, therefore, the potential drop across this arm is zero.

In order to achieve balance,the potential drop across arm '*ab*' should also be zero. Hence for this reason negative coupling is required for the mutual inductance.

At balance

$$I_1\,(R_1 + j\omega L_1) - (I_1 + I_2\,)\, j\omega M = 0 \tag{11.27}$$

and

$$I_1\left(R_3 + \frac{1}{j\omega C_3}\right) = I_2 R_4 \tag{11.28}$$

From Eq. (11.27)

$$I_1\,(R_1 + j\omega L_1) - I_1 j\omega M - I_2 j\omega M = 0$$

$$I_1(R_1 + j\omega L_1 - j\omega M\,) = I_2 j\omega M$$

$$I_1\left(R_3 + \frac{1}{j\omega C_3}\right) = I_2 R_4$$

Taking ratio of the above two equations, we have

$$\frac{I_1(R_1 + j\omega L_1 - j\omega M)}{I_1\left(R_3 + \dfrac{1}{j\omega C_3}\right)} = \frac{I_2 j\omega M}{I_2 R_4}$$

$$\frac{(R_1 + j\omega L_1 - j\omega M)}{\left(R_3 + \dfrac{1}{j\omega C_3}\right)} = \frac{j\omega M}{R_4}$$

Cross-multiplying, we have

$$R_4(R_1 + j\omega L_1 - j\omega M) = j\omega M\left(R_3 + \frac{1}{j\omega C_3}\right)$$

$$R_4 R_1 + j\omega(L_1 - M)R_4 = j\omega M R_3 + \frac{j\omega M}{j\omega C_3}$$

$$R_4 R_1 + j\omega(L_1 - M)R_4 = j\omega M R_3 + \frac{M}{C_3}$$

Equating the real and imaginary terms, we have

$$R_4 R_1 = \frac{M}{C_3} \text{ therefore, } M = R_1 R_4 C_3 \tag{11.29}$$

$$j\omega(L_1 - M)R_4 = j\omega M R_3 \text{ therefore, } (L_1 - M)R_4 = MR_3$$

$$L_1 R_4 = MR_3 + MR_4 \text{ therefore, } L_1 R_4 = M(R_3 + R_4)$$

Hence, $$L_1 = \frac{M(R_3 + R_4)}{R_4} \tag{11.30}$$

But $M = R_1 R_4 C_3$. Hence, $L_1 = \dfrac{M(R_3 + R_4)}{R_4}$ $L_1 = \dfrac{R_1 R_4 C_3 (R_3 + R_4)}{R_4}$

Therefore, $L_1 = R_1 C_3 (R_3 + R_4)$ (11.31)

If the bridge is used for measurement of capacitance equations (11.29) and (11.30) can be written as

$$C_3 = \frac{M}{R_1 R_4}$$

And $$R_3 = \frac{R_4(L_1 - M)}{M}$$

It can be seen that in the measurement of mutual inductance with this bridge, R_3 is a separate resistance while in the measurement of capacitance R_3 is not a separate unit but represents the equivalent series resistance of the capacitor and hence can be determined in terms of the bridge elements.

TYPES OF DETECTORS 11.22

1. For low frequency, the most convenient detector is the vibration galvanometer.
2. For ordinary laboratory work at frequencies up to a few 100 Hz, the moving coil type of instrument is usually employed. It has a high sensitivity.
3. In high voltage testing, the moving magnet type of vibration galvanometer with remote controlled tuning is used, (for 300 Hz – 1 kHz).
4. For higher AF frequencies (>800 Hz), the telephone (headphone) is the best detector.

   (Vibration galvanometers and headphones have no phase selectivity, i.e. they do not indicate whether it is resistance or reactance adjustments that are required.)
5. The ac galvanometer and separately excited dynamometer are phase selective, and are best suited at low frequencies. They have a high sensitivity.
6. In many cases, especially in bridges for routine use, a pointer instrument is used. It is advantageous if it can be made phase selective.

   These pointer instruments are generally moving coil milliammeters operated with some arrangement of copper oxide rectifiers (frequency range 40 Hz – 1 kHz).
7. Modern bridge techniques employ the amplifier as a regular feature.
8. At frequencies above about 3 kHz, and particularly at high AF or RF, a heterodyne or beat-tone detector is used.
9. With all detectors, the impedance should be selected to suit that of the bridge. A higher sensitivity can be obtained by using an interbridge transformer. Also, when headphones are used as detectors, precautions should be taken to eliminate capacitance effects between the observer and the headphones.
10. A moving magnet vibration galvanometer has a range of up to 1500 Hz.
11. An electrodynamometer can also be used as an ac detector.
12. Electrometers are used as detector because small capacitances possess a very large impedance when used with ac circuits at low frequency, and when measured in the bridge they form a high impedance branch. Hence, this detector is used to increase sensitivity.

PRECAUTIONS TO BE TAKEN WHEN USING A BRIDGE 11.23

Assuming that a suitable method of measurement has been selected and that the source and detector are given, there are some precautions which must be observed to obtain accurate readings.

The leads should be carefully laid out in such a way that no loops or long lengths enclosing magnetic flux are produced, with consequent stray inductance errors.

With a large L, the self-capacitance of the leads is more important than their inductance, so they should be spaced relatively far apart.

In measuring a capacitor, it is important to keep the lead capacitance as low as possible. For this reason the leads should not be too close together and should be made of fine wire.

In very precise inductive and capacitances measurements, leads are encased in metal tubes to shield them from mutual electromagnetic action, and are used or designed to completely shield the bridge.

Review Questions

1. What is a bridge.? What is the importance of a bridge?
2. Explain with diagram the operation of a Wheatstone bridge.
3. What is the criteria for balance of a Wheatstone bridge?
4. State the limitations of a Wheatstone bridge. How is it overcome?
5. Explain with a diagram the working of a unbalanced Wheatstone bridge.
6. Explain with a diagram the working principle of Kelvin's bridge.
7. Describe with diagram the operation of Kelvin's bridge.
8. How does the basic circuit of Kelvin's bridge differ from that of a Wheatstone bridge.
9. Derive the balance condition for a basic Kelvin's bridge.
10. Draw and explain a practical Kelvin's double bridge.
11. List and discuss the principle applications of a Kelvin's bridge.
12. Explain with a diagram how a bridge be used as an error detector.
13. Explain with a block diagram the working of a digital readout bridge.
14. How does the use of microprocessors are useful in bridge circuits?
15. Explain the operation of a microprocessor controlled bridge.
16. Describe how a Wheatstone bridge may be used to control various physical parameters.
17. Define the term 'null' as applied to bridge measurement.
18. What are some methods by which microprocessors are reducing the cost and complexity of analog measurements?
19. Explain with diagram a basic ac bridge.
20. Compare dc and ac bridges.
21. List various detectors used for ac measurements.
22. State the two conditions that must be satisfied to obtain bridge balance.
23. Describe how a similar angle bridge (comparison bridge) differs from a Wheatstone bridge.
24. Draw and derive the balance condition for a capacitance comparison bridge.
25. Draw and derive the balance condition for an inductance comparison bridge.
26. Explain with a diagram how Maxwell's bridge can be used to measure unknown inductance.
27. Draw the circuit diagram and obtain balance conditions for Maxwell's bridge. State the limitation of a Maxwell's bridge.
28. Draw the circuit diagram and obtain balance conditions for Hay's bridge.
29. Compare Maxwell's bridge and Hay's bridge.
30. Explain with a diagram how Schering's bridge can be used to measure unknown capacitance.
31. Draw the circuit diagram and obtain balance conditions for Schering's bridge.

32. Explain how dissipation factor of a capacitor can be measured.
33. Explain Wien's bridge with a diagram.
34. State and derive the two balance conditions for a Wien bridge.
35. How can a Wien bridge be used to measure frequency?
36. Explain with a diagram the working of a Maxwell Wien bridge.
37. Draw the circuit and derive the condition of balance for a Maxwell–Wien bridge.
38. Explain with a diagram the working of an Anderson bridge.
39. Draw the circuit and obtain the balance condition of an Anderson bridge.
40. Compare Maxwell–Wien bridge with that of an Anderson bridge.
41. Explain with a diagram the working of Owen's bridge.
42. Draw the circuit and obtain the balance condition of an Owen's bridge.
43. Compare Anderson bridge and Owen's bridge.
44. Explain with a diagram the operation of a De Sauty bridge.
45. Draw the circuit and obtain the balance condition of a De Sauty bridge.
46. Compare Schering bridge with De Sauty bridge.
47. What do you mean by Wagner's ground connection? What is its significance?
48. Explain with a diagram the working of a Wagner's ground connection.
49. Explain how stray capacitances can be eliminated using Wagner's ground connection.
50. Explain Resonance Bridge with a diagram.
51. Derive the balance conditions for a resonance bridge.

Multiple Choice Questions

1. A basic bridge consists of
   (a) two arms (b) three arms
   (c) four arms (d) single arm
2. Wheatsone bridge is used to measure
   (a) voltage (b) current
   (c) power (d) resistance
3. Kelvin's bridge is used to measure
   (a) voltage (b) current
   (c) power (d) resistance
4. An ac bridge uses a detector in the form of
   (a) ammeter (b) voltmeter
   (c) headphones (d) wattmeter
5. Maxwell's bridge is used to measure unknown
   (a) inductance (b) capacitance
   (c) resistance (d) Q
6. Maxwell's bridge is used to measure Q factor in the range
   (a) 1–10 (b) 30–50
   (c) 50–75 (d) 75–100
7. Hay's bridge is used to measure an inductance of
   (a) low Q (b) medium Q
   (c) high Q (d) very high Q
8. Schering bridge is used to measure unknown
   (a) inductance (b) capacitance
   (c) resistance (d) frequency
9. Schering bridge is also used to measure
   (a) Q factor
   (b) dissipation factor
   (c) resistance
   (d) frequency
10. Wien bridge in its basic form is used to measure unknown
    (a) inductance (b) capacitance
    (c) resistance (d) frequency
11. Anderson bridge is used to measure unknown
    (a) inductance (b) capacitance
    (c) resistance (d) frequency

12. To measure precise inductance from a few μH to several henries, the following bridge is used.
(a) Maxwell's (b) Hay
(c) Maxwell–Wien (d) Anderson

13. Wagner's ground is used to
(a) eliminate stray capacitances
(b) measure capacitance
(c) measure resistance
(d) measure inductance

Practice Problems

1. Calculate the value of R_x in a Wheatstone bridge if
(i) $R_1 = 400\ \Omega$, $R_2 = 5$ k, $R_3 = 2$ k
(ii) $R_1 = 10$ k, $R_2 = 40$ k, $R_3 = 15.5$ k
(iii) $R_1 = 5$ k, $R_2 = 40$ k, $R_3 = 10\ \Omega$
2. What resistance range must resistor R_3 have in order to measure unknown resistor in the range 1 – 100 kΩ using a Wheatstone bridge? Given $R_1 = 1$ k and $R_2 = 10$ k.
3. Calculate the value of R_x in Fig. Ex. 11.12, $R_a = 1600\ R_b$, $R_1 = 800\ R_b$ and $R_1 = 1.25\ R_2$.
4. Calculate the current through the galvanometer in the circuit diagram of Fig. 11.36.

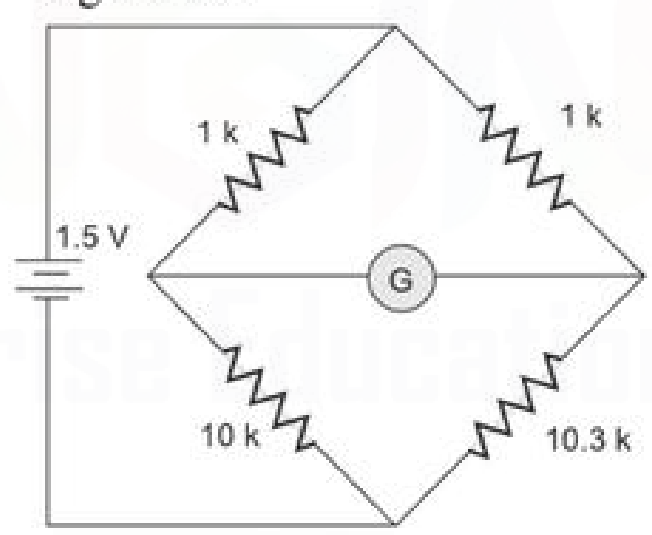


Fig. 11.36

5. If the sensitivity of the galvanometer in the circuit of Fig. 11.37 is 10 mm/μA, determine its deflection.

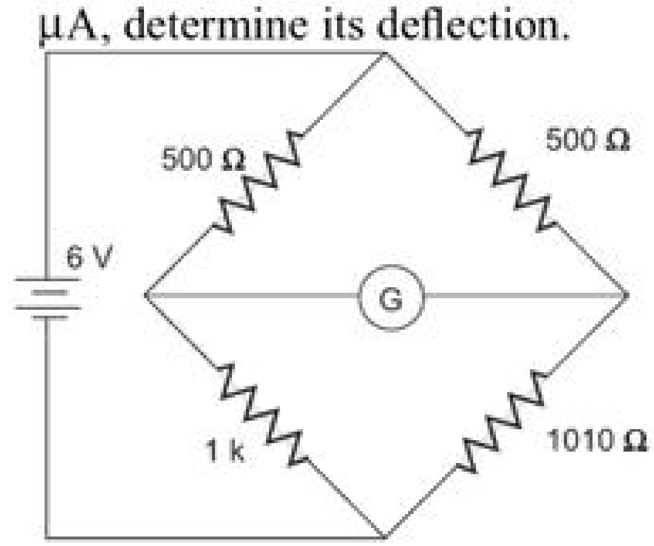


Fig. 11.37

6. A balanced ac bridge has the following constants.
Arm AB – R = 1 k in parallel with C = 0.047 μF
Arm BC – R = 2 k in series with C = 0.047 μF
Arm DC – unknown
Arm DA – C = 0.25 μF.
The frequency of the oscillator is 1 kHz. Determine the constants of arm CD.
7. A bridge is balanced at a frequency of 1 kHz and has the following constants.
Arm AB – 0.2 μF pure capacitor
Arm BC – 500 Ω pure resistance
Arm CD – unknown
Arm DA – R = 600 Ω in parallel with C = 0.1 μF.
Derive the balance condition and find the constants of arm CD, considered as a series circuit.
8. A 1000 Hz bridge has the following constants
Arm AB – R = 1 k in parallel with C = 0.25 μF
Arm BC – R = 1 k in series with C = 0.25 μF
Arm CD – L = 50 mH in series with R = 200 Ω
Arm DA – unknown
Find the constants of arm DA to balance the bridge.
Express the result as a pure R in series with a pure C or L, and as a pure R in parallel with a pure C or L.
9. An ac bridge has the following constants.
Arm AB – a pure capacitor C = 0.2 μF

Arm BC – a pure resistance $R = 500\ \Omega$

Arm CD a series combination of $R = 50\ \Omega$ and $L = 0.1$ H

Arm DA a capacitor $C = 0.5\ \mu F$ in series with a resistance R_s

If $\omega = 2000$ rad/s

(i) Find the value of R_s to obtain bridge balance.

(ii) Can complete balance be obtained by the adjustment of R_s?
If not, specify the position and value of an adjustable resistance to complete the balance.

10. A Maxwell–Wien bridge consists of the following:
Arm AB having resistance value of 1.2 kΩ in parallel with a capacitor of 1 μF
Arm BC having resistance value of 500 Ω
Arm AD having resistance value of 300 Ω
Arm BD having resistance and inductance in series.
Determine the value of the unknown resistance and unknown inductance.

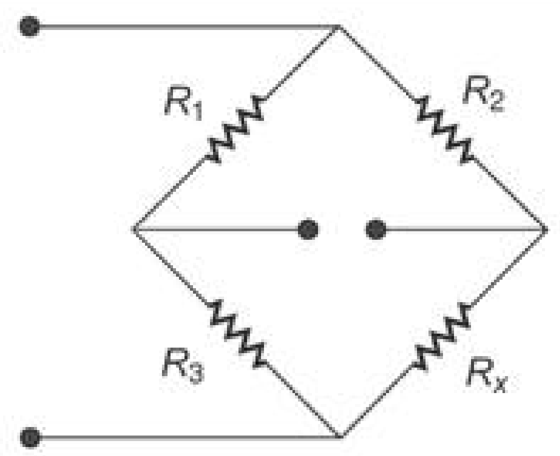
11. An Anderson's bridge consists of the following:
Arm AD having resistance value of 500 Ω
Arm CD having a resistance of 1000 Ω
Arm ED having a resistance of 600 Ω
Arm EC having a capacitor of 0.5 μF
Arm BC having resistance value of 300 Ω
Arm AB having resistance and inductance in series.
Determine the value of the unknown resistance and unknown inductance.

12. A Owen's bridge consists of the following:
Arm AB having a capacitor of 0.5 μF
Arm BC having resistance value of 600 Ω
Arm AD having resistance value of 300 Ω in series with a capacitor 0.75 μF
Arm BD having resistance and inductance in series
Determine the value of the unknown resistance and unknown inductance:

13. A De Sauty bridge consists of the following:
Arm AB having a resistance of 1 kΩ,
Arm BC having a capacitor value of 0.75 μF
Arm AD having resistance value of 300 Ω
Arm BD having unknown capacitor
Determine the value of the unknown capacitor.

Bridge Arrangements (Summary)

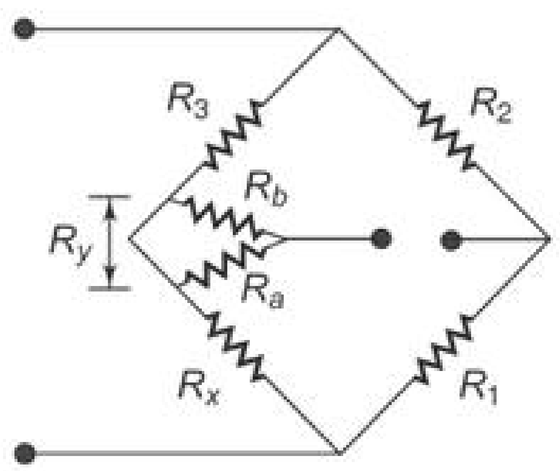
A. Resistance Measurement



Wheatstone's Bridge

$$R_x = \frac{R_2 R_3}{R_1}$$

Universally used circuit for resistance measurement. It can be used to make measurements from 1 Ω to 1 MΩ with an accuracy of ± 0.25%.



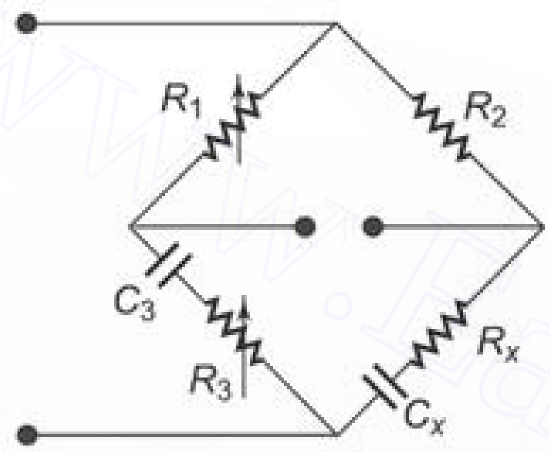
Kelvin's Double Bridge

$$R_x = \frac{R_1 R_3}{R_2}$$

Used for measuring small resistances as low as 0.001 Ω with an accuracy of ± 2%.

Fig. 11.31 (a)

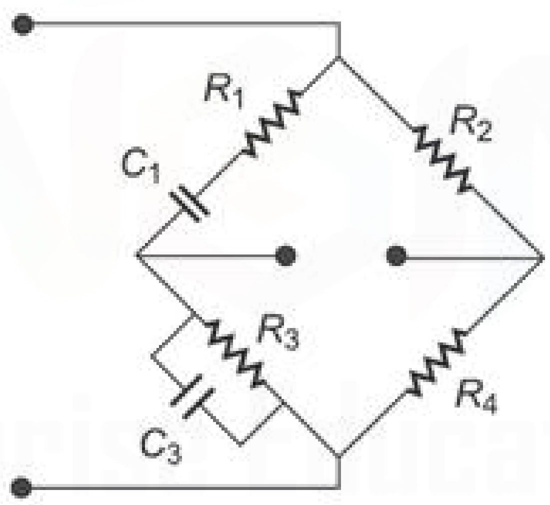
B. Capacitance Measurement



Capacitance Comparison

$$R_x = \frac{R_2 R_3}{R_1}$$

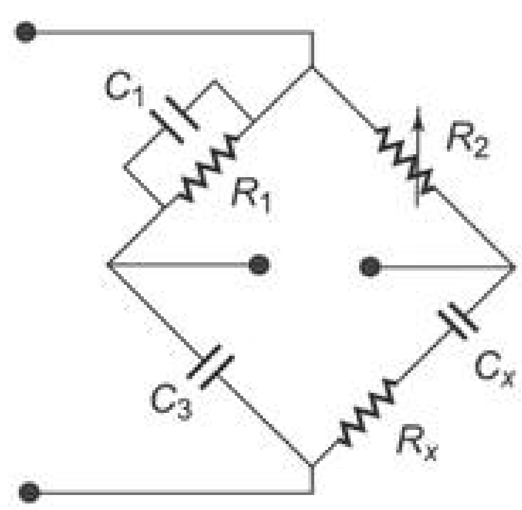
Used to measure unknown $C_x = \dfrac{C_3 R_1}{R_2}$ capacitances with reference to a standard capacitor. A fixed resistance ratio and variable standards are used. Balance is obtained by alternately varying C_3 and R_1.



Wien's Bridge

$$C_3 = \left(\frac{R_2}{R_4} - \frac{R_1}{R_3}\right) C_1$$

Used to measure capacitance to a high degree of accuracy when frequency and resistance standards are employed.



Schering's Bridge

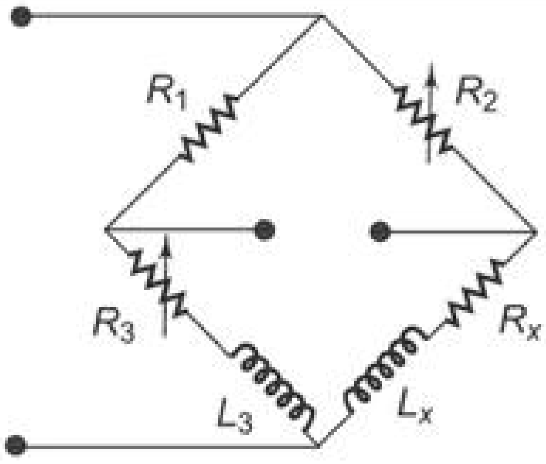
$$R_x = \frac{R_2 C_1}{C_3}$$

$$C_x = \frac{R_1 C_3}{R_2}$$

Most widely used bridge for capacitance measurements. Used for measurements of capacitance in the range of 100 pf – 1 μF, with an accuracy of ± 0.2%.

Fig. 11.31 (b)

C. Inductance Measurements

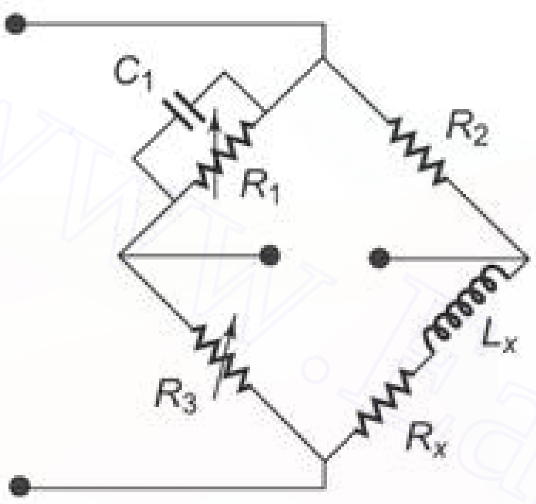


Inductance Comparison Bridge

$$R_x = \frac{R_2 R_3}{R_1}$$

$$L_x = \frac{L_3 R_2}{R_1}$$

Used to measure unknown inductances with reference to a standard inductor. A fixed resistance ratio and variable standards are used. Balance is obtained by alternately varying L_3 and R_3.

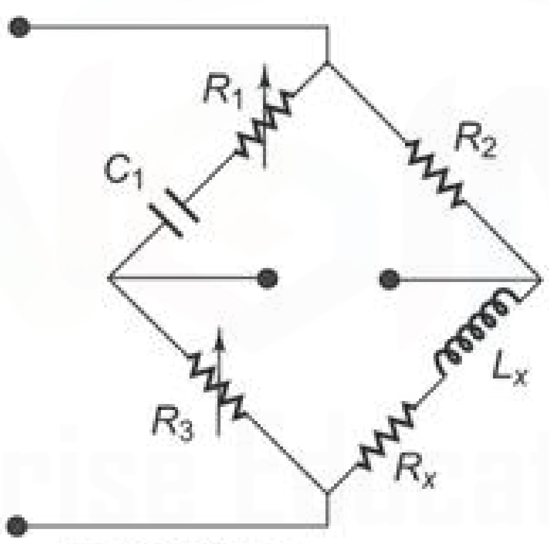


Maxwell's Bridge

$$R_x = \frac{R_2 R_3}{R_1}$$

$$L_x = C_1 R_2 R_3$$
$$Q = \omega C_1 R_1$$

Most widely used for Inductance measurements of low Q. Best suited for inductance measurement, since comparison with a capacitor is more ideal than with an inductor. It can measure from 1 μH to 1000 H with a ± 2% error (for $Q < 10$).



Hay's Bridge

$$R_x = \frac{R_2 R_3}{R_1[1+Q^2]}$$

$$L_x = \frac{R_2 R_3 C_1}{[1+1/Q^2]}$$

$$Q = \frac{1}{\omega R_1 C_1}$$

Mostly used for measurement of high Q (>10) coils. Not used for low Q, since the measurement depends on Q. It can measure from 1 μH to 100 H with a ± 2% error.

Fig. 11.31 (c)

Further Reading

1. B. Haque, *A.C. Bridges Methods*, Sir Issac Pitman & Sons, 1942.
2. Philco Technological Centre, *Electronic Precision Measurement Techniques and Experiment.*
3. *Handbook of Electronic Measurements*, Vols. I & II, Polytechnic Institute of Brooklyn; 1956. (Microwave Research Institute)
4. Larry D. Jones and A. Foster Chin, *Electronic Instruments and Measurements*, John Wiley & Sons, 1987.

Chapter 12

Recorders

INTRODUCTION 12.1

A recorder is a measuring instrument that displays a time-varying signal in a form easy to examine, even after the original signal has ceased to exist.

Recorders generally provide a graphic recod of variations in the quantity being measured, as well as an easily visible scale on which the indication is displayed.

The variety of recording instruments in the central monitoring and control stations of many industrial and utility plants is proof of their importance in industrial work. They provide a continuous, written record of the changes taking place in the quantity being measured. This chart record may be scaled off in electrical values (mV/mA) or in terms of some non-electrical quantity, such as temperature or pressure.

Many recording instruments include an additional provision for some sort of controlling action. If the control function is the primary one, the measuring instrument is called a controller.

The recorder usually provides an instantaneous indication for monitoring at the same time as it makes a graphic record.

Electronic recording instruments may be divided into three groups.

The easiest type is simply a meter having an indicating needle and a writing pen attached to the needle. If a strip of paper is pulled at a constant velocity under the writing pen (at a 90° angle to the direction of pen motion), the moving pen plots the time function of the signal applied to the meter. A highly special designed D'Arsonval movement is used to drive the writing pen. This type is called a *galvanometer recorder*.

Another recorder is the null or *potentiometric recorder*, operating on a self-balancing comparison basis by servomotor action. This recorder is basically a voltage responsive positional servo system using a motor to move a writing device back and forth across a piece of paper. The servo system can be made extremely accurate, rugged and powerful.

The *magnetic recorder* is the third type. In it, a thin magnetic tape or wire, is magnetised in accordance with a varying signal as the tape passes rapidly across a magnetic recording head. The frequency response of magnetic recorders can extend from 0 Hz to a few kHz to nearly 10 MHz. Because of the wide bandwidth of tape recorders, several modes of recording (direct, FM and digital) can be used.

There are two types of recording devices, (i) Analog, and (ii) Digital. Analog recorders may be (i) graphic or (ii) magnetic. Graphic recorders are devices which display and store a pen and ink record of some physical quantity. They are of three types (i) strip chart recorder, (ii) circular chart recorder, and an (iii) X-Y recorder. These and other types of recorders are discussed in detail in the following sections.

STRIP CHART RECORDER 12.2

Strip chart recorders are those in which data is recorded on a continuous roll of chart paper moving at a constant speed. The recorder records the variation of one or more variables with respect to time. The basic element of a strip chart recorder consists of a pen (stylus) used for making marks on a movable paper, a pen (stylus) driving system, a vertically moving long roll of chart paper and chart paper drive mechanism and a chart speed selector switch, (as shown in Fig. 12.1(a)).

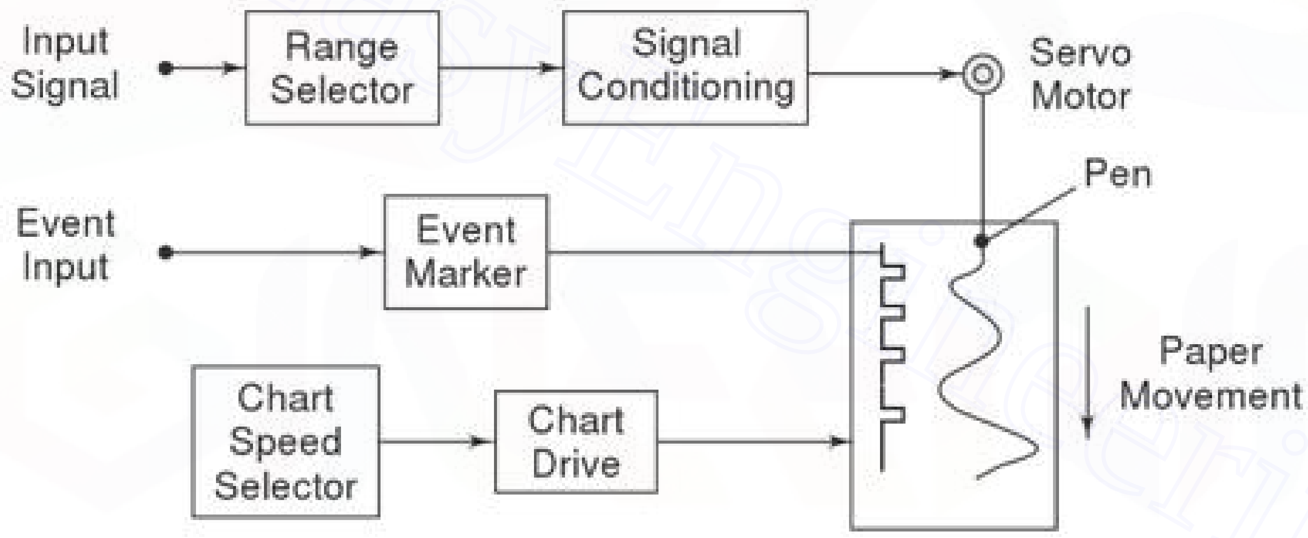


Fig. 12.1 (a) Basic strip chart recorder

Most recorders use a pointer attached to the stylus, so that the instantaneous value of the quantity being recorded can be measured directly on a calibrated scale. The assembly of a strip chart recorder is shown in Fig. 12.1(b). This recorder uses a single pen and is servo driven.

Most strip chart recorders use a servo feedback system, to ensure that the displacement of the pen (stylus) across the paper tracks the input voltage in the required frequency range.

A potentiometer system is generally used to measure the position of the writing head (stylus).

The chart paper drive system generally consists of a stepping motor which controls the movement of the chart paper at a uniform rate.

The data on the strip chart paper can be recorded by various methods.

1. Pen and Ink Stylus The ink is supplied to the stylus from a refillable reservoir by capillary action. Modern technology has replaced these pens by disposable fibre tip pens. In addition, multichannel operation can be performed, i.e. at any instant, a maximum of six pens can be used to record data. When using multiple pens, staggering of the pens are necessary to avoid mechanical interference.

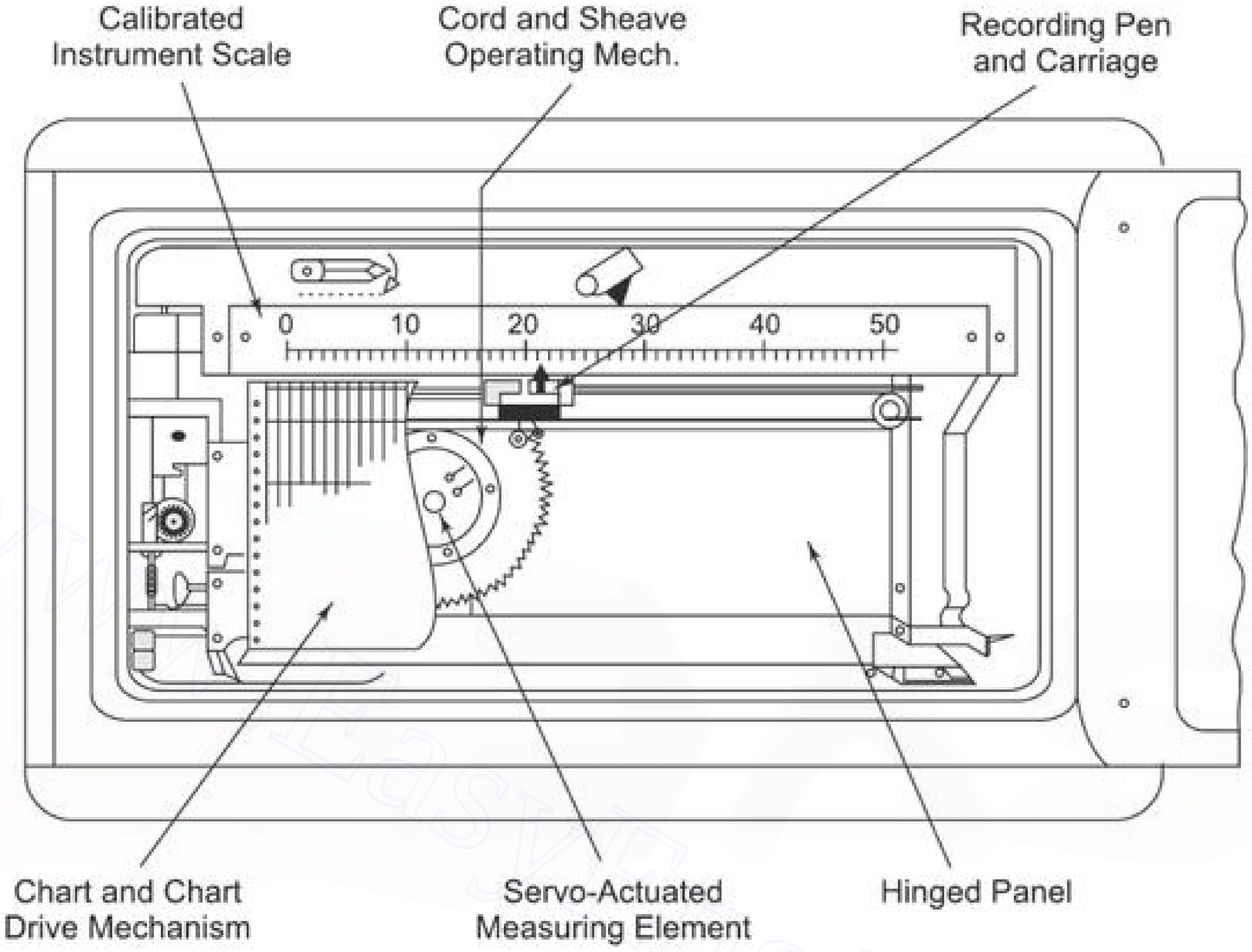


Fig. 12.1 (b) Assembly of a single pen servo operated strip chart recorder

2. Impact Printing The original impact system consisted of a carbon ribbon placed between the pointer mechanism and paper, which provided the ink for recording data. The mark was made on the paper by pressing the pointer mechanism on it. The advantage of impact printing over the pen and ink method is that, it can record data on up to 20 variables simultaneously. This is achieved with the help of a wheel with an associated ink pad which provides the ink for the symbol on the wheel. The wheel is moved across the paper in response to the variable being recorded.

In some mechanisms, pressure sensitive paper is used. The markings on the paper are done with chopper bar, which applies the pressure on the paper. The frequency of the chopper bar is once per second.

3. Thermal Writing In this system, a special movable pen which is thermally heated by passing an electric current through it is used. This system requires a thermally sensitive paper which changes its colour on application of heat.

4. Electric Writing This technique is based on the principle of electrostatics.

In this method, a special chart paper is used. This paper consists of a paper base coated with a layer of coloured dye (black, blue or red), which in turn is coated with a thin surface of aluminium.

The stylus (pen) consists of a tungsten wire moving over the aluminium surface. Markings on the paper are achieved by applying a potential of 35 V to the stylus. This causes an electric discharge which removes the aluminium, revealing the coloured dye.

5. Optical Writing In this technique of writing, a special photo sensitive chart paper, sensitive to ultra violet light is used. This technique is mostly used in galvanometer system.

Ultra violet light is used to reduce unwanted effects from ambient light. The paper can be developed in daylight or under artificial light without the need for special chemicals, which is not possible if ordinary light is used.

Most recorders use a pointer attached to the stylus. This pointer moves over a calibrated scale giving the instantaneous value of the quantity being recorded.

(a) *Paper drive system* The paper drive system should move the paper at a uniform speed. A spring wound mechanism may be used in most recorders. A synchronous motor is used for driving the paper.

(b) *Chart speed* Chart speed is a term used to express the rate at which the recording paper in a strip chart recorder moves. It is expressed in in/s or mm/s and is determined by mechanical gear trains. If the chart speed is known, the period of the recorded signal can be calculated as

$$\text{Period} = \frac{\text{time}}{\text{cycle}} = \frac{\text{time base}}{\text{chart speed}}$$

and frequency can be determined as $f = 1/\text{period}$.

Example 12.1 *The chart speed of a recording instrument is 40 mm/s. One cycle of the signal is recorded over 5 mm (this is referred to sometimes as the time base). Determine the frequency of the signal.*

Solution

$$\text{Period} = \frac{\text{time}}{\text{cycle}} = \frac{\text{time base}}{\text{chart speed}} = \frac{5\ \text{mm/cycle}}{40\ \text{mm/s}} = \frac{5\ \text{mm}}{\text{cycle}} \times \frac{\text{s}}{40\ \text{mm}}$$

Therefore, period = 5/40 s/cycle = 1/8 s/cycle = 0.125 s/cycle and frequency $f = 1/\text{period} = 1/0.125$ s/cycle = 8 cycles/s.

Example 12.2 *If the frequency of a signal to be recorded with a strip-chart recorder is 20 Hz, what must be the chart speed used to record one complete cycle on 5 mm of recording paper?*

Solution Given frequency = 20 Hz and time base = 5 mm

Period = 1/frequency = 1/20 = 0.05 s

$$\text{Period} = \frac{\text{time base}}{\text{chart speed}}, \quad \text{therefore} \quad 0.05 = \frac{5\ \text{mm/cycle}}{\text{chart speed}}$$

$$\text{Chart speed} = \frac{5\ \text{mm}}{\text{cycle}} \times \frac{1}{0.05\ \text{s/cycle}}$$

$$= \frac{5 \times 100}{5}\ \text{mm/s} = 100\ \text{mm/s}$$

There are basically two types of strip chart recorders, the (i) galvanometer type, and the (ii) null type (potentiometric).

GALVANOMETER TYPE RECORDER 12.3

The D'Arsonval movement used in moving coil indicating instruments can also provide the movement in a galvanometer recorder.

The D'Arsonval movement consists of a moving coil placed in a strong magnetic field, as shown in Fig. 12.2(a).

In a galvanometer type recorder, the pointer of the D'Arsonval movement is fitted with a pen-ink (stylus) mechanism.

The pointer deflects when current flows through the moving coil. The deflection of the pointer is directly proportional to the magnitude of the current flowing through the coil.

As the signal current flows through the coil, the magnetic field of the coil varies in intensity in accordance with the signal. The reaction of this field with the field of the permanent magnet causes the coil to change its angular position. As the position of the coil follows the variation of the signal current being recorded, the pen is accordingly deflected across the paper chart.

The paper is pulled from a supply roll by a motor driven transport mechanism. Thus, as the paper moves past the pen and as the pen is deflected, the signal waveform is traced on the paper.

The recording pen is connected to an ink reservoir through a narrow bore tube. Gravity and capillary action establish a flow of ink from the reservoir through the tubing and into the hollow of the pen.

Galvanometer type recorders are well suited for low frequency ac inputs obtained from quantities varying slowly at frequencies of upto 100 c/s, or in special cases up to 1000 c/s.

Because of the compact nature of the galvanometer unit (or pen motor) this type of recorder is particularly suitable for multiple channel operation. Hence it finds extensive use in the simultaneous recording of a large number of varying transducers outputs.

This recorder uses a curvilinear system of tracing. The time lines on the chart must be arcs of radius R (where R is the length of the pointer), and the galvanometer shaft must be located exactly at the center of curvature of a time line arc. Improper positioning of the galvanometer or misalignment of the chart paper in the recorder can give a distorted response, i.e. having a negative rise time or a long rise time. One method of avoiding the distorted appearance of recordings in curvilinear coordinates is to produce the recording in rectangular coordinates. In this design, the chart paper is pulled over a sharp edge that defines the locus of the point of contact between the paper and the recording stylus. The stylus is rigidly attached to the galvanometer coil and wipes over the sharp edge as the coil rotates.

In one of the recorders, the paper used is usually heat sensitive, and the stylus is equipped with a heated tip long enough to guarantee a hot point of contact with the paper, regardless of the stylus position on the chart. Alternatively the paper can be electrically sensitive, in which case the stylus tip would serve to carry current into the paper at the point of contact.

The recorders can work on ranges ranging from a few mA/mV to several mA/mV. These moving galvanometer type recorders are comparatively inexpensive instruments, having a narrow bandwidth of 0 – 10 Hz. They have a sensitivity of about 0.4 V/mm, or from a chart of 100 mm width a full scale deflection of 40 mV is obtained.

In most instruments, the speed of the paper through the recorder is determined by the gear ratio of the driving mechanism. If it is desired to change the speed of the paper, one or more gears must be changed.

Paper speed is an important consideration for several reasons.

1. If the paper moves too slowly, the recorded signal variations are bunched up and difficult to read.
2. If the paper moves too fast, the recorded waveform will be so spread out that greater lengths of paper will be required to record the variations of the signal. It also makes the task of reading and interpreting the waveforms more difficult.
3. Also, the operator can determine the frequency components of the recorded waveform, if he knows how fast the paper has moved past the pen position. The paper is usually printed with coordinates, such as graph paper.

Some recorders contain a timing mechanism that prints a series of small dots along the edge of the paper chart, as the paper moves through the recorder. This time marker produces one mark per second.

These types of recorders are mostly used as optical recorders, and contain a light source provided by either an ultra violet or tungsten lamp.

A small mirror is connected to the galvanometer movement and the light beam is focussed on this mirror, as shown in Fig. 12.2(b).

The beam reflected from the mirror is focussed into a spot on a light sensitive paper.

As the current passes through the coil, the mirror deflects. The movement of the light beam is affected by the deflection of the small mirror, and the spot on the paper also varies for the same reason, thus tracing the waveform on the paper.

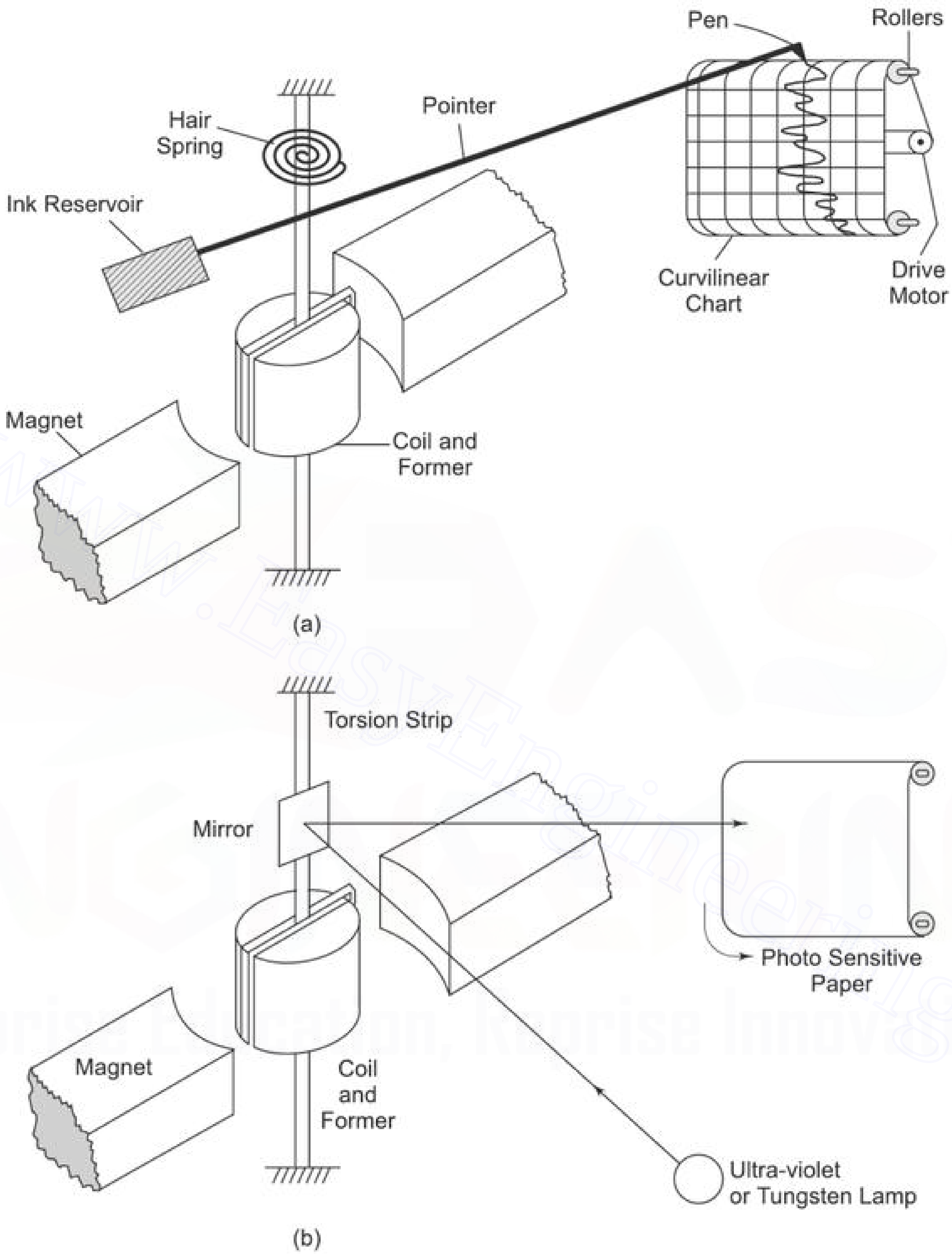


Fig. 12.2 (a) Galvanometer type recorder (b) Optical galvanometer recorder

NULL TYPE RECORDER (POTENTIOMETRIC RECORDERS) 12.4

These recorders work on the principle of self-balancing or null conditions.

When an input is given to the measuring circuit of the recorder from a sensor or transducer, it upsets the balance of the measuring circuit, producing an error voltage which operates some other device, which in turn restores the balance or brings the system to null conditions.

The magnitude of the error signal indicates the amount of movement of this balance restoring device and the direction of the movement indicates the direction of the quantity being measured. The different types of null recorders are as follows:

1. Potentiometric recorders
2. Bridge recorders
3. LVDT recorders (Linear Variable Differential Transformer)

12.4.1 Potentiometric Recorders

The basic disadvantage of a galvanometer type recorder is that is has a low input impedance and a limited sensitivity.

This disadvantage can be overcome by using an amplifier between the input terminals and the display or indicating instruments. This amplifier provides a high input impedance and improved sensitivity at the cost of low accuracy.

To improve the accuracy of the instrument, the input signal is compared with a reference voltage using a poteniometer circuit.

The self-balancing feature is obtained with a servo motor, a motor whose speed and direction of rotation follows the output of an amplifier. In a dc system, this is simply a reversible motor, such as the type that uses a permanent magnet for its field. In the ac system, it takes the form of a two-phase motor.

Figure 12.3 is a basic circuit of a potentiometric or self-balancing recorder.

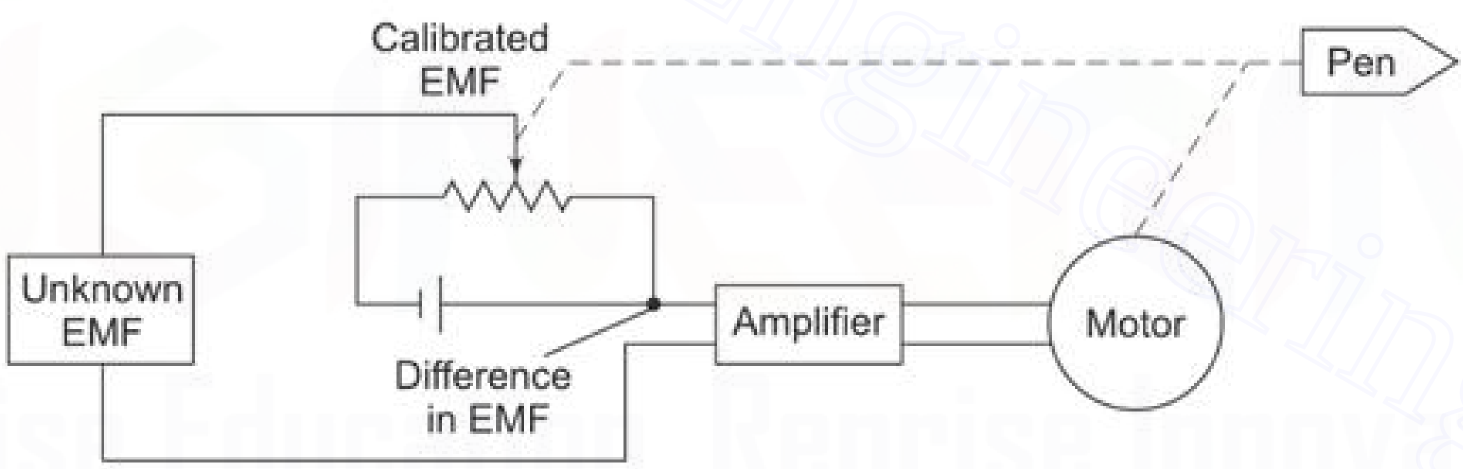


Fig. 12.3 Basic circuit of a self-balancing or potentiometric recorder

The difference between the input signal and the potentiometer voltage is the error signal. This error signal is amplified and is used to energize the field coil of a dc motor. In this circuit, instead of obtaining a balance between two opposing voltages by rotating the arm of the voltage divider, an error current is allowed to flow, either clockwise or counter clockwise, depending on which voltage is higher. This error serves as the input to the electronic detector, and the amplified error is then fed to the balancing motor. This motor is so connected that it turns in a direction that rotates the voltage divider arm (geared) to it in the direction that reduces the error. As the error becomes smaller, the motor slows down and finally stops at the point where the error is zero, thus producing the null balance.

This is achieved by mechanically connecting the wiper/variable arm to the armature of the dc motor. The pen is also mechanically connected to the wiper. Hence as the wiper moves in a particular direction, the pen also moves in synchronism in the same direction, thereby recording the input waveform. The wiper comes to rest when the unknown signal voltage is balanced against the voltage of the potentiometer. This technique results in graphical recorders having a very high input impedance.

A sensitivity of 4 V/mm is attained with an error of less than ± 0.25% with a bandwidth of 0.8 Hz.

A motor synchronised to power line frequency is used to drive the chart drive for most potentiometer recorders.

Hence the speeds of the chart drive can be changed by the use of a gear train which uses different gear ratios.

Potentiometer recorders are mostly used for the recording and control of process temperature.

Figure 12.4 is the basic block diagram of a dc self balancing system. Instrument that record changes of only one measured variable are called single point recorders.

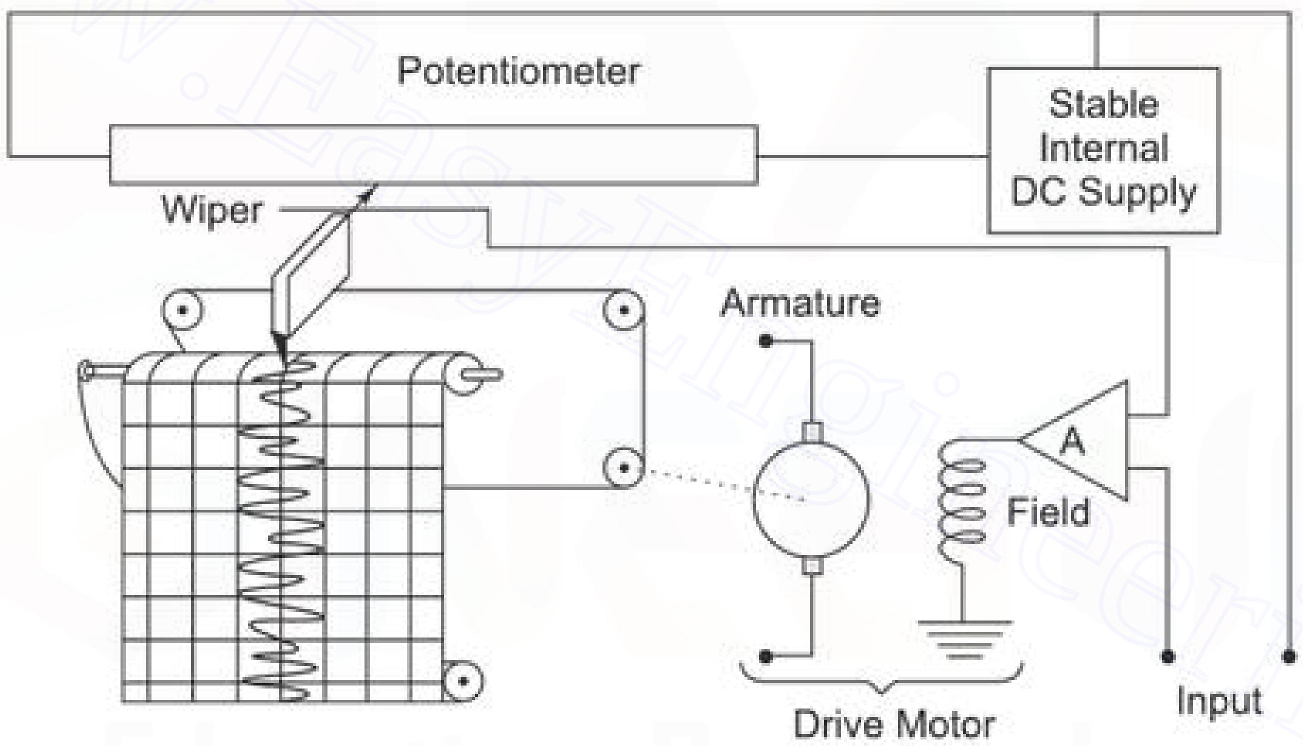


Fig. 12.4 Block diagram of self-balancing potentiometer recorder

Multipoint recorders are those in which one recorder may be used for recording several inputs. These may have as many as 24 inputs, with traces displayed in six colours. The data is recorded on an 8 inch chart, at frequencies from dc to 5 kHz, models up to 36 channels are also available.

12.4.2 Bridge Type Recorders

When a non-electrical quantity such as temperature is to be recorded, the transducer converts the temperature changes in to corresponding electrical variations.

If a thermistor or resistance thermometer were used as the transducer, the changes in temperature would produce variations in the resistance of the tranducer, rather than a change in voltage. In this case, the thermistor is made part of the bridge circuit, as shown in Fig. 12.5.

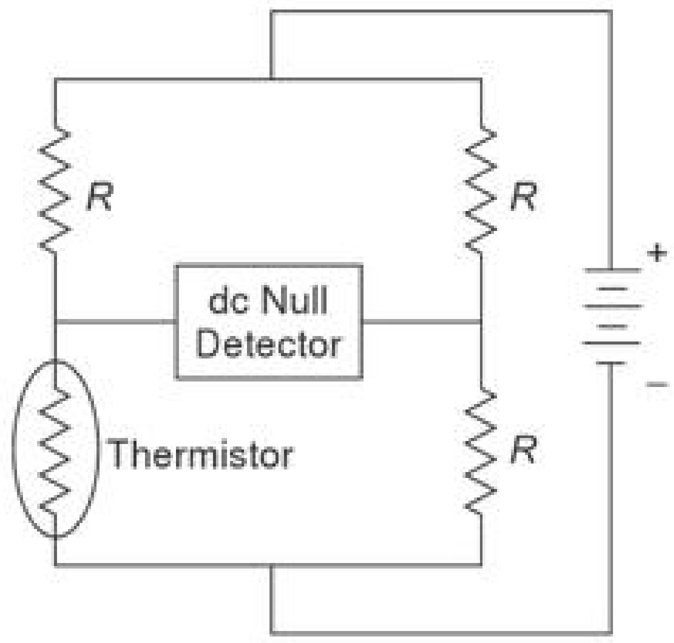


Fig. 12.5 Thermistor arranged in a dc bridge circuit

The resistance changes in the thermistor cause corresponding changes in the bridge output. These changes are applied to the detector. The bridge balance (null) can be restored by varying the resistance of another arm of the bridge, while recording in terms of current, voltage or temperature. Depending on the kind of voltage supplied to the bridge, the output can be chosen to be dc or ac.

12.4.3 Linear Servo Motor Recorder (LVDT)

Some temperature indicating and recording instruments incorporate a linear servo motor which dispenses with the conventional servo motor and error-prone gear train linkage and motor brushes. Improvement in reliability, speed of response, minimum resistance to movement and high accuracy are obtained with the use of linear servo motors.

The requirements of dc linear motor are as follows

1. It should produce motion in straight line in response to a direct current.
2. It should reverse its motion if the current polarity is reversed.
3. It should be easy to control and have a low inertia.
4. Its use and power requirements must be comparable with existing drive systems.

If two permanent magnets, parallel to one another, are fixed to a bench, a small free permanent magnet placed between them will move linearly in a direction which depend on the position of the north and south poles of the fixed magnets.

If a current is passed through a small coil, in place of the permanent magnet, the coil will move in a similar fashion but with the advantage that the direction of motion can be reversed by reversing the current flow.

Figure 12.6 indicates the simple nature of motor action.

Current flow through the coil assembly generates the motor action. The force F should be sufficient to overcome the friction in the moving parts supporting the coil, the inertia of the coil assembly, plus a suitable safety factor.

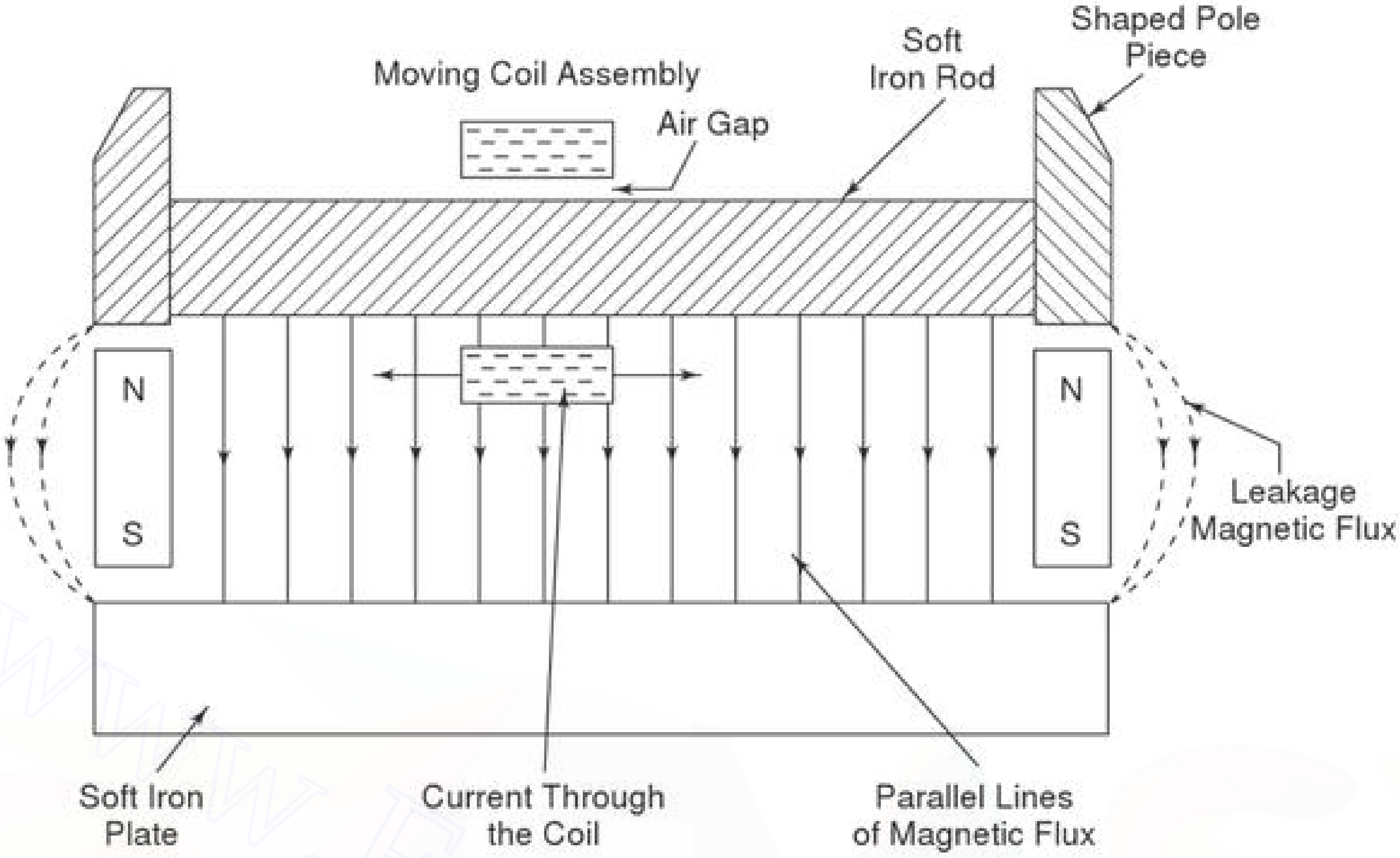


Fig. 12.6 LVDT (Basic principle)

The coil in the linear motor is supported by two small pulleys at the rear and the front with a spring affixed to the coil and resting on a slide wire. The pulleys are adjusted to maintain a clearance air gap around the rod. The scale pointer is part of the coil holder. This arrangement provides a direct drive for the scale pointer and slide wire contacts, enabling motion in straight line, which

(i) permits the use of a straight former for the slide wire, and
(ii) enables a flat scale to be used.

Ferrodynamic (LVDT) recorders are versatile instruments used for measuring and recording process variables such as pressure, vacuum, flow, level, and angle of rotation. These instruments work on the null balance principle and are used in conjunction with suitable primary transmitters (transducers), as different transformers or induction transducers. The accuracy of these instruments is of the order of ± 0.6% of full scale division. The threshold sensitivity is about ± 0.25% of span and the response time is about 6 seconds.

Principle of Operation

The instrument comprises the following main units.

1. Ferrodynamic compensating converter
2. Solid state amplifier
3. Balancing motor
4. Linkage mechanism
5. Chart drive mechanism (for recorders)

The ferrodynamic converter consists of a sturdy moving coil placed in an alternating magnet field. The magnitude and phase of the induced EMF in the moving coil depends upon the angle of rotation of the coil. A bias winding is introduced over the exciting winding, which can bodily shift the output characteristics of the ferrodynamic converter (LDVT), as shown in Fig. 12.7.

From Fig. 12.7, it can be seen that for a – 20° to + 20° rotation of the moving coil, the voltage induced varies by 2 V. By having a bias winding, it is possible to obtain signals of range – 1 V to + 1 V, 0 V to + 2 V, and + 1 V to + 3 V.

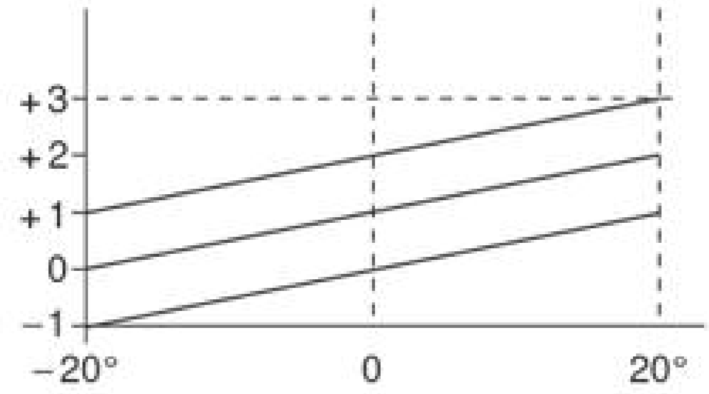


Fig. 12.7 Output characteristics of an LVDT (Ferro-dynamic converter)

The output from the primary transmitter (LVDT) is connected in phase opposition to the output from the ferrodynamic compensating converter. The resultant difference voltage, is amplified by the solid state electronic amplifier which drives the balancing motor. Through mechanical linkage, the balancing motor in turn positions the moving coil of the converter in such a way that the unbalance voltage becomes zero. The motor's output through some mechanical linkage and cam mechanism is also fed to the pointer and the pen, which moves on a scale calibrated in terms of the measured variable.

Chart Drive Mechanism

The usefulness of a recording instrument depends upon

(i) The selection of the proper chart speed, and
(ii) The selection of the suitable drive element.

The selection of chart speeds is an important factor for separating the records of specific deviation.

A drive element should be a positive drive, it should require minimum maintenance and be able to run under certain extreme ambient conditions.

CIRCULAR CHART RECORDER 12.5

As the name implies, the data is recorded on a flat circular chart. The basic assembly of a single pen circular chart recorder is shown in Fig. 12.8.

It consists of a measuring element, an operating mechanism, a chart drive, and a recording device, which may all be mounted on a single panel. The chart is usually mounted on a flat supporting plate and fastened in position by spring clips, which prevent it from curling. The measuring element could be a helical pressure tube or any other element. The operating mechanism consists of levers a and b and links c which convey motion from the measuring element to the recording device.

For optimum recording conditions, light uniform pressure, and a smooth flat chart surface must be ensured. The pen arm must be accurately fitted and locked. The chart is driven at a uniform rate by some timing device.

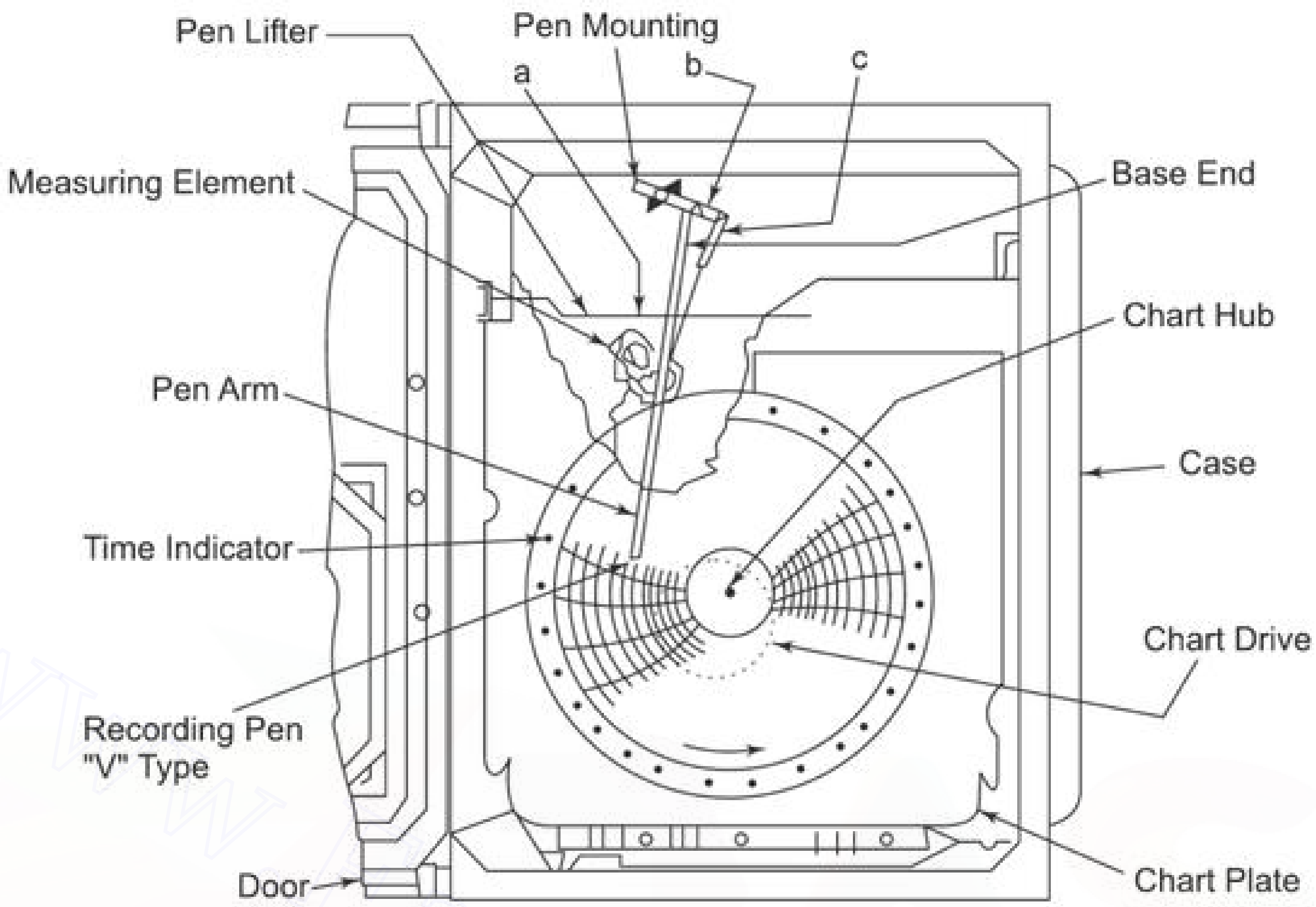


Fig. 12.8 Assembly of a single pen direct-acting circular chart recorder

Circular Chart Drive A conventional drive assembly consists essentially of a centre chart support spindle and an drive motor. The chart is generally centered and locked around the centre spindle. The chart speed may vary from one rotation in 15 minutes to one rotation in 30 days. A 30 cm circular chart has a maximum time-line length of approximately 100 cm in a revolution, whereas a 15 cm strip chart may move 25 m of chart in the same period. The various drives for circular charts are classified as follows.

1. Mechanical (spring clock drive).
2. Pneumatic (air lock drive).
3. Electric (synchronous regulated dc motor or motor wound spring).
4. Dual powered drive (duplex), i.e. a synchronous motor and spring clock mechanical drive.
5. Externally controlled drives.

X–Y RECORDER 12.6

In most research fields, it is often convenient to plot the instantaneous relationship between two variables [$Y = f(x)$], rather than to plot each variable separately as a function of time.

In such cases, the X–Y recorder is used, in which one variable is plotted against another variable.

In an analog X–Y recorder, the writing head is deflected in either the x-direction or the y-direction on a fixed graph chart paper. The graph paper used is generally squared shaped, and is held fixed by electrostatic attraction or by vacuum.

The writing head is controlled by a servo feedback system or by a self balancing potentiometer. The writing head consist of one or two pens, depending on the application.

In practice, one emf is plotted as a function of another emf in an X–Y recorder.

In some cases, the X–Y recorder is also used to plot one physical quantity (displacement, force, strain, pressure, etc.) as a function of another physical quantity, by using an appropriate transducer, which produces an output (EMF) proportional to the physical quantity.

The motion of the recording pen in both the axis is driven by servo-system, with reference to a stationary chart paper. The movement in x and y directions is obtained through a sliding pen and moving arm arrangement.

A typical block diagram of an X–Y recorder is illustrated in Fig. 12.9.

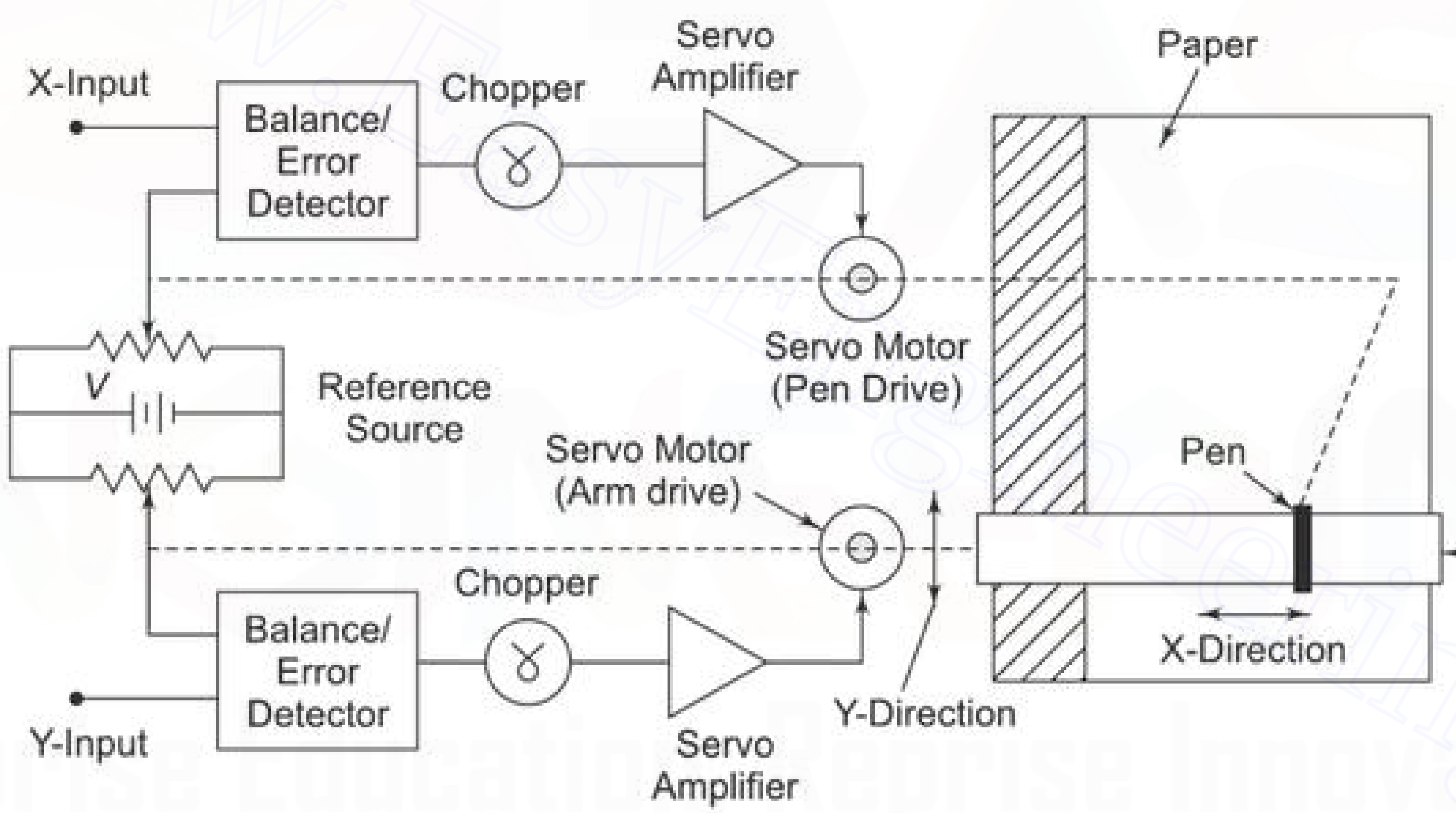


Fig. 12.9 Basic X–Y recorder

Referring to Fig. 12.9, each of the input signals is attenuated in the range of 0–5 mV, so that it can work in the dynamic range of the recorder. The balancing circuit then compares the attenuated signal to a fixed internal reference voltage. The output of the balancing circuit is a dc error signal produced by the difference between the attenuated signal and the reference voltage. This dc error signal is then converted into an ac signal with the help of a chopper circuit. This ac signal is not sufficient to drive the pen/arm drive motor, hence, it is amplified by an ac amplifier. This amplified signal (error signal) is then applied to actuate the servo motor so that the pen/arm mechanism moves in an appropriate direction in order to reduce the error, thereby bringing the system to balance. Hence as the input signal being recorded varies, the pen/arm tries to hold the system in balance, producing a record on the paper.

The action described above takes place in both the axes simultaneously. Hence a record of one physical quantity with respect to another is obtained.

Some X–Y recorders provides x and y input ranges which are continuously variable between 0.25 mV/cm and 10 V/cm, with an accuracy of ± 0.1% of the full scale. Zero offset adjustments are also provided.

The dynamic performance of X–Y recorders is specified by their slewing rate and acceleration. A very high speed X–Y recorder, capable of recording a signal up to 10 Hz at an amplitude of 2 cm peak to peak, would have a slewing rate of 97 cm/s and a peak acceleration of 7620 cm/s.

An X–Y recorder may have a sensitivity of 10 µV/mm, a slewing speed of 1.5 ms and a frequency response of about 6 Hz for both the axis. The chart size is about 250 × 180 mm. The accuracy of X–Y recorder is about ± 0.3%.

Applications of X–Y Recorders

These recorders are used to measure the following.

1. Speed-torque characteristics of motors.
2. Regulation curves of power supply.
3. Plotting characteristics of active devices such as vacuum tubes, transistors, zener diode, rectifier diodes, etc.
4. Plotting stress-strain curves, hysteresis curves, etc.
5. Electrical characteristics of materials, such as resistance versus temperature.

12.6.1 Digital X–Y Plotters

The rapid increase in the development in digital electronics has led to the replacement of analog X–Y recorders by digital X–Y plotters. The latter provide increased measurement and graphics capabilities. Digital X–Y plotters use an open loop stepping motor drive, in place of the servo motor drive used in analog X–Y recorders.

Digital measurement plotting systems provide the following features:

1. Simultaneous sampling and storage of a number of nput channels.
2. A variety of trigger modes, including the ability to display pre-triger data.
3. Multi-pen plotting of the data.
4. Annotation of the record with date, time and set up conditions.
5. An ability to draw grids and axis.

Communication with such devices can be done by means of the IEEE 488 or RS232 interface.

Graphic plotters are used to obtain hard copy from digital data input. By the use of appropriate software and hardware, these devices can draw grids, annotate charts and differentiate data by the use of different colours and line types. They are specified by their line quality, plotting speed and paper size.

MAGNETIC RECORDERS 12.7

The major advantage of using a magnetic tape recorder is that once the data is recorded, it can be replayed an almost indefinite number of times.

The recording period may vary from a few minutes to several days. Speed translation of the data captured can be provided, i.e. fast data can be slowed down and slow data speeded up by using different record and reproduce speeds.

The recorders described earlier have a poor high frequency response. Magnetic tape recorder, on the other hand, have a good response to high frequency, i.e. they can be used to record high frequency signals. Hence, magnetic tape recorders are widely used in instrumentation systems.

Basic Components of a Tape Recorder

A magnetic tape recorder consists of the following basic components.

1. Recording Head
2. Magnetic Head
3. Reproducing Head
4. Tape transport mechanism
5. Conditioning devices

Magnetic Recording The basic elements of a simple magnetic recording system are illustrated in Fig. 12.10(a).

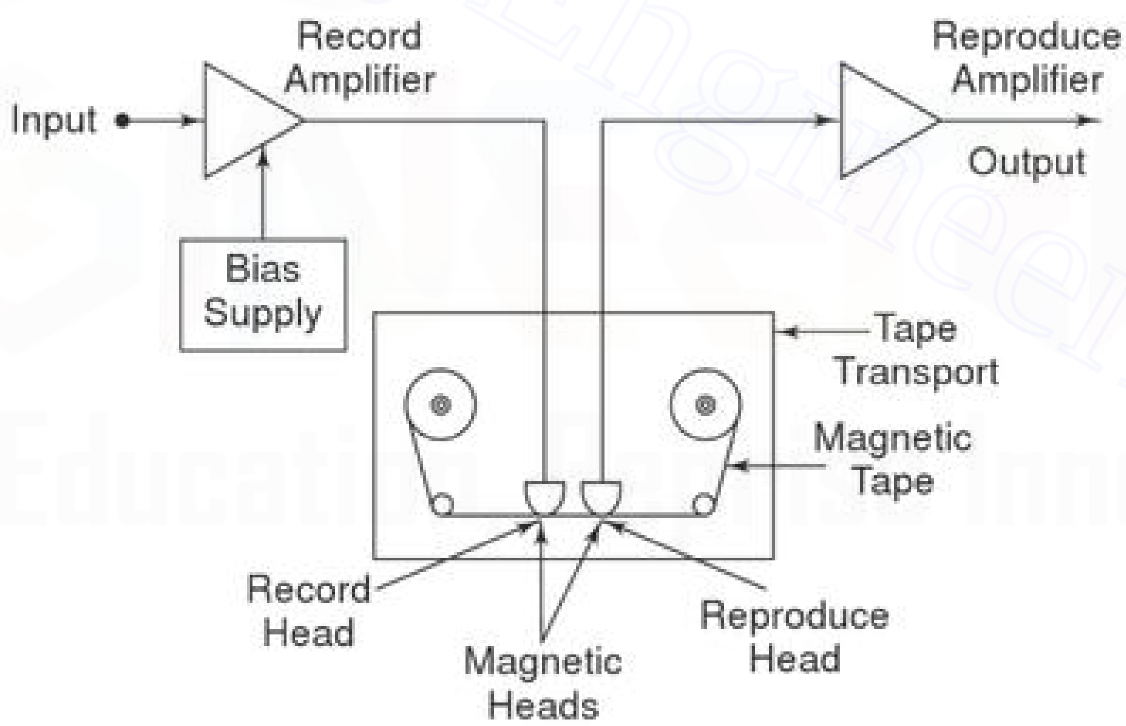


Fig. 12.10 (a) Elementary magnetic tape recorder

The magnetic tape is made of a thin sheet of tough, dimensionally stable plastic, one side of which is coated with a magnetic material.

Some form of finely powdered iron oxide is usually cemented on the plastic tape with a suitable binder. As the tape is transferred from one reel, it passes across a magnetising head that impresses a residual magnetic pattern upon it in response to an amplified input signal.

The methods employed in recording data on to the magnetic tape include direct recording, frequency modulation (FM) and pulse code modulation (PCM).

Modulation of the current in the recording head by the signal to be recorded linearly modulates the magnetic flux in the recording gap. As the tape moves under the recording head, the magnetic particles retain a state of permanent magnetisation proportional to the flux in the gap. The input signal is thus converted to a spatial variation of the magnetisation of the particles on the tape. The reproduce head detects these changes as changes in the reluctance of its magnetic circuit which induce a voltage in its winding. This voltage is proportional to the rate of change of flux. The reproduce head amplifier integrates the signal to provide a flat frequency characteristics.

Since the reproduce head generates a signal which is proportional to the rate of change of flux, the direct recording method cannot be used down to dc. The lower limit is around 100 Hz and the upper limit for direct recording, around 2 MHz. The upper frequency limit occurs when the induced variation in magnetisation varies over a distance smaller than the gap in the reproduce head.

The signal on an exposed tape can be retrieved and played out at any time by pulling the tape across the magnetic head, in which a voltage is induced.

It is possible to magnetise the tape longitudinally or along either of the other two main axis, but longitudinal magnetisation is the best choice.

Figure 12.10(b) shows simply how the tape is magnetised. If a magnetic field is applied to any one of the iron oxide particles in a tape and removed, a residual flux remains. The relationship between the residual flux and the recording field is determined by the previous state of magnetisation and by the magnetisation curves of the particular magnetic recording medium.

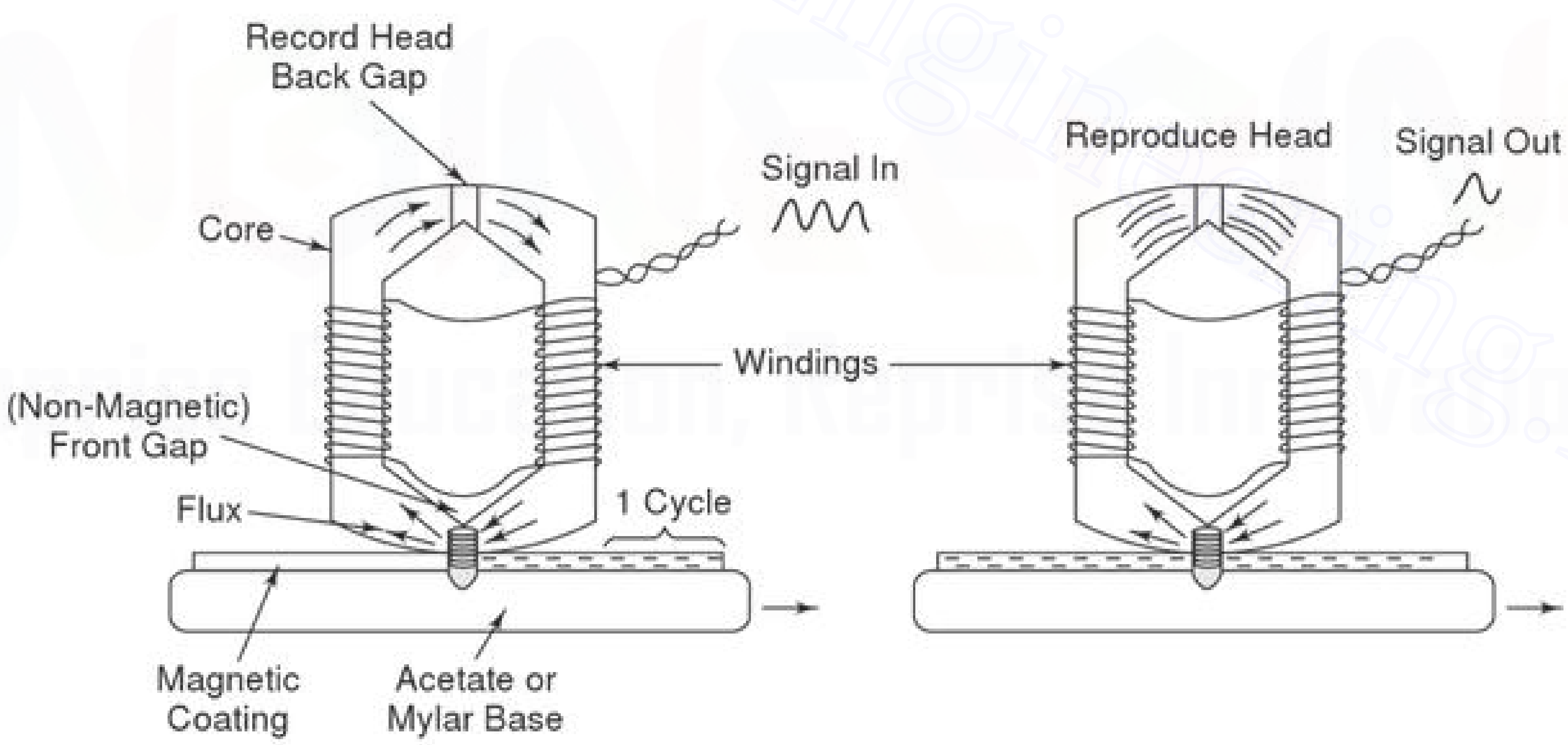


Fig. 12.10 (b) Magnetisation of tape

A simple magnetic particle on the tape might have the $B - H$ curve shown in Fig. 12.10(c) where H is the magnetising force and B the flux density in the particle.

Consider the material with no flux at all, i.e. the condition at point 0.

Now if the current in the coil of the recording head [Fig. 12.10(b)] is increased from 0 in a direction that gives positive values of H, the flux density increases along the path 0 – 1– 2, until the material is eventually saturated. If the operating point is brought from 0 only as far as 1, and H is brought back to 0, B follows a minor hysteresis loop back to point 6. A greater value of coil current would leave a higher residual flux, and a lower current a lower residual; a very simple recording process results.

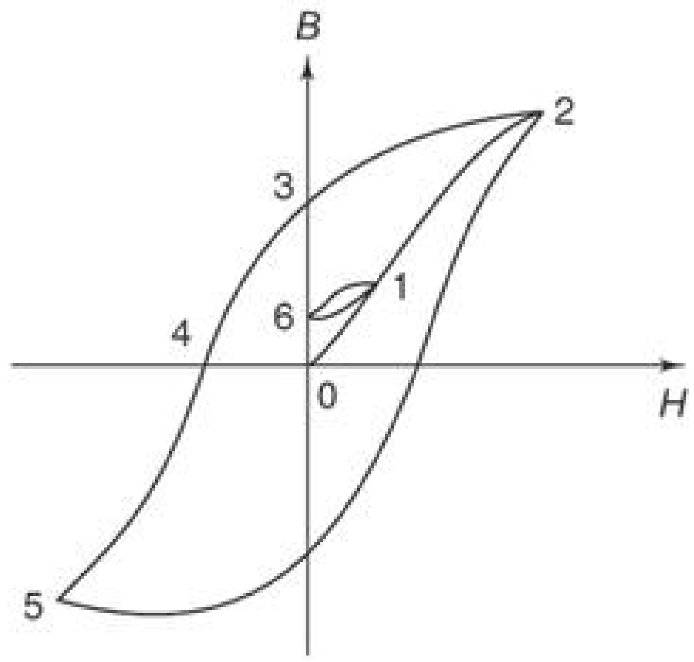


Fig. 12.10 (c) Typical magnetisation curve

However, the linearity between residual flux and recording current is very poor. Hence to obtain linearity in direct recording, FM is used. In all systems, the signal is reproduced by passing the magnetised tape over a magnetic head similar to the recording head. The magnetisation of the particles on the tape induces a varying flux in the reproducing head and a voltage is induced in the coil, proportional to the rate of change of flux.

Methods of Recording

There are three methods of magnetic tape recording which are used for instrumentation purposes.

1. Direct recording
2. FM recording
3. Pulse Duration Modulation recording (PDM)

FM recorders are generally used for instrumentation purposes. PDM recording is used in instrumentation for special applications where a large number of slowly changing variables have to be recorded simultaneously.

Direct Recording

This type of recording is described in the introduction of Sec. 12.7.

Advantage of Direct Recording

1. This recording process has a wide frequency response, ranging from 50 Hz – 2 MHz for a tape speed of 3.05 m/s. It provides the greatest bandwidth obtainable for a given recorder.
2. It requires simple electronic circuits.
3. It has a good dynamic response and takes overloads without increase in distortion. In general, instrumentation recorders have a signal to noise ratio of 22 – 30 db at 1% total harmonic distortion.
4. It is used to record signals where information is contained in the relation between frequency and amplitude, such as the spectrum analysis of noise.
5. It can be used for recording voice signals.

Disadvantage

1. The direct recording process is characterised by some amplitude instability caused by random surface inhomogeneities in the tape

coating. Some portion may not be perfectly recorded owing to dirt or poor manufacture.

2. This recorder is only used when maximum bandwidth is required.

FREQUENCY MODULATION (FM) RECORDING 12.8

When a more accurate response to dc voltages is required, an FM system is generally used.

In this FM system, the input signal is used to frequency modulate a carrier, i.e. the carrier signal is frequency modulated by the input signal (FM modulation), which is then recorded on the tape in the usual way.

The central frequency is selected with respect to the tape speed and frequency deviation selected for the tape recorders is ± 40% about the carrier frequency.

The reproduce head reads the tape in the usual way and sends a signal to the FM demodulator and low pass filter, and the original signal is reconstructed. The signal to noise ratio (S/N) of an FM recorder is of the order of 40 – 50 db, with an accuracy of less then ± 1%.

This ± 1 db flat frequency response of FM recorders can go as high as 80 kHz at 120 in/s tape speed, when using very high carrier frequencies (above 400 kHz).

When high frequency (HF) is not needed, and with a view to conserving tape. A tape speed range selector is generally provided. When the tape speed is changed, the carrier frequency also changes in the same proportion. Therefore, no matter what tape speed is being used, the recorded wavelength of a given dc input remains the same, since ± 40% full scale frequency deviation is utilised in all cases. A common set of specifications are given in Table 12.1.

Table 12.1

Tape speed in/s	*Carrier frequency kHz*	*Flat frequency response ± 0.5 db, Hz*	*RMS (S/N) ratio*
120.0	108.0	0 – 20,000	50
60.0	54.0	0 – 10,000	50
30.0	27.0	0 – 5,000	49
15.0	13.5	0 – 2,500	48
7.5	6.75	0 – 1,250	47
3.75	3.38	0 – 625	46
1.88	1.68	0 – 312	45

Input to the tape recorders is generally at the 1 V level, and so most transducers require amplification before recording.

An FM recording system is illustrated in Fig. 12.11. In this system a carrier oscillator frequency f_c, called the centre frequency, is modulated by the level of the input signal.

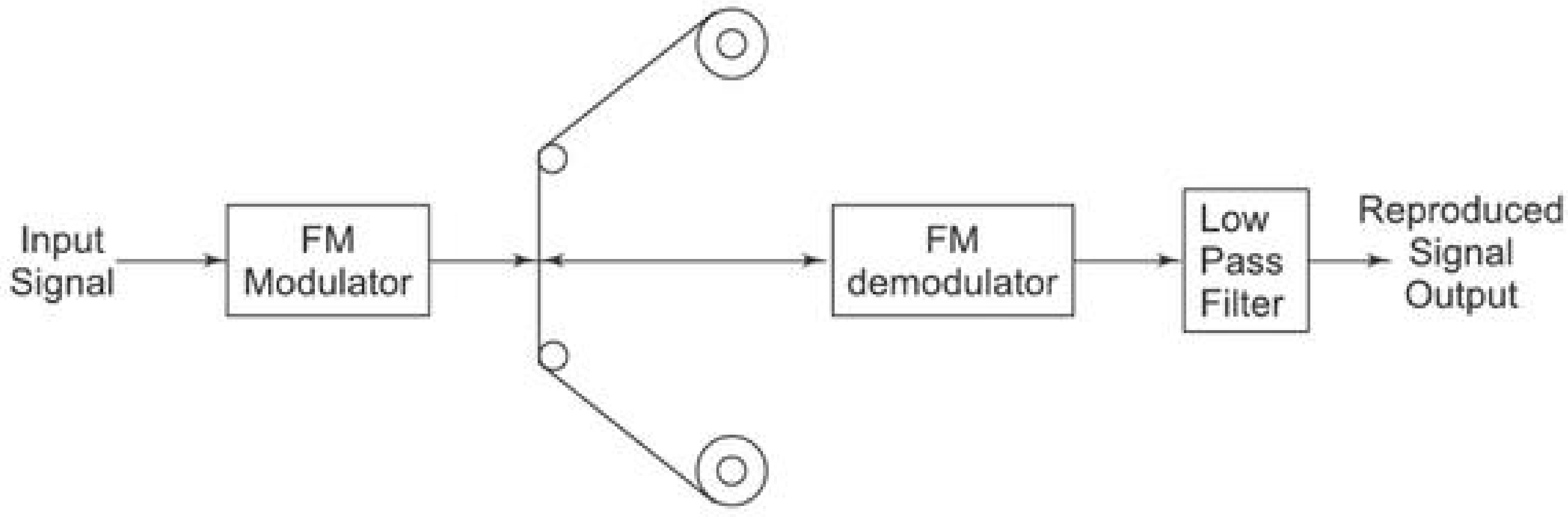


Fig. 12.11 FM recording system

When there is no input signal, i.e. zero input, the modulation is at centre frequency f_c. If a positive input signal is applied, the frequency deviates from the centre frequency by some amount in a certain direction; the application of a negative input voltage deviates the carrier frequency in the opposite direction.

The output of the modulation, which is fed to the tape, is a signal of constant frequency for dc inputs, and varying frequency for ac inputs. The variation of frequency is directly proportional to the amplitude of the input signal.

On playback, the output of the reproduce head is demodulated and fed through a low pass filter which removes the carrier and other unwanted frequencies reproduced due to the modulation process.

The operation of FM modulation can be easily checked by applying a known input voltage and measuring the output frequency with an electronic counter. This signal is applied to the tape with no further conditioning, as the signal is independent of the amplitude.

The FM demodulator converts the difference between the centre frequency and the frequency on the tape, to a voltage proportional to the difference in the frequencies. This system can thus record frequencies from dc to several thousand Hertz. Residual carrier signals and out of band noise are removed by a low pass filter.

Advantages of FM Recording

1. FM recording is useful primarily when the dc component of the input signal is to be preserved.
2. This system has a wide frequency range and can record from dc voltages to several kHz.
3. There is no drop-out effect due to inhomogeneties of the tape material.
4. Independent of amplitude variations, and accurately reproduces the waveform of the input signal.
5. Used extensively for recording voltages derived from non-electrical quantities, such as force, acceleration and pressure.
6. It is extremely useful for multiplexing in an instrumentation system.

Disadvantages

1. FM recording is extremely sensitive to tape speed fluctuations.
2. FM recording circuitry is more complicated than that of direct recording systems.
3. FM system has a limited frequency response.
4. It requires a high tape speed.
5. It requires a high quality of tape transport and speed control.

Pulse Duration Modulation

Pulse width modulation is also called pulse duration modulation (PDM). In this system, the amplitude and the starting time of each pulse is kept fixed, but the width of the pulse is made proportional to the amplitude of the signal at that instant. This type of system is mostly used for Digital recording.

DIGITAL DATA RECORDING 12.9

Digital magnetic tapes are often used as storage devices in digital data processing applications. Digital tape units are of two types, incremental and synchronous.

Incremental digital recorders are commanded to step ahead (increment) for each digital character to be recorded. Input data may be at a relatively slow, or even discontinuous rate. In this way, each character is equally and precisely spaced along the tape.

In a synchronous digital recorder, the tape moves at a constant speed (about 75 cm/s) while a large number of data characters are recorded. The data inputs are at precise rates, up to tens of thousands of characters per second. The tape is rapidly brought up to speed, recording takes place, and the tape is brought to a fast stop. In this way a block of characters (a record) is written with each character spaced equally along the tape. Blocks of data are usually separated from each other by an erased area on the tape called the record gap. The synchronous tape unit starts and stops the tape for each block of data to be recorded.

Characters are represented on magnetic tape by a coded combination of 1-bit in appropriate tracks across the tape width. The recording technique used in most instrumentation tape recorders is the industry accepted IBM format of Non-Return Zero (NRZ) recording.

In this system the tape is magnetically saturated at all times in either the positive or the negative direction.

The NRZ method uses the change in flux direction on the tape to indicate 1 bit, and no change in flux direction to indicate 0 bit. This method is illustrated in Fig. 12.12, where the binary numbr 11101011 is represented by a flux pattern in the NRZ system.

The simplest method of coding the recording head field is to reverse its direction.

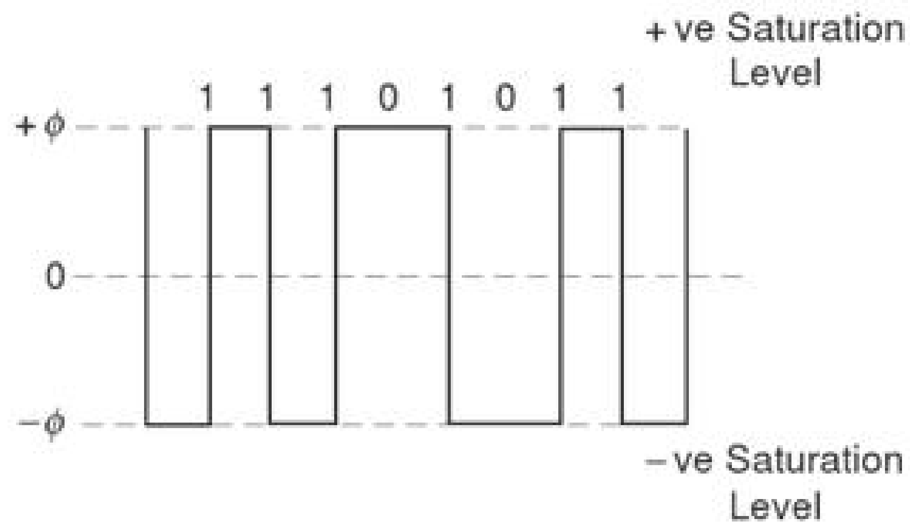


Fig. 12.12 NRZ method of digital recording

In digital data recording, a recording field of amplitude sufficient to produce magnetic saturation through the complete tape layer thickness is reversed to record a 1 signal and kept constant to record a 0 signal.

Reproduction of this recording is achieved by using a timing signal obtained from a separate clock track, corresponding to the time when a 1 or 0 is recorded.

Self-clocking systems, where the recording field is reversed at regular intervals and 1 or 0 signals are recorded between these clock signals, are also used.

It is evident that the highest resolution is obtained in NRZ recording by adjusting the field amplitude, so that maximum longitudinal decrement occurs in the surface layer of the tape. In practice, larger fields are usually employed to ensure more reliable recordings on a coated thicker tape. To minimise the effects of dropouts, large recording fields are used and resolution is sacrificed for increased reliability.

Present high density data recording on oxide powder tape is in the range of 1500 – 2000 flux reversals per inch. (By using thin metallic coatings with high coercive force, extensions up to 10000 reversals per inch are possible in future.)

Since magnetisation is independent of frequency and amplitude but relies only on the polarity of the recording current, the usual problems of non-linearity and distortion found in direct and FM recordings do not exist. The write coils of the tape head require only sufficient current, of the correct polarity, to saturate the tape. Two of the problems encountered in digital recording are signal drop out and spurious pulses (losing or adding data). Signal dropout or loss of pulses becomes serious when the packing density increases (a large number of bits per unit tape length).

As a check on dropout errors, most tape systems include a parity check. This check involves keeping track of the number of 1 bits of information initially recorded on the tape by writing a parity check pulse on an extra tape track. If the number of 1's recorded is even it is called an even parity check, and if the number of 1's recorded is odd, then it is an odd parity check. When a dropout occurs, the parity check does not agree with the actual recorded data and a parity error is detected.

Some systems use the parity error system to insert missing bits in the appropriate places in addition to indicating that a parity error has occurred.

Another scheme, called bipolar or alternate mark inversion, is illustrated in Fig. 12.13.

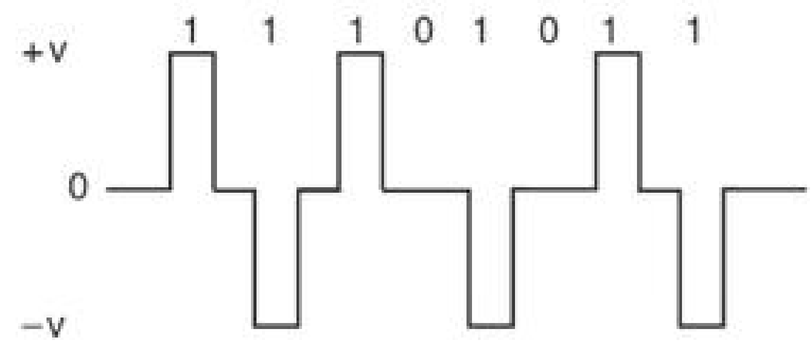


Fig. 12.13 Bipolar (Alternate mark inversion

This format has no residual dc component and has zero power in the spectrum at zero frequency, as shown in Fig. 12.13. These are pulses of 50% duty cycle (they are only half as wide as the pulse interval allows) and by inverting the polarity of alternate 1 bits. The bipolar format is really a three state signal (+ V, 0, – V).

Advantages of Digital Data Recording

1. High accuracy.
2. Insensitivity to tape speed.
3. Use of simple conditioning equipment.
4. The information is fed directly to a digital computer for processing and control.

Disadvantages of Digital Data Recording

1. Poor tape economy.
2. The information from transducers is in analog form, hence an A/D converter is required.
3. A high quality tape and tape transport mechanism are required.

OBJECTIVES AND REQUIREMENTS OF RECORDING DATA 12.10

1. Recording is often carried out in order to preserve the details of measurement at a particular time.
2. The accuracy of the recording must be the same as the accuracy of the measurement, for best results.
3. A record should be legible and capable of being maintained properly.
4. Most of the critical parameters which influence the performance of the process or equipment has to be recorded for taking necessary action from time to time.
5. The recorded chart at a glance provides an overall picture of the performance of the unit. (All parameters automatically regulated are invariably recorded to depict the performance of automatic regulating loop.)
6. The recorded chart also reflects immediately what actions the operator had taken during his shift.
7. The necessary data for determining the efficiency, etc. is easily and readily provided.

8. Charts are also used as permanent records to provide answers to queries which may come up at a later time with respect to product quality.
9. It is also very valuable from the point of preventive maintenance.
10. Manufacturers of equipment often ask for the use of a recorder for recording certain parameters which are very critical for the performance of the equipment. The recorded chart indicates whether the equipment has been used as per their instructions or not.

RECORDER SELECTIONS FOR PARTICULAR APPLICATIONS 12.11

When selecting a recorder for a particular application, the following points should be considered.

The basic consideration is the frequency of the waveform to be recorded. For signals in the frequency range of about 125 Hz to a few thousand Hz, an optical recorder is well suited. This is a strip chart recorder that directs a light beam through an optical system and onto a photographic plate. The paper used in such instruments may require darkroom developing or the paper may be light sensitive and self develop when exposed to light. (See Fig. 12.2(b).) Optical recorders can also be used for low frequencies. The disadvantage is that the photographic plate is much costlier than the paper in instruments using a pen and ink system.

For signals in the frequency range of 50 – 125 Hz, a servo-type strip chart recorder with a preamplifier is most suitable. The preamplifier is recommended to provide additional energy to the pen or stylus at the rate required to record waveforms. At frequencies of 10 Hz or less, a servo-type recorder offers the user sensitivity, linearity, stability, mechanical sluggishness and sufficient energy to drive the pen or stylus, as well as a control device if it is part of the control system.

RECORDER SPECIFICATIONS 12.12

The following general features should be considered whenever one is examining a recorder.

1. The type of writing instrument desired, such as pen and ink, heated stylus or electric stylus.
2. The type of recorded chart desired, such as paper, wax-coated paper, or photographic film with or without darkroom developing.
3. Maximum amplification, if the signal is to be recorded.
4. Frequency response (Hz).
5. Recording speed adjustors.
6. Input signals voltage or current.
7. Input impedance, should be several hundred thousand ohms for a general purpose recorder.
8. Charts speed expressed in inches or centimeters per second, per min. or per hour.

POTENTIOMETRIC RECORDER (MULTIPOINT) 12.13

12.13.1 Principle of Operation

The thermocouple or millivolt signal is amplified by a non-inverting MOSFET, chopper stabilised, feedback amplifier. This configuration has a very high input impedance and the current passing through the signal source is a maximum of 0.5 nA (without broken sensor protection). With the use of span control, the output signal is adjusted to 5 V (nominal), for an input signal change, e.g. to full scale deflection of the pen.

The pre-amplifier output signal is then compared with a reference voltage picked off the measuring slide wire, which is energised by a stabilised power supply, and the difference amplified by a servo amplifier, whose output drives a linear motor. The motor carriage carries the indicating pointer pen and the sliding contact on the slide wire.

The motor itself consists of a coil assembly, travelling in a magnetic field (Fig. 12.14). The servo amplifier drives the carriage in the appropriate direction, to reduce the difference signal to zero.

An input filter circuit reduces any spurious signals picked up by the input leads. The B–E junctions of the transistor are used for overload protection.

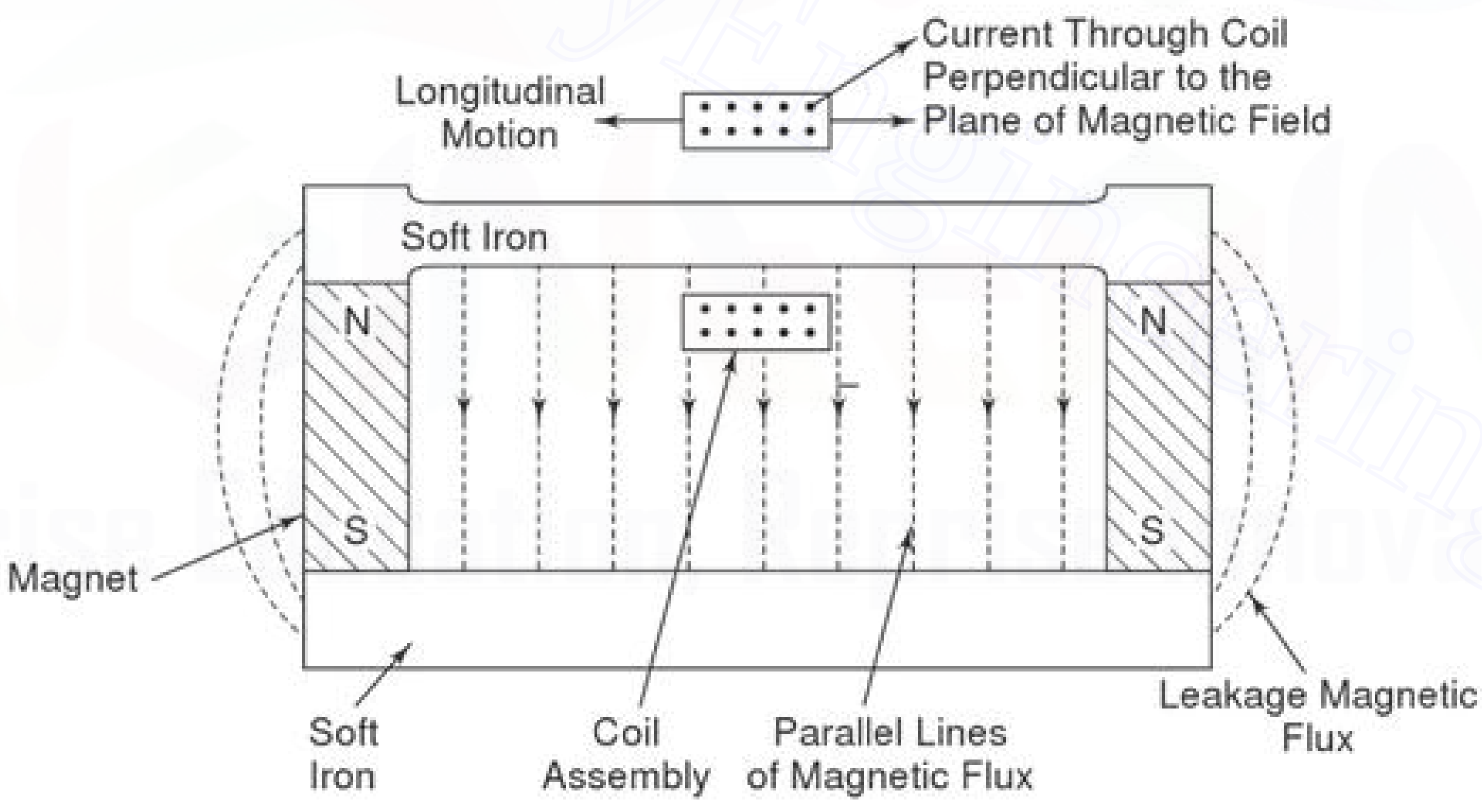


Fig. 12.14 Linear motor operating principle

In multipoint versions of the recorder, a signal selector switch is driven by a synchronous motor. The pen changeover and dotting action are actuated by a second synchronous motor (Fig. 12.15). The pen operation is electrically synchronised to the rotation of the signal selector switch—should they get out of step, the pen motor stops at a predetermined point and restarts only when the signal selector switch has rotated to its correct alignment. The linear motor is muted during the signal changeover, but dotting always takes place with the system live. The standard dotting interval is 6s (Fig. 12.15). The linear motor consists of a coil assembly travelling in a magnetic field. The direction of the field is as shown in Fig. 12.14. The current passing through the coil produces a magnetic field which is perpendicular to the existing field and causes the carriage to move in a direction given by Fleming's left hand rule.

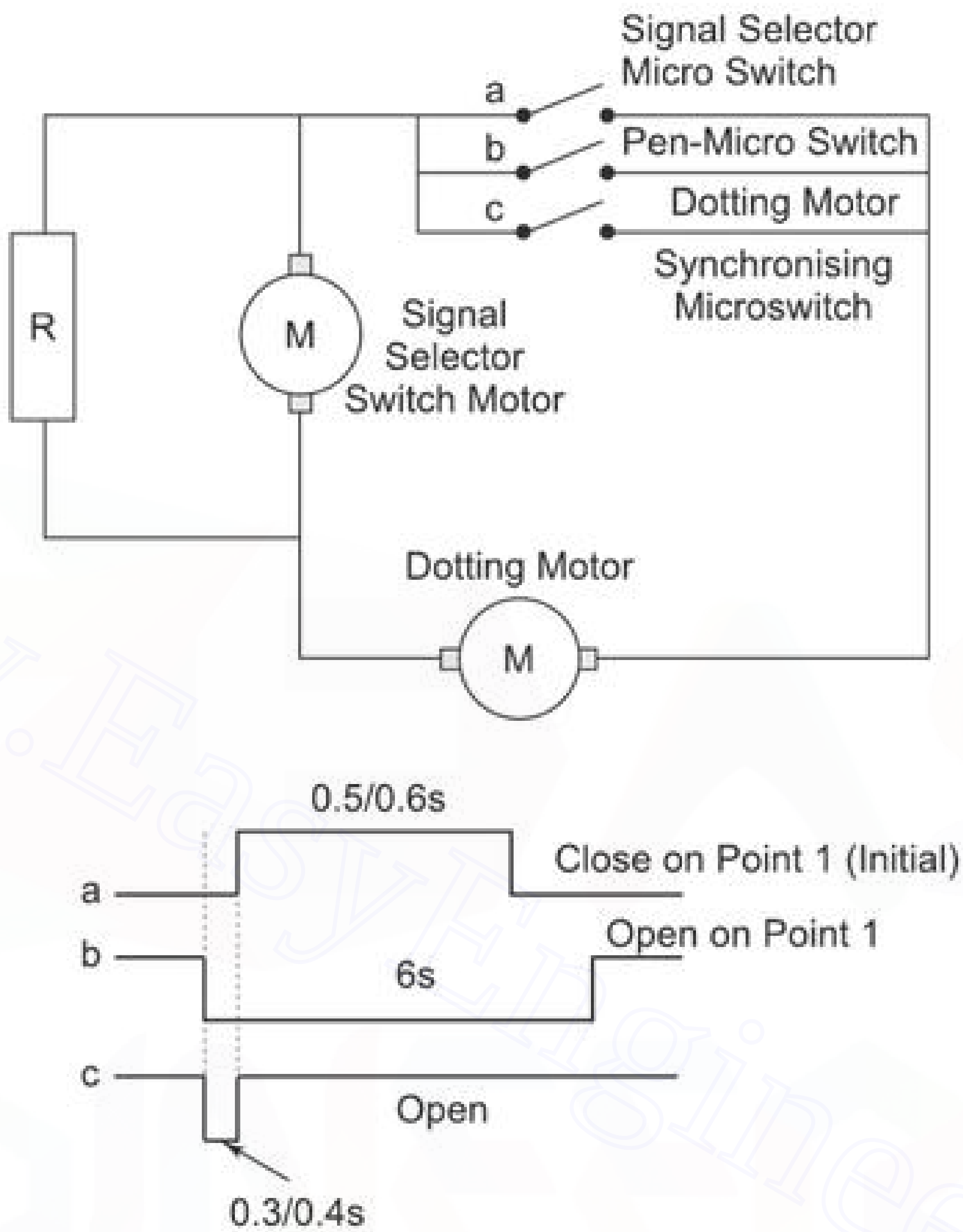


Fig. 12.15 Multipoint recording synchronising circuit

12.13.2 Ranging Circuit

With the indicating pointer positioned at the minimum of the scale, the output from the preamplifier should be zero. A small voltage appears across R_1 and R_4 due to current feeds from R_2 and R_3 respectively. R_1 is kept less than R_4 (in general, but $R_1 > R_4$ in thermocouples) and additional current is passed through R_1 from RV_1, so that the output can be adjusted to read zero corresponding to a zero input signal. When a signal input equivalent to full scale is given, RV_3 is adjusted to make the indicating pointer read the maximum on the scale. For thermocouple inputs, the circuit remains as above. For automatic cold junction compensation, the variation in the base-emitter voltage of the transistor with respect to temperature is made use of. The resistance R_7 injects current through R_4. The value of R_4 depends on the type of thermocouple used. Figure 12.16(a) shows a ranging circuit.

For input signals greater than 100 mV, an additional range card is used. Figure 12.16(b) shows the diagram of a resistance thermometer. For resistance thermometer input, a separate power supply gives the bridge supply as 6.2 V. One

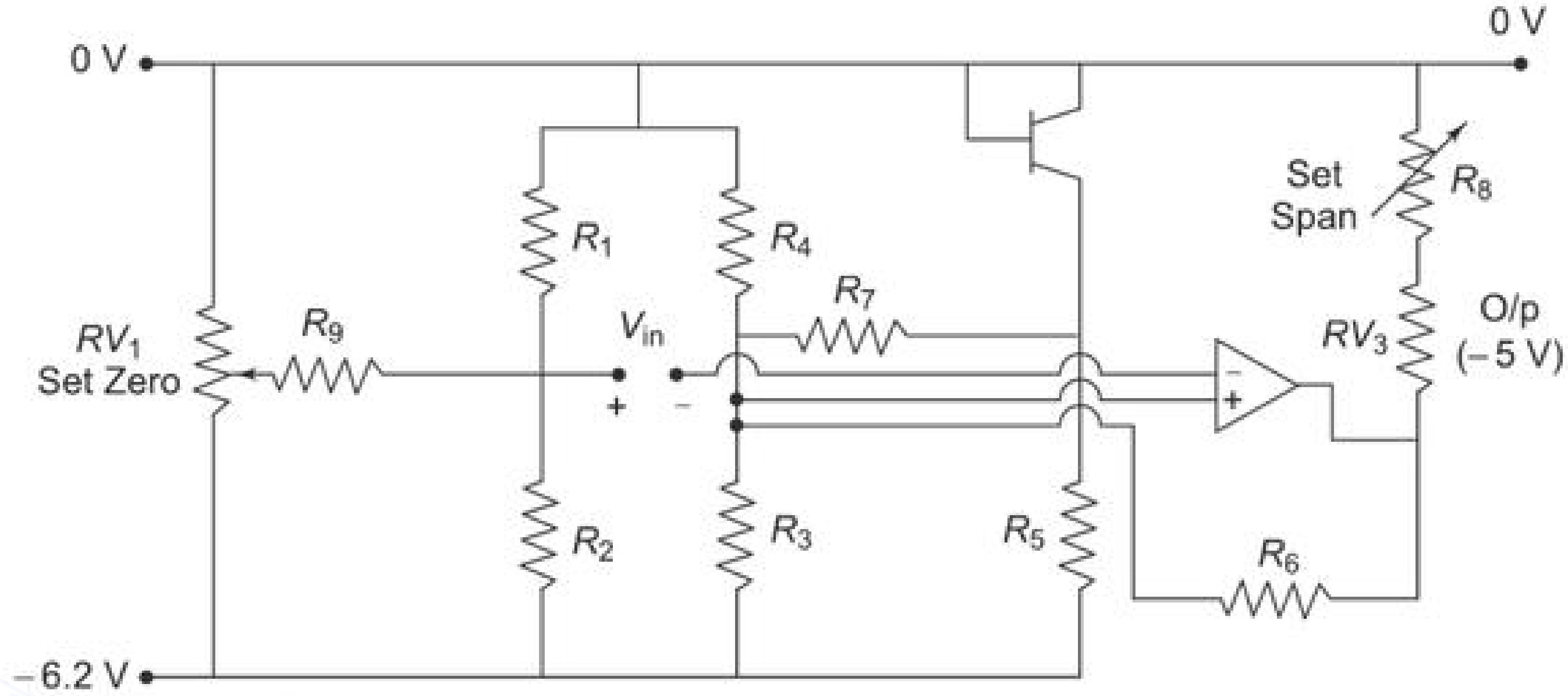


Fig. 12.16 (a) Ranging circuit (Millivolt and thermocouple inputs)

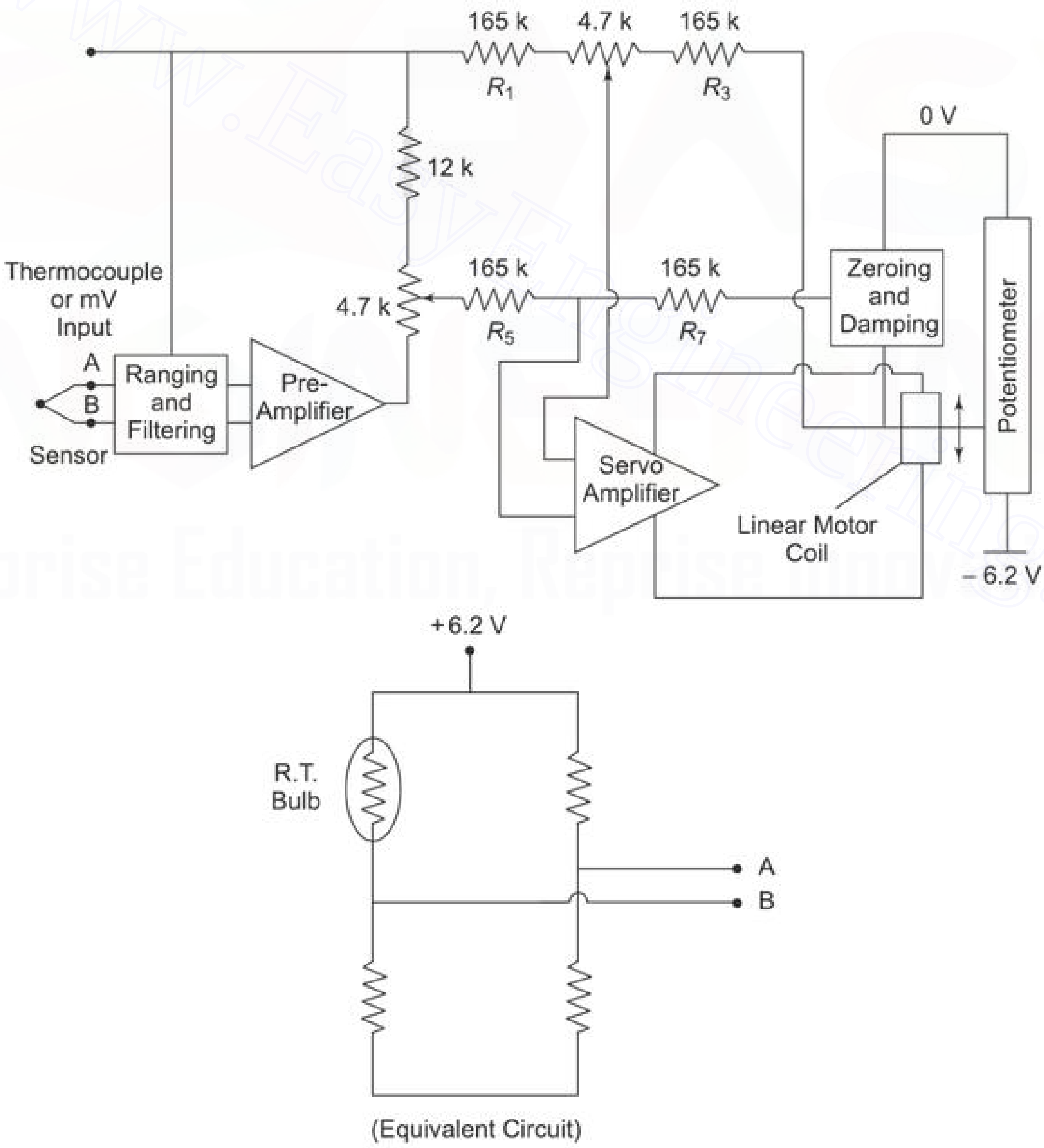


Fig. 12.16 (b) Basic diagram of a resistance thermometer

of the arms of the bridge is a resistance bulb (the standard three wires connection of the resistance thermometer). The other three arms of the bridge are mounted on an additional range card. The bridge gives 10 mV nominal output for the range of temperatures under consideration.

12.13.3 Servo Amplifier

The servo amplifier shown in Fig. 12.16(c) compares the output from the preamplifier with the voltage picked off the measuring slide wire. The output of the preamplifier and the voltage picked up by the slide wire obtained via an emitter follower stage are connected in a high resistance bridge circuit ($R_1 = R_3 = R_5 = R_7 = 165$ kΩ), the balance of which is adjusted for maximum common mode rejection by adjusting the potentiometer, R_{V_1} (4.7 kΩ). The output is fed to the differential amplifier (consisting of a matched pair Opamps).

The signal voltage picked from the slide wire is also used to control the damping of the servo system. For this, signal voltage from the slide wire is fed to a differentiator circuit using an Opamp and its associated circuit and damping control.

The indicating point may be adjusted to set scale minimum, when the preamplifier output is zero. This is done by adjusting a set zero potentiometer (1 k value) coming in the damping circuit.

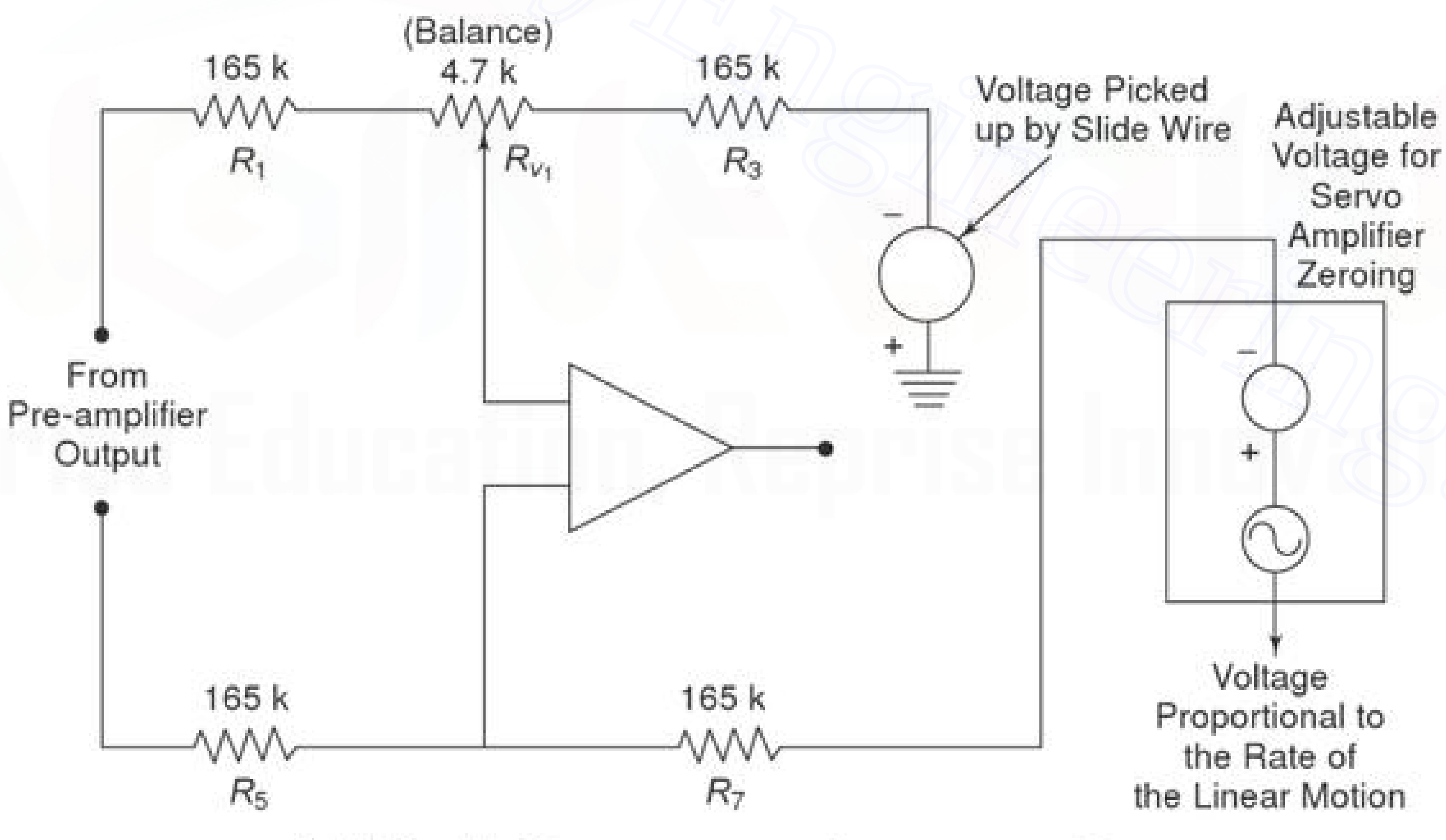


Fig. 12.16 (c) Schematic section for servo amplifier

The output of the differential amplifier is fed to a dc amplifier (consisting of typical NPN/PNP transistor stages), which give sufficient output to drive the linear motor in the appropriate direction. This reduces the differential input signal to the servo amplifier to zero.

12.13.4 Multipoint Variation

In multipoint recorders, each signal to be measured is connected in turn to the ranging circuit input terminals by means of a rotating selector switch, which is driven from a synchronous motor having a speed of 10 rpm via an intermittent motor. Each signal is sampled for a period of 3 or 6 seconds, depending on the switch motor fitted.

A second synchronous motor (10 rpm – 24 V ac) is mounted and fitted with cams and microswitches (Fig. 12.15).

The cam at the extreme end actuates the pen lifting (and dotting) bar and initiates the pen dotting. As the stylus lifts off the paper, a pawl and ratchet system in the pen head rotates the stylus and ink well to the next point.

A synchronising microswitch, mounted under the pen head, is operated by a pip on the stylus shaft. The contacts are open while the pen stylus is at initial point 1.

Fitted to the shaft of the dotting motor is a second cam, which operates a second microswitch in the synchronising circuit. The contact switches are open for a period of 0.3 – 0.4s, once in each revolution of the dotting motor, which rotates once during the sampling period of each print, i.e. 6s.

The third synchronising microswitch is operated by the projection on the side of the plastic intermittent advance gear on the same shaft of the signal switch. The contact of this microswitch closes for a period of 0.5 – 0.6s once in each revolution of the signal switch, i.e. once every 72s for a 6s sampling.

When the recorder goes out of synchronisation, if the cams and pen stylus are set correctly, the dotting motor will continue operating until the stylus comes around to the initial point. At this point the pen microswitch opens, as does the dotting microswitch. The dotting motor then stops.

The signal selector switch motor operates continuously, and when the microswitch operated by this motor closes, the dotting starts again.

(Note: The closing time of the signal selector microswitch is slightly more than the open time of the dotting motor microswitch, ensuring that the dotting motor microswitch be closed again before the signal selector switch motor microswitch opens.)

12.13.5 Multiple Recorders (6 Point Recorders)

The controller consists of a high gain opamp in comparator configuration, with one input from the pre-amplifier and another from the set point potentiometer. The output of the comparator is connected to the Schmitt trigger via both high and low control microswitches, operated by control cams, as shown in Fig. 12.17.

The Schmitt trigger circuit maintains the relay state after the input is disconnected, i.e. while the signal selector switches scan the other signal input. The control microswitch ensures that the relay does not change state during signal changeover, while the pre-amplifier input is open-circuit. Once the relay gets energised, it remains in that state via its own (normally open) contacts and through the Reset button.

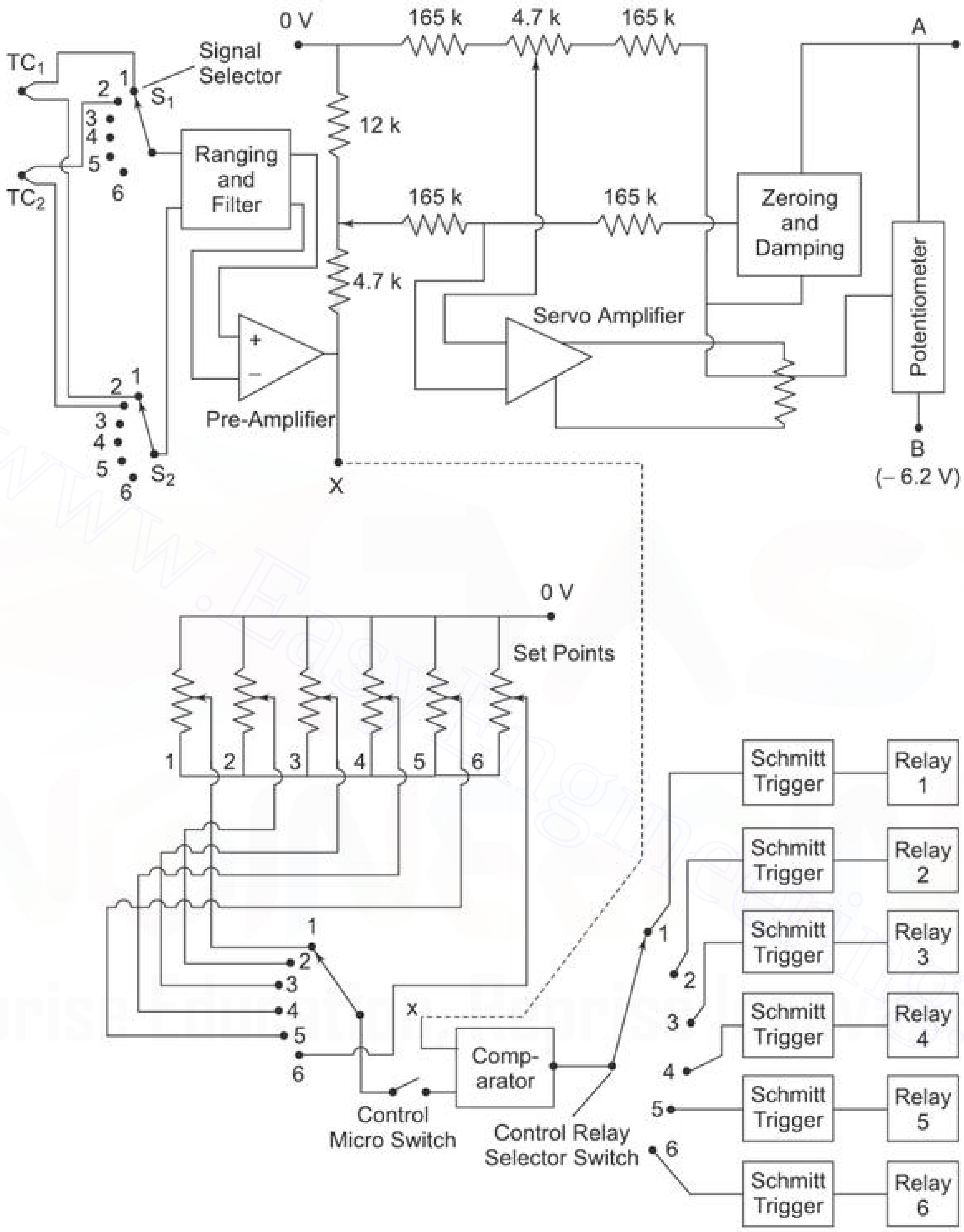


Fig. 12.17 Multipoint decoder having 6 on/off control points for a 6 point recorder

When the Reset button is pressed, the relay gets de-energised, which again gets latched if the same condition ($V_{in} > V_{set}$) prevails for the same or any other channel.

DIGITAL MEMORY WAVEFORM RECORDER (DWR) 12.14

The digital memory waveform recorder shown in Fig. 12.18, provides capability which is difficult to achieve by other methods. The block diagram (Fig. 12.18) is of a unit capable of recording four independent signals simultaneously.

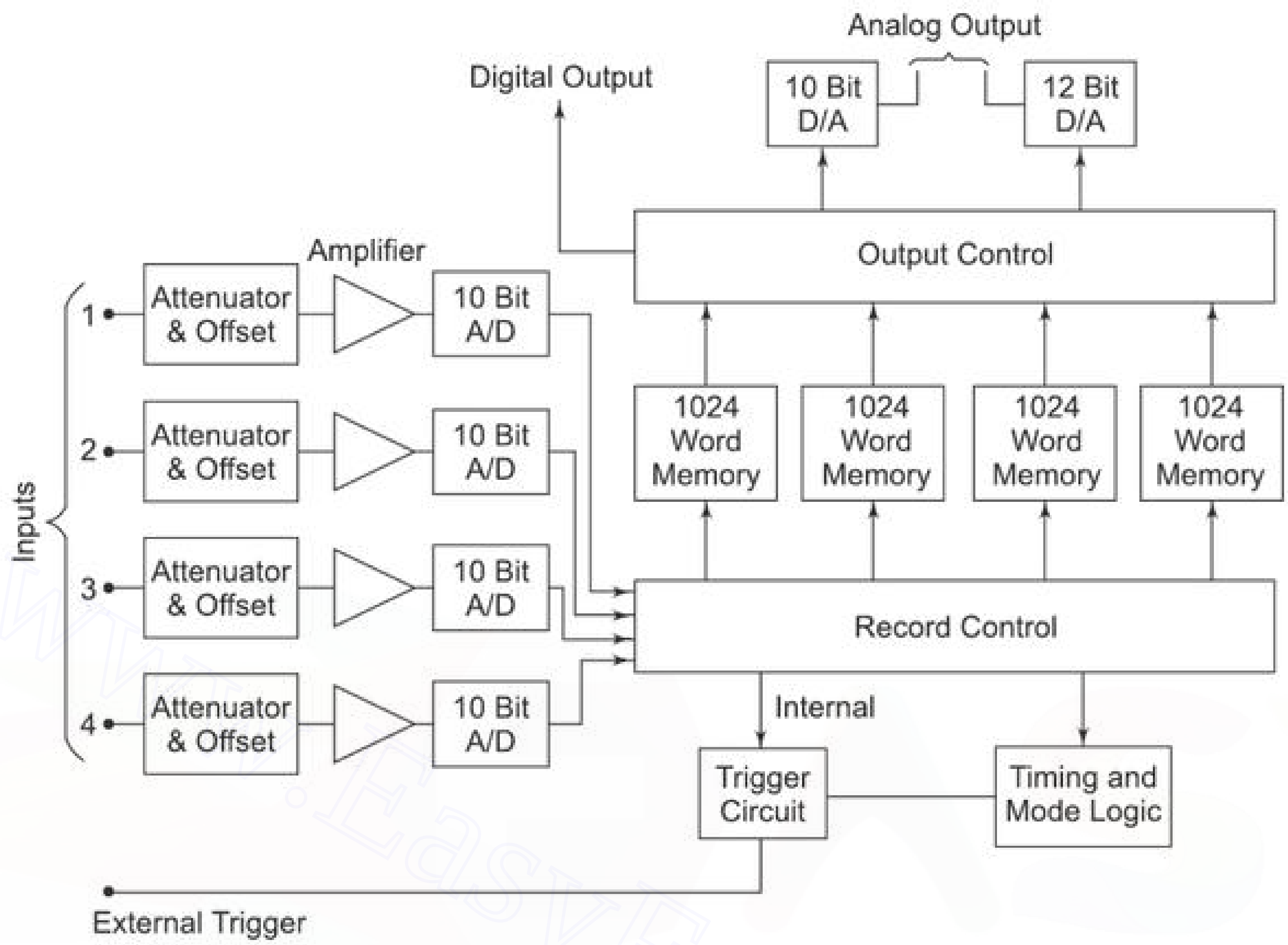


Fig. 12.18 Digital memory waveform recorder

The practical implementation of this concept rests on the ready availability, small size and reasonable cost of digital memories and associated digital hardware.

Consider a signal channel, the analog voltage input signal is digitised by a 10 bit A/D converter with a resolution of 0.1% (1 part in 1024) and frequency response of 25 kHz.

The total digital memory of 4096 words can be used for a single channel 2048 words can be used for each of the two channels an 1024 for each of the four channels.

The analog input voltage is sampled at adjustable rates (up to 100000 samples per second) and the data points are read into the memory. A maximum of 4096 points are storable in this particular instrument.

(Sampling rate and memory size must be selected to suit duration and waveform of the physical event being recorded. Some models have sampling rates up to 200 MHz.)

Once the sampled record of the event is captured in the memory, many useful manipulations are possible, since the memory can be read without erasing it (non-destructive readout).

By reading the memory out slowly through a digital to analog converter, the original event (which could have been extremly rapid) is reproduced as a slowly changing voltage, that is easy to record permanently in large size on a slow X–Y plotter.

If the memory is read out rapidly and repetitively, an input event which has a one shot transient becomes a repetitive waveform that now may be observed easily on an ordinary oscilloscope (not a storage CRO). The digital memory also may be readout directly (without going through a digital to analog converter) to say, a computer where a stored program can manipulate the data in almost any desired way.

Pre-trigger recording allows the device to record the input signal preceding the trigger point, a unique and often useful capability. In ordinary triggering, the recording process is started by the rise of the input signal (or some external triggering signal) above some preset threshold value. If this threshold is set too low, random noise will trigger the system; too high a threshold prevents recording of the initial rise of the desired signal. The digital recorder can be set to record continuously (new data coming into the memory pushes out the old data, once the data memory is full), until the trigger signal is received. Then the recording process is stopped, thereby freezing in the memory data received prior to the trigger signal.

An adjustable trigger delay allows operator control of the stop point, so that the trigger may occur near the beginning, middle or end of the stored information.

While digital memory waveform recorders are marketed without attached recording devices for analog outputs, such packages are available as a digital memory oscillographs or oscilloscopes.

The usual 40 Hz frequency response of pen/ink recorders can be extended to 20 kHz with a plug-in module using waveform digitising principles. This principle of waveform digitising makes direct recording easier. Direct writing instruments of high recording quality are available for recording a very wide range of signals.

APPLICATIONS OF A STRIP CHART RECORDER 12.15

The following are some of the thousands of applications for recorders in industry.

1. Temperature Recording A strip chart recorder may be used to provide a graphical record of temperature as a function of time. There are two primary methods used for recording temperature, the thermocouple method and the resistance method.

The thermocouple method utilises commercially available thermocouples that cover a wide range of temperature. These serve very well as temperature-sensing elements and are readily compatible with strip-chart recorders.

The circuit shown in Fig. 12.19(a), is a basic circuit used to record the thermocouple voltage.

A thermocouple (discussed in Sec. 3.6) is made by joining two dissimilar metals. A potential difference, which is proportional to the temperature, exists across the junctions. This potential difference has an almost linear relationship with the temperature and is very repeatable.

Review Questions

1. Differentiate between indicator and recorder.
2. List various types of recorders.
3. State the working principle of a strip chart recorder.
4. List three major types of a strip chart recorder.
5. List various pen mechanisms used for recording.
6. Define chart speed.
7. Describe the operation of a strip chart recorder.
8. Explain the working principle of a galvanometer type recorder.
9. Describe the operation of a galvanometer type recorder with the help of a diagram. State the disadvantages of a galvanometer type recorder.
10. State the limitations of a galvanometer recorder and how is it eliminated.
11. Why does the galvanometer recorder uses a curvilinear chart.
12. State the importance of paper speed.
13. Explain the basic principle of null type recorders.
14. State different types of null type detectors.
15. Describe the operation of null type recorder with the help of a diagram.
16. Compare between galvanometer and null type recorders.
17. Describe with diagram the working of a bridge type recorders.
18. Explain with diagram the operation of a LVDT type recorder.
19. State the requirement of a dc linear motor used in LVDT type recorder.
20. List three functions that a recorder may simultaneously serve in industrial applications.
21. List minimum five specifications that should be considered while selecting a recording instrument.
22. Describe three applications for recording instruments.
23. What is the approximate maximum frequency response of a galvanometer type recorder?
24. What are the primary functions of a galvanometer recorder?
25. Differentiate between galvanometer type recorder and potentiometric recorder.
26. Define single point recorder and multipoint recorder.
27. Define a circular recorder.
28. Explain the working principle of a circular recorder.
29. Describe the operation of a circular chart recorder. List various applications of a circular chart recorder.
30. Define a plotter.
31. Differentiate between plotter and recorder.
32. Describe the operation of a X-Y plotter. List the various applications of a XY plotter.
33. Classify different types of recorders used in instrumentation.
34. State the advantage of using a potentiometer circuit.
35. What is a servo system?
36. List the various objective and requirements of recording data.
37. List the various specification of a recorder.
38. List various applications of strip chart recorder.
39. State the purpose of error detector in a recorder.
40. How is automatic balance achieved in a recording instrument?
41. Give the constructional features of strip chart recorders. State its various applications.
42. An ADC signal cannot be reproduced if recorded on a direct recording system. Comment.
43. What are the basic components of a magnetic recorder.

44. Explain with diagram the operation of a magnetic recorder.
45. State the advantages of direct recording.
46. Explain with diagram the working of an FM recording system. State the advantages and disadvantages of FM recording.
47. Describe with the help of a block diagram the operation of an *X-Y* recorder. List the applications of an *X-Y* recorder.
48. Differentiate between strip chart and *X-Y* recorders.
49. Differentiate between circular chart and *X-Y* recorder.
50. Explain the working principle of a digital memory waveform recorder.
51. List the various mode of operation of a digital recorder.
52. Explain NRZ method of recording.
53. State the advantages and disadvantages of digital recording.
54. List the feature provided by a digital X-Y plotter.
55. Describe the operation of a digital memory waveform recorder.
56. Explain how transients can be recorded using digital waveform recorders.
57. Explain the concept of Pre-triggering as used in digital waveform recorders.
58. Explain A to D converter and D to A converter.
59. Explain the working principle of a digital *X-Y* plotter.
60. Explain the working principle of a digital recorder
61. Describe the operation of a digital recorder.

Multiple Choice Questions

1. A recorder is an instrument used for
   (a) recording (b) indicating
   (c) display (d) measurement
2. A strip chart recorder uses
   (a) a long roll of paper
   (b) a circular paper
   (c) a stationary paper
3. A galvanometer type recorder uses
   (a) taut band
   (b) PMMC movement
   (c) moving iron type
4. A null type recorder uses
   (a) amplifier (b) inductor
   (c) capacitor (d) potentiometer
5. A galvanometer recorder has
   (a) very high input impedance
   (b) high input impedance
   (c) low input impedance
   (d) very low input impedance
6. A circular recorder uses
   (a) rectilinear chart
   (b) curvilinear chart
   (c) square chart
   (d) circular chart
7. A circular chart uses principle of
   (a) electrostatic
   (b) mechanical and link levers
   (c) galvanometer
   (d) self-balancing potentiometer
8. A *X-Y* recorder uses the principle of
   (a) galvanometer
   (b) mechanical levers
   (c) electrostatic
   (d) self-balancing potentiometer
9. An *X-Y* plotter, plots
   (a) one variable with respect to time
   (b) an emf against a physical quantity
   (c) one variable against another variable
10. An *X-Y* plotter uses
    (a) a single pen
    (b) a single pen/arm mechanism
    (c) a double pen
    (d) a double pen/arm mechanism

11. A digital memory waveform recorder records
    (a) slow variation
    (b) transient
    (c) high frequency
    (d) very low variation

12. Pre-triggering is used in digital memory waveform recorder to record
    (a) input signal preceding the trigger point
    (b) to trigger the memory
    (c) to start the operation

Practice Problems

1. The frequency of a signal to be recorded with a strip chart recorder is 15 Hz. What chart speed must be used to record one complete cycle on a 5 mm of recording paper?
2. If the frequency of a signal to be recorded with a strip chart recorder is 30 Hz, what chart speed must be used to record one complete cycle on 5 mm of recording paper?
3. The chart speed of a recording instrument is 10 mm/s. If the time base of the recorded signal is 20 mm, what is the frequency of the recorded signal?
4. The chart speed of a recording instrument is 25 mm/s. If the time base of the recorded signal is 10 mm, what is the frequency of the recorded signal?

Further Reading

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