11

Measurement and Measuring Instruments

TOPICS DISCUSSED

- Concept of measurement and measuring systems
- Analog and digital instruments
- Static and dynamic characteristics of instruments
- Classification of instruments
- Measurement error
- Permanent magnet moving-coil, moving-iron, and dynamometer-type instruments
- Extension of instrument range
- Measurement of power
- Measurement of energy
- Instrument transformers
- Megger and multimeter

11.1 INTRODUCTION

Measurement of any quantity, like length, mass, time, speed, piece of cloth is the direct method of measurement. In engineering applications, for measurement of a variable quantity like pressure, velocity, temperature, etc., indirect methods are used. In on indirect method, a sensing element called transducer converts the quantity to be measured into an analogous electrical signal. This signal is then amplified and processed, and fed to a final recording device. A system comprising a transducer, signal amplifier, converter which changes the signal from analog to digital form, transmission system, and recording or display device is called instrumentation system. A thermocouple, which converts an unknown temperature into an electrical signal can be used for measurement of temperature. The voltage induced across the thermocouple terminals (between hot and cold junctions) can be recorded on a calibrated instrument in terms of temperature of the hot junction.

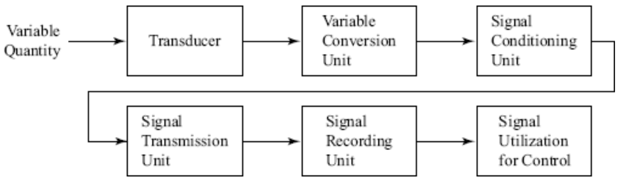


Figure 11.1 Basic measuring system elements represented in block diagram form

Elements or components of a measuring system is shown in Fig. 11.1.

It may be noted that the common element of any measuring instrument is the primary transducer which provides an output when input is applied to it.

A thermometer is a single measuring unit but is an example of complete measurement system by itself. The level of mercury in the capillary tube which rises on application of temperature to the base of the tube is used to measure temperature directly against a graduated scale. However, most often the transducer is only a part of the whole measurement system. The output of the transducer often requires conversion to another form to make it suitable for processing or conditioning. For example, a strain gauge used as transducer causes a change in resistance when encountered with a variable quantity. We may have to change resistance into a voltage by some method. Such unit is called variable conversion unit as shown in Fig. 11.1.

Instruments which are used to measure various quantities that normally change with time are called measuring instruments.

The subject instrumentation and measurement is considered most important in any engineering and scientific activity. If we want to control a certain quantity, e.g., the output voltage of a generator, we have to continuously measure the output voltage because it tends to change when the load on the generator changes. If we want to keep the output voltage constant even when the load on the generator transmitted, again converted to analog form and recorded. The input signals received through a transducer are required to be processed, i.e., amplified or attenuated, filtered, and converted before transmitting to the desired destination. Signal conditioning, data acquisition, data transmission, etc., are the important components of an instrumentation system.

Application of computers in industrial process control and monitoring has necessitated the requirement for instruments to measure, record, and control process variables.

Automatic control operation in practical applications require a measurement and feedback system. Let us take the example of speed control of a dc motor as shown in Fig. 11.2. The desired speed is, say 1500 rpm. If the motor develops speed somewhat more than the desired speed, a small tachogenerator mounted on the motor shaft will send some negative signal to decrease the voltage applied to the motor armature. If the speed of the motor is 1500 rpm, no error signal is generated.

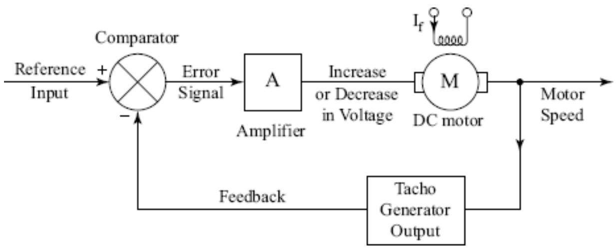


Figure 11.2 Speed control scheme for a dc motor

Input voltage to the motor is changed automatically according o the difference between the measured speed and the required speed. Amplifier, A is used to amplify the signal.

Precision, accuracy, sensitivity, etc., are considered the most important attributes of any measurement system. The more precise the instrument is, the more expensive it becomes.

A measuring instrument provides information about the magnitude of a certain variable quantity. In its simplest form it is a single unit which provides readings on a graduated scale according to the magnitude of the unknown quantity applied to it.

11.2 ANALOG AND DIGITAL INSTRUMENTS

An analog instrument provides output (measured value) continuously as the quantity being measured changes. A deflection-type instrument as shown in Fig. 11.3 is an example of an analog instrument. Here, the pressure of the liquid inside a container is measured by recording the deflection of a pointer on a calibrated scale as shown.

As the pressure of liquid changes due to heating, the pointer moves will read speed in discrete numbers and not as fraction of a revolution. Digital instruments have come into wide use due to the rapid growth of computers in control operations of systems and production processes. Instruments whose output is in digital form is suitable in computer-based control operations as the instrument can be directly interfaced with the computer. However, analog instruments can also be interfaced with computers by an A to D (analog to digital) converter which will convert the analog output signal into digital form for the computer to read and further process. Where control operations must be fast as also the money spent on the instrumentation system has to be kept low, digital instruments are preferred over analog instruments alongwith A to D converters.

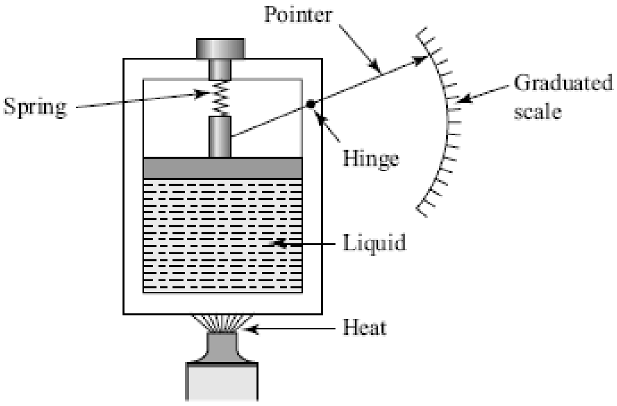


Figure 11.3 An analog instrument measuring pressure of liquid

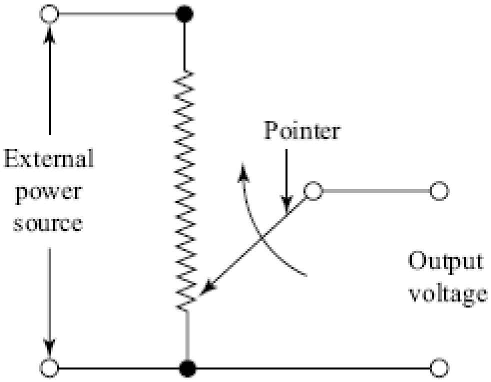


Figure 11.4 Active instrument illustrated

11.3 PASSIVE AND ACTIVE INSTRUMENTS

Instruments can either be active or passive. In *active instruments* the output is produced entirely by the quantity being measured.

For example, the instrument shown in Fig. 11.3 is an active instrument because the deflection of the indicator is produced entirely the figure, the pointer moves due to, say movement of some liquid level in a tank. The output voltage can be calibrated as proportional to the level of liquid in the tank since the pointer will move on the resistance due to rise of liquid level.

11.4 STATIC CHARACTERISTICS OF INSTRUMENTS

Static characteristics of instruments are defined in terms of accuracy, precision, sensitivity, resolution, etc. Normally, these values do not change with time once the instrument is manufactured. The quality of measurement depends on these characteristics. The cost of an instrument will increase when we want to achieve higher values of these characteristics. The terms used to express the static characteristics of a measuring instrument are explained below.

11.4.1 Accuracy

You must be acquinted with deflecting-type instruments like ammeters and voltmeters used in laboratories. Let us consider a voltmeter which can read a maximum voltage of 100 V. Its accuracy is mentioned in terms of its full-scale deflection. As for example, accuracy of ±1% will mean that for a reading of 100 V, the actual value of voltage could be 100, ±1% of 100 i.e., either 101 V or 99 V.

Accuracy, therefore, tells us about the nearness of the measured value (indicated value of the instrument) to the actual or true value of the quantity being measured.

Now, suppose an instrument whose measuring range is 0–100 V with an accuracy of say, 1 per cent has been selected to measure a low value of voltage, say 10 V.

Since the error of the instrument is expressed in terms of its full-scale deflection, the maximum error could be 1 V. For a 10 V measurement using the same voltmeter, could give rise to a possible error of 1 V which is 10 per cent of 10 V.

The accuracy of measurement is drastically reduced from 1 per cent to 10 per cent. It is therefore advisable not to use instruments of higher range to measure low values. In your laboratory while doing experiments you must select instruments such that their range is appropriate to the range of values being measured. That is to say, to measure 5 V you should not use a voltmeter of range 0–100 V. Instead you should use a voltmeter of lower range, say 0–10 V.

11.4.2 Precision

Precision is often confused with accuracy. Suppose with a voltmeter of 1 per cent accuracy we take a number of readings of a particular voltage. If the instrument is a high-precision one, the recorded values will not differ much. Thus, for a high-precision instrument the spread of the number of readings taken at a point of time while measuring a particular value will be very narrow. Precision, therefore, means the degree of agreement of several readings taken for the same value. High precision does not guarantee anything about the accuracy of measurement. Although several readings taken by a precision instrument may be very close to each other, like 1.1110, 1.1108, 1.1109, 1.1111, etc., the readings may have low accuracy, i.e., they may vary significantly from the true value which could be, say 1.2. Precision and accuracy of instruments are dependthe method of measurement and the person making the measurement also changes. Repeatability indicates closeness of readings for the same input with no changed conditions of measurement.

The degree of repeatability or reproducibility in measurement is also a way of expressing the precision of an instrument. To further illustrate the difference between accuracy and precision, let us assume that true value of voltage to be measured is 100 V. The voltmeter readings are taken five times. If the readings are, say 98.01 V, 98.05 V, 98.03 V, 98.01 V, 98.02 V, we can say that the instrument is a precision instrument but not an accurate one as there is considerable error in measurement, which is nearly2 per cent. However, if the consequitive readings taken were closely spread near 100 V i.e., 100.01, 100.02, 99.09, 100.01, 99.08, we could say that the instrument is precise as well as accurate.

It is an usual practice to record a measurement with all digits which can be read with surity about the true value. For example, a resistor of true value 25 Ω if read as 25 Ω, than we may say that its value is nearer to 25 Ω than to 24 Ω or 26 Ω. If the value of the resistor is expressed as 25.0 Ω, it would mean that the resistor is closer to 25.1 Ω or 24.9 Ω. In 25 Ω there are two significant figures and in 25.0 Ω there are three significant figures. An indication of the precision of measurement is given from the number of significant figures in which the measurement reading is expressed. The more is the number of significant figures used in recording the measurement value, the more is the precision of measurement.

11.4.3 Sensitivity and Resolution

Sensitivity: It is the ratio of the output of the instrument to the input, i.e., the quantity being measured. Resolution is defined as the smallest change in input that can be read or detected by an instrument. For a deflection-type instrument, the torque developed by the instrument should be high and the weight of the moving system of the instrument must be low. If the torque by weight ratio is high, the instrument will have a high resolution.

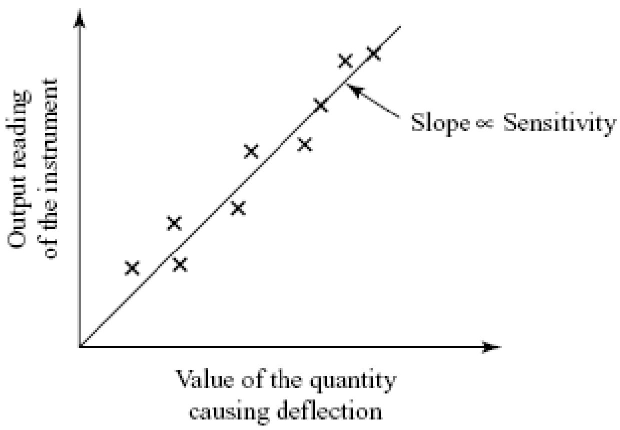


Figure 11.5 Instrument output against the value of the quantity being measured

quantity being measured changes. Fig. 11.5 shows the output readings of measured quantity of a certain variable, say, current in a circuit. Sensitivity, by definition is the gradient or slope of the straight line drawn as in Fig. 11.5. Higher the slope, higher is the sensitivity. Sensitivity is high when there is large deflection of the instrument pointer for a small value of the quantity being measured. For example, if the deflection of the pointer is by 10° for the input voltage of 1 V, then sensitivity is 10°/Volt.

Resolution: While taking measurement, if the input is slowly increased from a certain value, it may be found that the output does not change until a certain increment is exceeded. This small value of input quantity is expressed as resolution. Hence, we may define resolution as the smallest value of input quantity that can be detected by an instrument with certainty. For example, let us assume that an ammeter has a uniform scale having 10 divisions. The full scale deflection is intended to record 100 V as shown in Fig. 11.6. If each division on the scale is divided into 10 parts, the smallest amount of reading that can be read by the instrument is 1 V. The resolution of the instrument is therefore 1V.

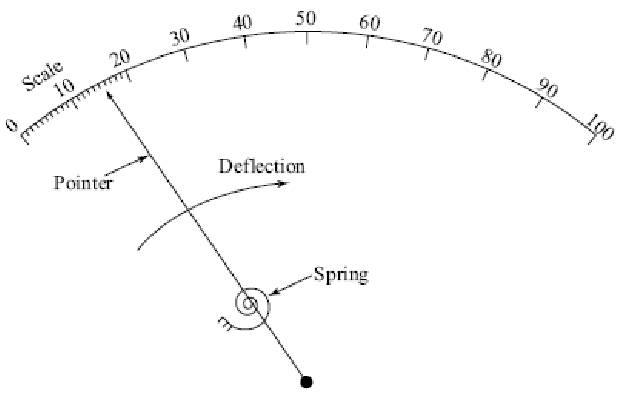


Figure 11.6 Illustrates resolution of an instrument

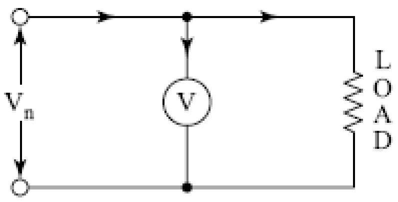


Figure 11.7 Loading effect illustrated

11.4.4 Error, Threshold, and Loading Effect

Error: Error is the deviation of the measured value from the true value. There are different types of errors. Correction in the readings of the instruments is required to be made to eliminate error in the values recorded.

instrument. This minimum value of input quantity is called threshold. Threshold should be as small as possible.

Loading effect: While making measurement using instruments, the original value of the quantity being measured should not change, otherwise we may get wrong results. For example, when a voltmeter is used to measure voltage by connecting the meter across two terminals, the voltmeter, which although has high resistance, will also draw some current as shown in Fig. 11.7.

If the load resistance is high as compared to the voltmeter resistance, the voltmeter may give misleading readings. However, if the load resistance is low we may get dependable readings. Thus, we may say that the measuring instrument should draw only a very infinitesimal current so that the whole current flows through the load. The effect of measuring instrument on the measuring quantity is called loading effect which causes error in reading. Here, in case of a voltmeter, the resistance of the voltmeter should be very high as compared to the load resistance so that the loading effect is minimum.

11.5 LINEAR AND NON-LINEAR SYSTEMS

A measurement system comprises a number of components or subsystems connected together for the purpose of measurement and control of certain variable quantity.

In studying the characteristics of such a system, we generally write mathematical equations representing the system. Such representation in terms of equations is called mathematical modelling. The mathematical model of describing a system is generally expressed with the help of differential equations. The coefficients of the differential equations can either be constants or time variant. Mathematical equations describing a system can be called linear if the laws of superposition and homogeneity are applicable to the system. Suppose, x_1 (t) and x_2 (t) are the two inputs to the system and the corresponding outputs are y_1 (t) and y_2 (t), respectively, then by applying the principle of superposition we will be able to write

$$a_1 x_1 (t) + a_2 x_2 (t) = a_1 y_1 (t) + a_2 y_2 (t)$$

where a_1, a_2 are constants.

Such a system is linear and time invariant. If the coefficients of the differential equations describing a linear system are functions of time, then the system is called linear time-variant system.

Linear systems can be analysed using Laplace transform and Fouriers series. Since almost all measurement systems are nonlinear in nature, they are first linearlized through approximations and then their analysis is done to study the dynamic performance of systems.

11.6 DYNAMIC CHARACTERISTICS OF INSTRUMENTS

Systems are often subjected to inputs which are varying with time. The output of such systems are to be measured. The behaviour of the system under such varying input conditions are called dynamic not be a true reflection of the input in terms of magnitude and phase relationship. The difference between the true value (actual value) of the quantity which is varying with time and the value indicated by the measurement system is called the *dynamic error* of measurement. The rapidity of response of a measurement system is its *speed of response*. The delay or lag in response of a measurement system to the changes in the input quantity being measured is called *measuring lag*.

In dynamic analysis, we determine the characteristics like measuring lag, speed of response, dynamic error, etc.

For the purpose of analysis of a system, equations representing the system are written first. System response is studied by applying different kinds of test signals (like step input signal, ramp input signal, etc.) either in time domain or in frequency domain. In time-domain analysis a time-varying test input signal is applied to the system and the output behaviour of the measurement system is studied as a function of time. In frequency response analysis, the behaviour of the system is studied by applying sinusoidal input, as a function of frequency.

11.7 CLASSIFICATION OF THE INSTRUMENT SYSTEM

Measuring instruments can be classified into separate categories on the basis of different criteria. These classifications are useful in knowing the characteristics of instruments and their selection for a particular use. Instruments are classified as primary or absolute instruments, secondary or derived instruments, null-type and deflection-type instruments, indicating instruments, integrating instruments, recording instruments, analog and digital instruments, monitoring and control instruments, electromechanical and electronic instruments, etc. These are discussed in brief as follows.

11.7.1 Active and Passive Instruments

In active instruments, the measurement output is entirely produced by the quantity being measured. In passive instruments, the quantity being measured simply modulates or changes the magnitude of some external source of power. For example, a current flowing through a coil placed in a constant magnetic field produces a torque. The magnitude of the torque can be used as proportional to the current flowing provided the strength of the magnetic field is constant.

A thermocouple used to measure temperature is a self-generating-type instrument system, and falls under active instrumentation systems or simply active instruments.

The output of a potentiometer having a fixed source of supply can be used to indicate the level of a liquid and is termed as passive instrumentation system.

11.7.2 Analog and Digital Instruments

Analog instruments provide output as a function of time, i.e. the output of the instrument varies continuously as the magnitude of the quantity being measured changes. A deflection-type instrument where the output is indicated by a deflecting needle moving over a graduated scale is an analog instrument. As the input changes, the needle or the pointer moves smoothly and continuously till the final

In digital instruments the output varies in discrete steps, and therefore can have only a finite number of values. A digital revolution counter will count the number of revolutions in discrete numbers and not as a fraction of a revolution. Digital instruments and instrumentation system has a number of advantages over the analog system. Digital instruments measuring the magnitude of some signals can be transmitted over long distances without much distortion. The output of a digital instrument can be fed directly into a digital computer system. An instrument whose output is in digital form can be directly interfaced with the computer for monitoring and control operations.

The output of analog instruments has to be converted into digital form using analog to digital converters (A to D converters) before interfacing with computers. However, this conversion costs money and some time is lost which may be critical in a fast-changing control-system operation. That is why digital instruments are preferred where fast measurement and control operations are involved.

11.7.3 Indicating, Recording, and Integrating Instruments

Indicating instruments give the output as a function of time through the movement of a pointer over a graduated scale. These are, therefore, called analog instruments. The deflection-type ammeters, voltmeters and wattmeters in your laboratory are indicating instruments.

Recording instruments create a written record usually on paper of the time-varying quantity. The measurement system carries a pen which is used to record the value of the time-varying quantity on a paper which is driven by a slow-moving motor drive. The curve traced on the paper indicates the actual variation in the value of the quantity being measured. For example, temperature can be measured and recorded continuously using a recording-type instrument. In an ECG machine the status of health of your heart is recorded on a slow-moving paper and can be classified as a recording-type instrument

Integrating instruments record the total value of the variable quantity over a period of time. For example, the electric meter (kilowatt hour meter) installed in our residences records the total amount of electricity consumed over a period of time. It is a summing or integrating instrument.

11.7.4 Deflection- and Null-type Instruments

In deflection-type instruments deflection of a movable pointer provides a basis for measurement of the quantity which has created the deflection. This deflection is controlled by an opposing force created by some spring action. At a steady-state deflected position, deflecting torque is equal and opposite to the controlling torque. The deflection is measured on a calibrated scale.

In null-type instruments, a null or zero indication of the pointer is used as criteria for determining the value of an unknown quantity. Generally null-type instruments are uncalibrated instruments with the pointer placed on the middle of the graduated but uncalibrated scale.

Accuracy of a deflection-type instrument depends upon the degree of accuracy of the calibration. The accuracy of null-type instruments are higher than deflection type of instruments because null indication means zero current flowing through the instrument, and hence there is no effect of error in measurement due to calibration. However, null-type instruments are not suitable for the measurement of a quantity which changes with time.

11.8 MEASUREMENT ERROR

When we take the measurement of a certain quantity there may be some error in the measurement due to a number of reasons. It is essential, therefore, to know the causes of such error and find ways to reduce them. Study and analysis of errors will determine the degree of accuracy of our measurements. Measurement error can take place if the reading of the instrument is not recorded correctly; if a large capacity instrument is used to measure a small quantity, ie, because of improper selection of instruments; if the adjustment of the instrument prior to measurement is not done (zero reading adjustment); if there are changes in the environmental conditions like temperature, electromagnetic interference, etc., during the measurement; if there are defects in the instrument itself; if there are random variations in the parameters or the system of measurement etc. Thus, we can see that errors can be due to mistakes made by the person taking the measurement; due to defects in the instrument or an improper use of instrument; due to changes in the environmental conditions or changes in measurement parameters.

Errors are generally classified into three categories, namely, gross error, systematic error, and random error.

Gross errors are human errors; systematic errors are instrumental errors; and random errors are because of random variations in measurement parameters.

Example 11.1 It is intended to measure an unknown resistance by the ammeter–voltmeter method. For this, a voltmeter is connected across the unknown resistance and the current flowing through the resistance is measured by an ammeter as shown in fig. 11.8.

The voltmeter used has full scale range of 0–100 V and has sensitivity of 1000 Ω/V. The milliammeter has negligible resistance. Assume that the voltmeter reads a voltage of 80 V across the terminals P and Q. Let us calculate the value of unknown resistance R and then calculate the error in measurement due to current drawn by the voltmeter.

Solution:

$$R = \frac{V}{I} = \frac{80}{5 \times 10^{-3}} = 16 \times 10^{3}\,\Omega = 16\ \text{k}\Omega$$

A voltage of 80 V will also cause a small amount of current flowing through the voltmeter. Voltmeter resistance, R_n = 1000 Ω/V × 100 = 100 kΩ

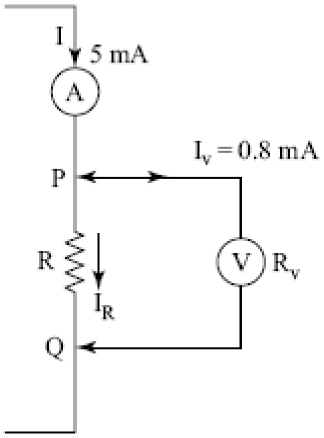


Figure 11.8 Loading effect illustrated

To calculate the value of R we had taken current flowing through it as 5 mA. In fact, this has not been the case. Current through R is I_R.

$I_R = I - R_V = 5 \text{ mA} - 0.8 \text{ mA} = 4.2 \text{ mA}$

The actual resistance value, $R_a = \dfrac{80 \text{ V}}{4.2 \text{ mA}} = 19 \text{ k}\Omega$

Measurement error in percentage $= \dfrac{\text{actual value} - \text{measured value}}{\text{actual value}} \times 100$

$$= \frac{19 - 16}{19} \times 100 = 15.8 \text{ per cent}$$

Now, let us examine the effect of using a voltmeter of high input impedance in this measurement. Let the sensitivity of the voltmeter be 5000 Ω/V instead of 1000 Ω/V.

The voltmeter resistance, $R_V = 5000 \times 100$ W

= 500 kΩ

Current drawn by the voltmeter,

$$I_V = \frac{80}{500 \times 10^3} = 0.16 \text{ mA}$$

Actual value $= \dfrac{80 \text{ V}}{4.84 \text{ mA}} = 16.5 \text{ k}\Omega$

Percentage error $= \dfrac{16.5 - 16}{16.5} \times 100 = 3 \text{ per cent}$

be very very high. Otherwise there will be considerable measurement error due to the loading effect of the voltmeter. In the ideal case the voltmeter used should not draw any current while measuring the voltage across the terminals.

Carelessness in taking readings and their recording, incorrect adjustment of the instrument, incorrect choice of instruments, etc. are attributed to gross error. These errors can be avoided by a careful choice of instruments and recording of measured data. Normally, a number of readings are taken instead of depending upon one or two readings.

Systematic errors are due to instrumental error or due to the effect of environment on measurement.

Random errors are due to unknown causes. While measuring some quantity through an instrument we may find that the readings vary for reasons not known to us. Such variations are not attributed to reasons mentioned under gross error and systematic error. While we are particular about the accuracy of measurement, we make corrections in the measured value by using statistical methods of calculations. For this purpose a large number of readings are taken of the quantity and through statistical analysis the best approximation about the true value is arrived at.

Example 11.2 Calculate the error due to the loading effect of a voltmeter used to measure voltage across the terminals in the circuit as shown in Fig. 11.9. The voltmeter is having an internal resistance of 925 kΩ.

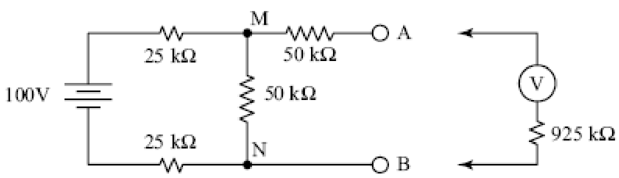


Figure 11.9 Loading effect illustrated

Solution:

Voltage across terminals A and B, $$V_{AB} = \frac{100 \times 50}{25 + 25 + 50}$$

= 50 V

Note that voltage across the 50 kΩ resistor is the same as voltage across terminals A and B. That is voltage across terminals MN is the same as across terminals AB.

Thevenin's equivalent resistance across terminals A and B is calculated by replacing the EMF source by its internal resistance which is zero in the case. Hence, we just short the voltage source and calculate the equivalent resistance across terminals AB as shown in Fig.

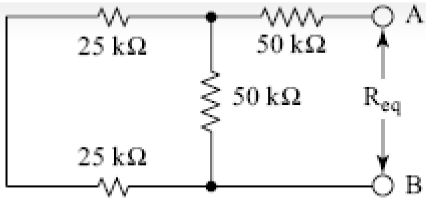


Figure 11.10

Thevenin's equivalent circuit of Fig. 11.9 is represented as shown in Fig. 11.11.

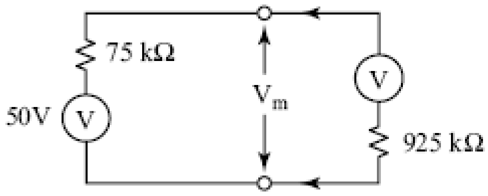


Figure 11.11

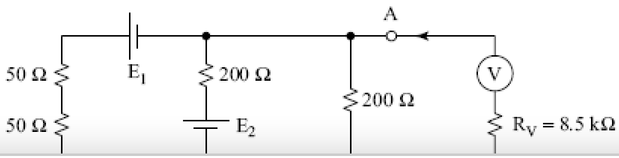
The voltage measured by the voltmeter as a consequence of its internal resistance is calculated as

$$V_m = \frac{50 \times 925}{75 + 925} \text{Volts} = \frac{50 \times 925}{1000} = 46.25 \text{V}$$

$$\text{Loading Error} = \frac{\text{Actual voltage} - \text{Measured voltage}}{\text{Actual voltage}} \times 100$$

$$= \frac{50 - 46.25}{50} \times 100 = 7.5 \text{ per cent}$$

Example 11.3 Calculate the error in the measured value of voltage across terminals A and B as shown in Fig. 11.10, using a voltmeter having an internal resistance of 8.5 kΩ. What would be the error if the voltmeter internal resistance is 2 kΩ?



Solution:

Thevenin's equivalent resistance, R_{AB} of the circuit by assuming zero resistance of the voltage sources is calculated as shown in Fig. 11.13.

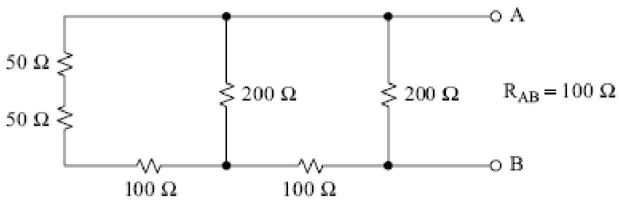


Figure 11.13

Let the open-circuit voltage across terminals A and B be E_0

Thevenin's equivalent circuit can be represented as shown in Fig. 11.14.

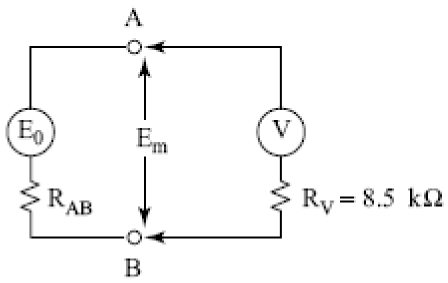


Figure 11.14

The measured value by the voltmeter across terminals A and B is E_m.

E_m can be calculated as

$$E_m = \frac{E_0 \times R_V}{R_{AB} + R_V} = \frac{E_0 \times 8500}{100 + 8500}$$

Now, actual value of voltage across AB is E_0, its measured value is E_m.

Error in percentage $= \frac{E_0 - E_m}{E_0} \times 100$

$$= \left[\frac{E_0 - E_0 \times \frac{8500}{8600}}{E_0} \right] \times 100$$

$= 1.16$ per cent

Now, let us assume $R_V = 2000\ \Omega$

$$E_m = \frac{E_0\ R_V}{R_{AB} + R_V} = \frac{E_0 \times 2000}{100 + 2000} = E_0\ \frac{2000}{2100}$$

Error in percentage $= \frac{E_0 - E_m}{E_0} \times 100$

$$= \left[\frac{E_0 - E_0 \times \frac{20}{21}}{E_0} \right] \times 100$$

$= 4.76$ per cent

Thus, we see that the voltmeter resistance must be very high as compared to the circuit resistance R_{AB} so as to make the measurement error negligible. Now, let us consider a case of error in measurement due to wrong selection of instrument range. For example, a voltmeter rated at 0–300 V has its full scale deflection upto 300 V. Its accuracy is specified in terms of its full scale deflection. If the same voltmeter is used to measure a low voltage, the accuracy of measurement will get reduced. That is why, while selecting measuring instruments, we should select instruments of proper range to avoid too much error in measurement. This is explained with the help of one example.

Example 11.4 A voltmeter of range 0–300 V, and accuracy of 0.1 per cent on full scale deflection has been used to measure 15 V. Calculate the error in measurement as a result of using an instrument of higher voltage range to measure a comparatively low voltage.

Solution:

The magnitude of error on full scale deflection, i.e., 300 V is

$$0.1 \text{ per cent of } 300 \text{ V} = \frac{0.1 \times 300}{100} = 0.3 \text{ V}$$

Therefore, percentage error = $\frac{0.3}{15}$ ×100 = 2 per cent.

It is to be noted that the error is much higher now. That is why one should not use a high-range instrument to measure a low value.

Example 11.5 A voltmeter of the range 0–300 V has a guaranteed or limiting error mentioned by the manufacturer as 1.0 per cent. Calculate the limiting error (relative error) when the same instrument is used to measure lower voltages.

Solution:

Limiting error for full-scale deflection is 1 per cent magnitude of limiting error for

full scale deflection $= \frac{300 \times 1}{100} = 3\ \text{V}$

If the same instrument is used to measure a voltage, say 150 V, then the relative limiting error would be

$$= \frac{3}{150} \times 100 = 2\ \text{per cent}$$

For measurement of 75 V using the same instrument, the relative limiting error would be equal to

$$\frac{3}{75} \times 100 = 4\ \text{per cent}$$

So, we may conclude that measurement of lower voltages using the same instrument results in less accurate measurement.

11.9 INDICATING-TYPE INSTRUMENTS

In this type of instruments, measurement is indicated by a pointer moving over a graduated scale. Voltmeters, ammeters, wattmeters, etc., are of indicating type which are extensively used in laboratories and control panels. Different types of indicating instruments are described in the following sections.

11.9.1 Permanent Magnet Moving Coil Instruments

Permanent magnet moving coil (PMMC)-type instrument is the basic dc measuring instrument. In these instruments a permanent magnet, generally of horseshoe type, creates a magnetic field in which a coil of fine wire of number of turns is placed. The coil is wound on a very light aluminium drum and is pivotted on jewel bearings so that the coil is free to move when current flows through it. The current-carrying coil placed in the magnetic field experiences action. A simplified diagram of a PMMC-type instrument has been shown in Fig. 11.15.

When the coil alongwith its pointer moves because of deflecting torque, it should be free from oscillations, i.e., the pointer should quickly come to its deflected position over a graduated scale so that the reading can be taken. To reduce any oscillation of the pointer, a damping mechanism is provided which produces a *damping torque* which damps or reduces the oscillation.

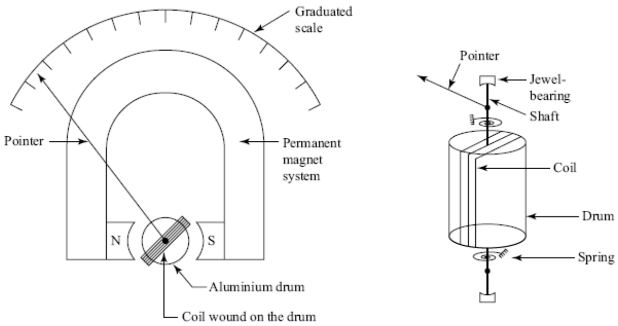


Figure 11.15 (a) PMMC-type instrument; (b) moving system

Thus, there exists three types of torques on the moving system, i.e., *deflecting torque, control torque,* and *damping torque*. Note that if the control torque is not provided for, then for any amount of deflecting torque the pointer will give full-scale deflection.

Equation for deflecting torque

Let I be the current flowing through the moving coil N be the number of turns of the moving coil B be the flux density due to the magnetic field created by the magnet in which the moving coil is placed ℓ be the length of one side of the coil and r be the radial distance of the coil from its axis of rotation (deflection).

Then, force on each coil side is BI ℓ

For N number of turns

$$F = NBI\,\ell$$

Torque = Force × Distance

Therefore, deflecting torque, $T_d = BI\,\ell \times 2r$

$= NBAI$

$= KI$

Where K = NBA = meter constant.

d is the diameter or width of the coil.

Thus, we see that deflecting torque is proportional to the current flowing through the coil. This deflecting torque is being opposed by the control torque. If a spring is used to produce control torque (through winding and unwinding of the spring), the control torque, T_c will be $T_c = K_s\,\theta$ where K_s is the spring constant and θ is the angle of deflection of the moving coil.

It can be seen that more the deflection, more is the winding of the spring, and hence, more is the control torque.

When T_d is higher than T_c, the coil will get deflected more and more, till T_c, the opposing torque becomes equal to the deflecting torque. Thus, for final deflection

$$T_d = T_c$$

or, $$KI = K_s\theta$$

or, $$I = \frac{K_s}{K}\theta \quad \text{or} \quad \theta = \frac{k}{k_s} I$$

Thus, deflection, θ is directly proportional to the current being measured.

A pointer is attached to the spindle (shaft) of the moving coil which moves over a graduated scale. The scale is calibrated in terms of amperes or volts depending upon whether the instrument is designed for the measurement of current or voltage, respectively. Since the deflection is directly and linearly related to the current flowing through the coil, the scale of the instrument will be a linear one. That is to say, the calibrations will be equally spaced as shown in Fig. 11.16.

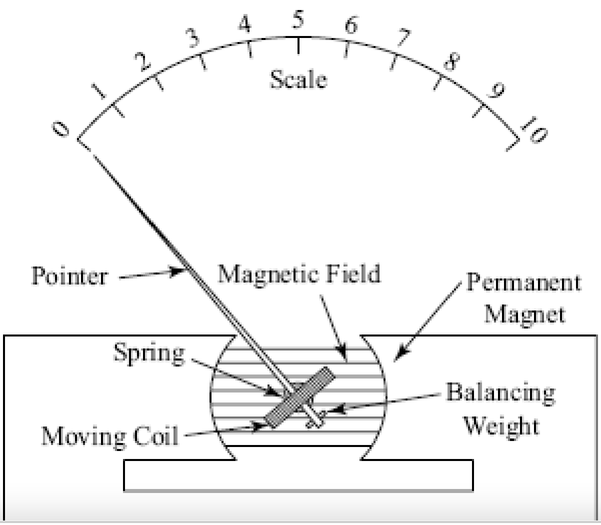


Figure 11.16 Constructional details of a PMMC-type measuring instrument

Fig. 11.16 shows the inside of a PMMC instrument with a U-shaped permanent magnet. For producing high flux density, magnetic materials such as Alnico (alminium-nickel-cobalt) are used so that magnets of smaller size could be used and the overall size of the instrument could be reduced.

The weight of the moving system is made very low by choosing a light aluminium drum as the armature on which coils are placed. For higher sensitivity, the requirement is that the ratio of torque and weight of the moving system should be high. The requirements are, therefore, for a strong magnetic field, reduced size, and reduced weight of the moving system. The range of deflection of the pointer has to be made high, ranging from 120° or more so as to achieve better and correct recording of meter readings. The two hair springs made of phosphor bronze provide the control torque. They also provide path for entry and exit of current to and from the moving coil. Hair springs are attached to the spindle and carry current to the moving coil and also provide the return path.

Damping of the moving system, i.e., the reduction of oscillation under the deflected condition is reduced because of opposing torque developed due to induced eddy currents in the aluminium drum. Interaction between eddy currents and the flux produces opposing torques reducing oscillations of the moving system. This is known as *eddy current damping*. Note that oscillations produce eddy current in the drum, and torque produced by the induced eddy current and magnetic field flux opposes the oscillation. This is an example of the application of Lenz's law.

A properly damped (also called critically damped) moving system will move reasonably fast but without overshoot and oscillations in the deflected position. Damping may be of any of the following types, viz (a) eddy current damping; (b) air friction damping; (c) fluid friction damping.

The pointer fixed on the spindle moves over a graduated scale. To keep the moving system light, the pointer is also made up of a very light-weight material with a fine edge for accurate measurement. The weight of the moving system is balanced by using some counter weight on the pointer on one side. The scale of a PMMC-type instrument is linear, i.e., its divisions are equally spaced. This is because the torque developed is directly proportional to the current flowing through the coil, i.e., the current to be measured. For low range of currents, say upto 20 mA, the entire current to be measured is allowed to pass through the moving coil. However, for larger currents to be measured, the moving coil is shunted by a parallel resistance of very low value so that the majority of the line current flows through the shunt resistance. However, reading of the instrument has to be in terms of the total current. An instrument of lower range can be used for higher range by connecting a *shunt* resistance of appropriate value and accordingly changing the calibration of the scale of measurement.

A PMMC-type milliammeter can be used to measure dc voltage by

Now suppose we connect a PMMC-type instrument for measurement of ac voltage or current. Can you imagine what would happen? If the frequency of supply is low, the instrument will show positive reading for one half cycle and negative reading for the next half cycle. For a centre *r* zero instrument where the pointer is at the middle, on low-frequency supply the pointer will be seen oscillating at the same frequency of the supply. For normal power frequency, i.e., 50Hz supply, the oscillations will be very quick. However, due to inertia, the moving system will not be able to respond to the quick positive and negative pulses but will somewhat vibrate in its initial position of rest indicating that the average value of the quantity to be measured is zero. PMMC instruments are therefore not suitable for measurement of alternating quantities.

Temperature compensation: We have seen that torque developed is proportional to magnetic field strength of the permanent magnet used and the current flowing through the coil. The deflecting torque is balanced by control torque produced by spring tension. The temperature variation affects both magnetic field strength and spring tension. The resistance of the coil used also increases with temperature. The reduced spring tension will cause the pointer to read higher than the actual value. The increase in coil resistance (i.e., reduced current) and the reduced magnetic field strength (reduced flux) will cause the pointer to read lower than the actual value. Since these effects are not balancing each other's effect of reduced or enhanced meter reading, some temperature compensating arrangement has to be made to increase the accuracy in meter readings.

If a PMMC instrument is not compensated against temperature effects, it has been observed that for each degree of temperature rise the meter tends to read 0.2 per cent lower than the actual value.

We have known that manganin has negligible temperature coefficient of resistance. If we connect a high-value manganin resistor in series with the moving coil, the total change in resistance of the combination of resistance of manganin resistor and the copper coil will be negligible and the temperature effect due to change in resistance can be avoided. The other two effects, i.e., reduction of spring tension causing increased reading and reduction of flux density causing reduced reading should more or less cancel each other. The manganin resistor which is made 20 to 30 times more than the resistance of the moving coil is called *swamping resistor*.

An uncalibrated PMMC instrument is also known as *galvanometer* which is generally used as a null detector in a bridge circuit. The galvanometer is used only to detect any flow of current and not the amount of current. When a galvanometer scale is calibrated in terms of current or voltage, it can be used as an ammeter or a voltmeter. So, the basic moving element of a dc ammeter or a dc voltmeter is a PMMC galvanometer. However, since the winding of the moving coil is made up of very thin wire to keep it light, it can carry only a very small amount of current, of the range of few milliamperes. When calibrated in milliamperes, the instrument becomes a milliammeter. When the galvanometer is to be converted into an ammeter of higher ranges, very-low-value resistances are connected in parallel with the moving coil so as to bypass the excess current (i.e., the current which is more than a few milliamperes that

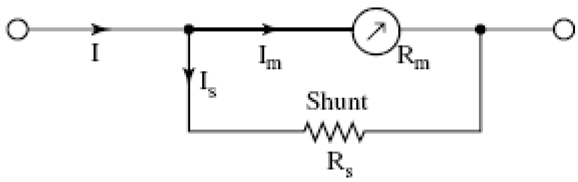


Figure 11.17 Basic ammeter circuit with a low-value shunt resistance

$I_m R_m = R_s I_s$ and $I = I_m + I_s$

Therefore, $$R_s = \frac{I_m R_m}{I_s} = \frac{I_m R_m}{I - I_m}$$

The value of shunt resistance, R_s has to be calculated for each range of current measurement. For example let us consider a 0–1 mA instrument having a coil resistance of 80 Ω to be used for measurement of larger current in two ranges, i.e., 0–100 mA and 0–1 A. The values of two shunt resistances are calculated as follows.

For the range of current measurement of 0–100 mA, we have to take, I = 100 mA, i.e., full-scale deflection value of current.

Shunt current, $I_s = I - I_m = 100 - 1 = 99$ mA.

Shunt resistance,

$$R_s = \frac{I_m R_m}{I_s} = \frac{1\,\text{mA} \times 80}{99\,\text{mA}} = 0.808\ \Omega$$

For the range of current measurement of 0–1 A using the same instrument we need to have a separate shunt whose value is calculated as

$$R_s = \frac{I_m R_m}{I_s} = \frac{1\,\text{mA} \times 80}{I - I_m} = \frac{1\text{mA} \times 80}{1000\,\text{mA} - 1\,\text{mA}} = 0.080\ \Omega$$

11.9.2 Use of Shunts and Multipliers

Shunts are small resistances connected in parallel to increase the range of an ammeter. For multi-range ammeters, the moving coil remaining same, separate shunts are used to increase the range of measurement of a single instrument.

Multipliers are high resistances connected in series with the moving coil to extend the range of measurement of PMMC-type voltmeters.

A dc ammeter can be used as a multi-range ammeter by using a number of shunt resistances in parallel with the instrument. Their values are to be calculated according to the range of measurement scale as has already been explained with an example.

the terminals. The high resistance connected in series with the instrument limits the current flowing through the coil of the instrument. The value of the multiplier is calculated as shown in Fig. 11.18.

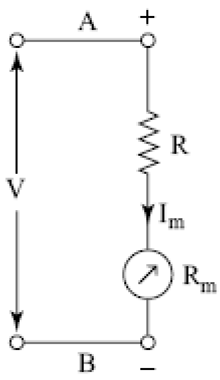


Figure 11.18

Let R be the series resistance of the multiplier as shown in Fig. 11.18.

I_m is the full-scale deflection current of the instrument.

R_m is the resistance of the moving coil.

V is the desired full-scale voltage range of the instrument being used as a voltmeter.

From the circuit of Fig. 11.18

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

or, $$R = \frac{V - I_m R_m}{I_m} = \frac{V}{I_m} - R_m \quad \text{(i)}$$

For example, let $R_m = 50\ \Omega$, $I_m = 1$ mA and the range of the voltmeter be 0–100 V.

Then the multiplier resistance R is calculated by using relation (i) as

$$R = \frac{100}{1 \times 10^{-3}} - 50 = 100{,}000 - 50$$

$$= 99{,}950\ \Omega$$

This shows that the value of multiplier is very high whereas a shunt resistance used in dc ammeters is very low. The multiplier resistor is ances are placed inside the instrument box, a selector switch can be used to choose the particular range of the instrument for the measurement of voltage accurately as shown in Fig. 11.19.

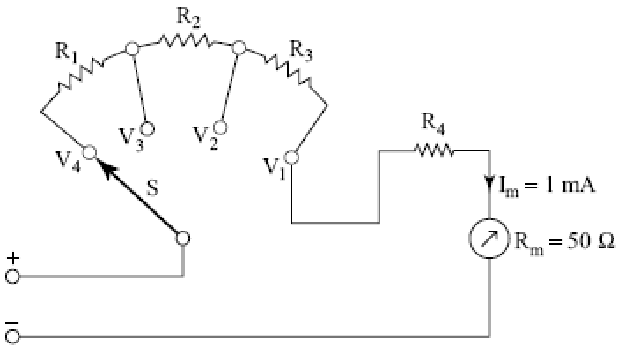


Figure 11.19 Multi-range dc voltmeter

V_1 is for the lowest range of measurement of voltage. As the voltage range is higher, higher is the value of multiplier resistance like R_4 + R_3 for range V_2, R_4 + R_3 + R_2 for range V_3, etc.

Let us assume that the moving coil is to be converted into a voltmeter of different ranges, viz 0–10 V, 0–50 V, 0–50 V, and 0–500 V.

For 0–10 V measurement the selector switch S has to be put at V_1. The series multiplier resistance is R_4. Since, R_4 and R_m are in series across 10 V and for full-scale deflection I_m is equal to 1 mA, we can write

$$V = I_m (R_m + R_4)$$

or,

$$10 = 1 \times 10^{-3} (50 + R_4)$$

or,

$$R_4 = \frac{10}{1 \times 10^{-3}} - 50 = 9{,}950\ \Omega$$

The total circuit resistance is R_4 + R_m

= 9950 + 50

= 10,000 W

Similarly, the values of R_3, R_2, and R_1 can be catantated for higher voltage ranges.

The *sensitivity* of a voltmeter is expressed as the ratio of the total circuit resistance to the voltmeter rating, i.e., in terms of ohms per volt.

11.9.3 Moving Iron Instruments

Attraction-type MI instruments: In this type of instruments there is one fixed coil and one moving iron. The fixed coil is wound on a former. The current to be measured or a current proportional to the voltage to be measured is allowed to flow through this fixed coil. A disc made of iron is attached to the spindle. A pointer is also attached to the spindle. Current passing through the fixed coil produces a magnetic field inside the coil. This magnetic field attracts the piece of iron which is free to move around the spindle. When the iron disc gets attracted it moves inside the coil. When this happens, the pointer moves over a graduated scale. The movement of the iron piece is always from the weaker magnetic field that exists outside the coil towards the strong magnetic field that exists inside the coil irrespective of the direction of current flow through the coil. The deflection of the pointer has to be controlled. The control torque is provided by a spring. The control torque is proportional to deflection θ. The deflecting torque is proportional to the square of the current.

$$T_d \propto I^2$$

$$T_c \propto \theta$$

where θ is the angle of deflection of the pointer over the scale.

T_d is the deflecting torque.

T_c is the control torque.

For a steady deflection, $T_d = T_c$

Therefore, $\theta \propto I^2$

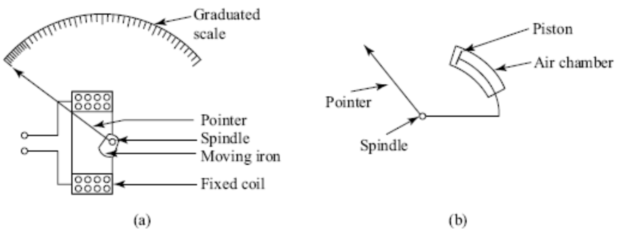


Figure 11.20 (a) Attraction-type moving iron instrument; (b) air friction damping mechanism

Deflection of the pointer is proportional to the square of the current flowing through the coil. The scale of the instrument is therefore a cramped scale, i.e., there will be congestion at the beginning of the scale. The instrument will measure both ac and dc and deflection of the pointer will be unidirectional. Damping, i.e., reduction of oscillation of the pointer is achieved by air friction damping mechanism veloped which reduces any oscillation of the pointer on the scale when measurement is taken.

Repulsion-type MI instruments: Like in attraction type, the fixed coil carries the current or current proportional to the voltage to be measured. On the inner surface of the coil, a specially shaped iron piece is attached. See Fig. 11.21 (b). This is the fixed iron piece. On the spindle is attached another piece of iron in the form of a fin. This is the moving iron. The current passing through the coil produces a magnetic field. In this magnetic field are placed both the fixed iron and the moving iron. Both these iron pieces will be similarly magnetized due to the influence of the magnetic field. This will create a force of repulsion among the two pieces of iron. One piece of iron being fixed, the other piece of iron will move which will create a deflecting torque. This deflecting torque has to be opposed by a control torque such that under steady deflection, $T_d = T_c$.

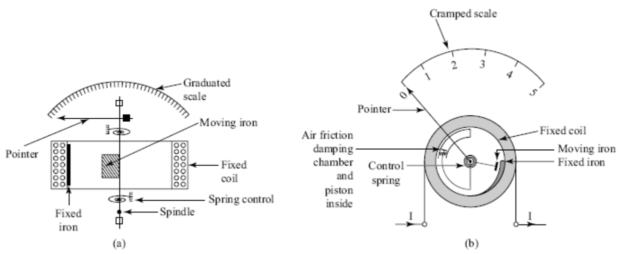


Figure 11.21 (a) Repulsion-type moving iron instrument; (b) another view of a repulsion-type MI instrument

If T_d is more than T_c, the pointer will move. Its movement will stop when the deflecting torque, T_d equals the control torque, T_c. Since the magnitude of the deflecting torque depends upon the magnetism of the two pieces of iron, and since this magnetism is produced by the current to be measured, we can write

$$T_d \propto I^2$$

and $T_c \propto \theta$, as more the deflection, θ more is the control torque, T_c.

Thus, deflection of the pointer, θ is directly proportional to the square of the current to be measured. Control torque is provided by spring attached to the spindle and damping (reduction of oscillation of the pointer in the deflected position) is provided by the air friction damping mechanism. As $\theta \propto I^2$, this instrument can be used for both ac and dc measurement.

11.9.4 Dynamometer-type Moving Coil Instruments

In dynamometer-type instruments, there is one fixed coil and one moving coil. The fixed coil is however, made in two sections, and measurement of current, voltage, and power, respectively. For use as ammeter and voltmeter, both the fixed coils and the moving coil are connected in series as shown in Fig. 11.22. For use as wattmeter, the fixed coils will carry the line current while the moving coil will carry a current proportional to the voltage. That is, in a wattmeter, the fixed coils, which are also called the current coils, are connected in series with the load whose power is being measured and the moving coil, which is also called the voltage coil or pressure coil, is connected across the supply voltage. As wattmeter the deflecting torque will be proportional to power in an ac circuit, i.e.,

$$P = VI \cos \phi$$

where cos ϕ is the power factor of the circuit.

In dynamometer instruments, torque is developed due to the interaction of the two magnetic fields produced by the current flowing through the fixed coils and the moving coil.

The control torque is provided by a set of helical springs attached to the spindle such that, $T_c = K\theta$. where K is the spring constant.

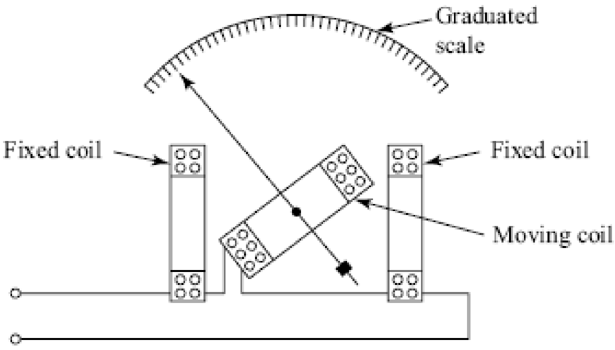


Figure 11.22 Connection diagram of a dynamometer-type ammeter or voltmeter

The deflecting torque T_d is proportional to the product of the current flowing through the fixed coils and the moving coil. As in ammeter and voltmeter, same current flows through these coils; therefore

$$T_d \propto I^2$$

and $$T_c \propto \theta$$

Thus, $$\theta \propto I^2$$

The torque developed will always be positive irrespective of the direction of current. Therefore, the instrument can be used for both ac and dc measurements.

Although dynamometer-type instruments can be used for both ac and dc measurements, they are mostly used for ac measurement.

The weight of the moving system of this type of a instrument is high as compared to other types of instruments. Hence, the torque by weight ratio is low, and therefore the sensitivity is low. Error due to friction is also considerable. Power consumption is considerably high as both the coils will draw currents. Thus, the loading effect will be more.

Dynamometer-type instruments have the advantage of measurement of rms. values of ac quantities irrespective of their wave shapes.

Errors that usually occur in such diffecting-type measuring instruments are as follows.

1. *Frictional error:* This is due to the movement of the deflecting system. If torque developed is high and the weight of the moving system is kept low, frictional error will be minimized.
2. *Temperature error:* Current flowing through the coil providing the magnetic field raises the temperature of the copper wires used thereby contributing to error in measurement. Even changes in ambient temperature (operating temperature or room temperature) adversely increases error in measurement.
3. *Effect of stray magnetic field:* The deflection of the moving system may get affected due to the presence of any magnetic field around. Since the magnetic field produced by the measuring instruments is not so strong, their operation may get affected if any strong magnetic field exists nearby. Such effect of stray magnetic field (outside magnetic field) is eliminated by proper *shielding of the instrument*. Shielding involves placing the instruments inside a laminated steel container such that the whole of the instrument is shielded (insulated) from outside the magnetic field.
4. *Error due to changes in frequency:* In certain types of instruments, like in moving iron instruments, the change in frequency causes error due to the change in magnitude of eddy currents set up in the metal portion of the instruments. Changes in frequency causes changes in reactance of the operating coil ($X = 2\pi f$). This causes change in the current flowing and field produced as in the case of ac operation of instruments as voltmeters.

11.10 MEASUREMENT OF POWER

Power in dc circuit is the product of voltage and current. In ac circuit power is a product of voltage, current, and power factor. Using an ammeter and a voltmeter power cannot be measured in ac circuits as this method would not take care of the power factor. For measuring power in ac circuit we use a wattmeter.

11.10.1 Power in dc and ac Circuits

In ac circuits, power is the product of instantaneous value current and instantaneous value voltage. Thus, in an ac circuit with R–L load

AC Power, $p = v \times i$

where $v = V_m \sin \omega t$

and $i = I_m \sin(\omega t - \phi)$

ϕ = power factor angle

Substituting

$$P = V_m \sin \omega t \times I_m \sin(\omega t - \phi)$$
$$= \frac{V_m I_m}{2} \times 2 \sin \omega t \sin(\omega t - \phi)$$
$$= \frac{V_m I_m}{2} [\cos\phi - \cos(2\omega t - \phi)]$$

[since 2 sin A sin B = cos (A – B) – cos (A + B)]

Average power is calculated over one cycle.

Thus,

$$P_{av} = \frac{V_m I_m}{2}\left[\frac{1}{2\pi}\int_0^{2\pi}\left[\cos\phi - \cos(2\omega t - \phi)\, d\omega t\right]\right]$$
$$= \frac{V_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}}\cos\phi$$
$$= V\, I \cos\phi$$

where V and I are the rms values of voltage and current and cos ϕ is the power factor of the circuit.

11.10.2 Measurement of Power in Single-phase Ac Circuit

For measurement of power we generally use an electrodynamometer-type wattmeter. The wattmeter has two coils; one is a stationary or fixed coil and the other is a moving a coil. The moving coil terminals and stationary coil terminals are brought out in the instrument for connection to the circuit for power measurement. The fixed coil is connected in series with the load whereas the moving coil is connected in series with a high resistance and is connected in parallel, i.e., across the load as shown in Fig. 11.23.

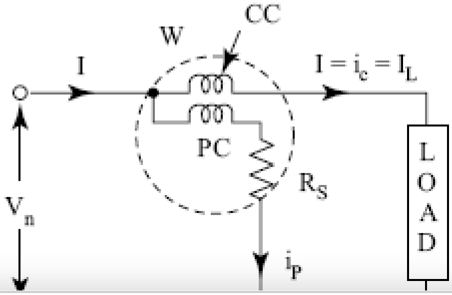


Figure 11.23 Measurement of power in an ac circuit using a wattmeter

It can be seen from Fig. 11.23 that the coil *cc*, called the current coil carries the current, i_c which is the same as the load current because this coil is connected in series with the load. The coil pc, called the pressure coil or voltage coil is connected in parallel with the load. This coil carries a current, i_p. Current, i_p flows through the pressure coil and through the high resistance R_s. Neglecting the impedance of the pressure coil, i_p can be taken as equal to $\frac{V}{R_s}$.

$$T_d = i_1 i_2 \frac{dM}{d\theta}$$

Here, $$T_d = i_p i_c \frac{dM}{d\theta}$$

where M is the mutual inductance of the two coils and θ is the angle of deflection.

Let the supply voltage be, $v = V_m \sin \omega t$. Then

$$i_p = \frac{V_m}{R_s} \sin \omega t \quad \text{and} \quad i_c = I_m \sin(\omega t - \phi) \text{ for lagging power factor load}$$

Therefore, $$T_d = \frac{V_m}{R_s} \sin \omega t \; I_m \sin(\omega t - \phi) \frac{dM}{d\theta}$$

$$= \frac{V_m I_m}{2 R_s} [2 \sin \omega t \sin(\omega t - \phi)] \frac{dM}{d\theta}$$

$$= \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}} \frac{1}{R_s} \frac{dM}{d\theta} [2 \sin \omega t \sin(\omega t - \phi)]$$

Average deflecting torque

$$T_{dav} = \frac{VI}{R_S} \frac{dM}{d\theta} \frac{1}{2\pi} \int_0^{2\pi} [\cos\phi - \cos(2\omega t - \phi)] d\omega t$$

$$= \frac{VI}{R_s} \cos\phi \frac{dM}{d\theta}$$

The control torque is provided by the spring control mechanism.

$$T_c = K_s\theta$$

where θ is the angle of deflection and K_s is the spring constant

Under steady-state deflection, $T_{d_{av}} = T_c$

∴ $$K_s\theta = \frac{VI\ \cos\varphi}{R_s}\frac{dM}{d\theta}$$

or, $$\theta = \frac{VI\ \cos\varphi}{K_s R_s}\cdot\frac{dM}{d\theta}$$

By proper design of the instrument, the rate of change of mutual inductance, M of the moving coil and stationary coil with respect to deflection, θ, i.e., $\frac{dM}{d\theta}$ is kept constant over the range of deflection of the moving coil.

The deflection θ is written as

$$\theta\ \alpha\ VI\ \cos\ \varphi$$

i.e., deflection of the moving coil is proportional to the power of the ac circuit.

In ac circuits, the deflection of the moving system will always be positive. This is because in ac as the polarities of supply change, current through both the current coil and pressure coil will change, and hence the deflection always remains positive. The wattmeter is suitable for both ac and dc power measurements.

11.10.3 Sources of Error in Measurement Using Dynamometer-type Wattmeters

A wattmeter has two coils, namely, the current coil which carries the load current and the voltage coil or the pressure coil which is connected in series with a non-inductive high-value resistance across the load terminals. Torque is produced due to the interaction between the fields created by the current flowing through these two coils. Since the coils are air cored, the fields produced are comparatively weaker than the field produced in a PMMC instrument. For this reason the reading of a wattmeter may get somewhat affected due to any strong magnetic field. Temperature rise due to current flow through the coils is another source of error in the instrument reading.

If the pressure coil inductance is considerable, it will create some error in the instrument reading. There are other reasons for causing error in the reading of a wattmeter unless some remedial measures are taken in the design of the instrument. The various other sources

The pressure coil of the wattmeter has some inductance as it is made up of a number of turns and the current flowing through it is alternating in nature. While deriving the torque equation for the wattmeter, however, we neglected this inductance and had considered only the resistance of the pressure coil circuit. By assuming the pressure coil circuit as resistive we had considered the pressure coil circuit current being in phase with the voltage.

In Fig. 11.24, the pressure coil current, i_P has been shown lagging the voltage, V by a small angle, θ. This is by considering the inductive reactance of the pressure coil circuit in addition to the high-value resistance, R_P in the circuit.

The angle of lag of current coil current, I_c which is equal to I is φ, which is the power factor angle of the load.

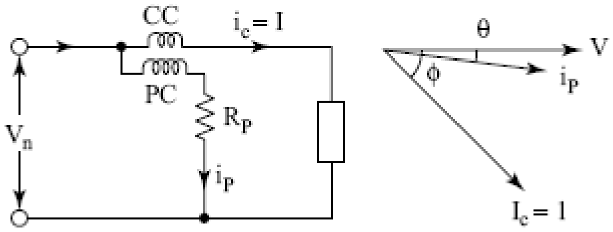


Figure 11.24

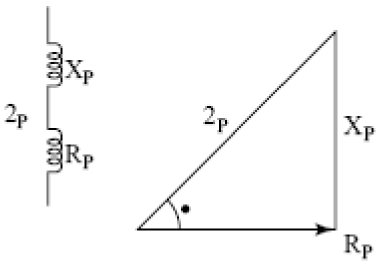


Figure 11.25

Actual reading of the wattmeter, W_a considering the inductance of the pressure coil

$$W_a \propto I_p I_c \cos(\varphi - \theta)$$

$$\propto \frac{V}{Z_p} I_c \cos(\varphi - \theta)$$

Therefore, $W_d \propto I_p I_c \cos\varphi$

$$\propto \frac{V}{R_p} I_c \cos\varphi$$

The ratio of the two wattmeter readings, i.e., W_a and W_d are

$$\frac{W_d}{W_a} = \frac{V}{R_p} I_c \cos\theta \div \frac{V}{Z_P} I_c \cos(\varphi - \theta)$$

or,

$$\frac{W_d}{W_a} = \frac{V\ I_c \cos\phi}{Z_P\ \cos\theta} \times \frac{Z_p}{VI_c\ \cos\ (\phi - \theta)}$$

$$= \frac{\cos\phi}{\cos\theta\ \cos\ (\phi - \theta)}$$

Therefore, the true or desirable reading

$$W_d = \frac{\cos\varphi}{\cos\theta\ \cos\ (\varphi - \theta)} \times W_a$$

or, $W_d = C.F \times W_a$

The actual reading of the wattmeter has to be multiplied by a factor called the correction factor, CF, which is

$$CF = \frac{\cos\varphi}{\cos\theta \cos(\varphi - \theta)} = \frac{\sec^2\theta}{\cos(\varphi - \theta)/\cos\varphi\cos\theta} = \frac{\sec^2\theta}{(\cos\varphi\cos\theta + \sin\varphi\sin\theta)/\cos\varphi\cos\theta}$$

$$= \frac{1 + \tan^2\theta}{1 + \tan\varphi\ \tan\theta}$$

The angle θ is very small, therefore $\tan^2\theta$ is negligible.

Thus, $CF = \dfrac{1}{1 + \tan\varphi\ \tan\theta}$, Again $W_d = C.F.\ W_a$

or,

$$\frac{W_a}{W_b} = \frac{1}{C.F.} = 1 + \tan\varphi \tan\theta$$

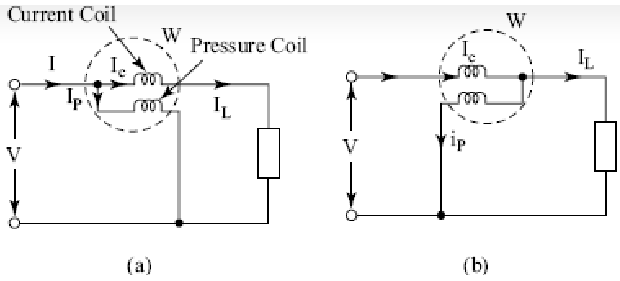


Figure 11.26 Error due to wattmeter connections: (a) when pressure coil is connected before the current coil; (b) when the pressure coil is connected after the current coil

$$\text{Error} = \frac{\text{actual reading} - \text{true or desirable reading}}{\text{true or desirable reading}} = \frac{W_a}{W_d} - 1 = 1 + \tan\varphi \tan\theta - 1$$
$$= \tan\varphi \tan\theta$$

If the power factor of the load is leading, than the correction factor is calculated as

$$CF = \frac{\cos\phi}{\cos\theta\cos(\phi+\theta)}$$

Instead of applying a correction factor in the reading of the wattmeter, the error due to the inductive effect of the pressure coil can be neutralized by connecting a capacitor in series with the pressure coil so that the inductive reactance is balanced by the capacitive reactance.

(b) Error due to method of connection of the current coil and pressure coil

There will be a certain amount of error due to the two types of connections of the wattmeter current coil and pressure coil as shown in Fig. 11.26 (a) and (b). For correct reading, the current coil should carry the load current and the pressure coil be connected across the load. It may be noted that in Fig. 11.26 (b), the current coil carries a current, i_C which is slightly more than I_L ($i_c = I_L + i_p$). In Fig. 11.26 (a), the current coil carries a current i_c which is equal to I_L but the voltage across the pressure coil is slightly more than voltage across the load. Normally, the current flowing through the pressure coil is kept very low by connecting a high resistance in series with the pressure coil so as to reduce error due to connections as described.

11.11 MEASUREMENT OF ENERGY

11.11.1 Introduction

We know that electrical energy is the product of electrical power and time. A wattmeter gives the measure of power at a particular in

An energy meter is basically a wattmeter fitted with some recording mechanism. An energy meter is also called a kWh meter, i.e., kilo Watt hour meter. The meter which is installed at the main distribution board of power supply at residences is a kWh meter. The energy consumed over a period of time, say two months, is recorded in the form of digits. The electricity supply authority prepares the energy consumption bill according to the consumption made.

The most commonly used energy meter is the induction-type Watt hour meter.

11.11.2 Constructional Details and Working Principle of Single-phase Induction-type Energy Meter

The basic components of a kWh meter are as follows.

1. Pressure coil placed on a magnetic core.
2. Current coils placed on a magnetic core; the mmf of these coils produce the driving torque.
3. The moving system which is an aluminium disc placed between the pressure coil magnetic core and the current coil magnetic core.
4. The braking system which is a U-shaped permanent magnet called the brake magnet which offers a braking effect to the rotating disc.
5. The registering or counting mechanism which consists of a gear train. The mechanism adds together the revolutions made by the rotating aluminium disc. That is, the counting mechanism integrates the instantaneous values of power consumed by the connected load over a period of time.

The constructional details of an induction-type kWh meter has been shown in Fig. 11.27.

The pressure coil is made of a large number of turns and is connected across the supply. The pressure coil is highly inductive as is surround by iron. The core is made of laminated steel sheets. The current coil is shown in two parts wound around a laminated core and is made of thick wire of a few turns. The current coil is connected in series with the load.

Working principle: Let V be the supply voltage and I be the load current. The current flowing through the pressure coil is I_{sh}. Since the pressure coil is highly inductive, I_{sh} will lag voltage V by 90°. Let load power factor be cos ϕ. The load current I will lag the supply voltage by an angle ϕ. Current flowing through the series coil is I. The flux produced by the series coil will be in phase with I. The flux produced by the shunt or pressure coil ϕ_{sh} will be in phase with current I_{sh} as shown in Fig. 11.28.

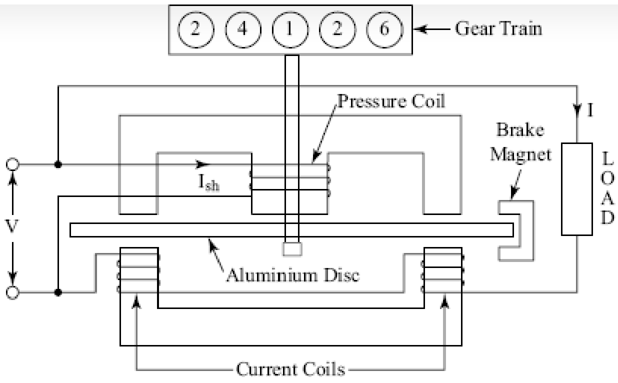


Figure 11.27 Induction-type single-phase energy meter

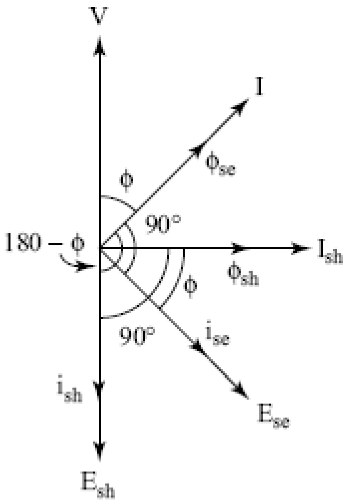


Figure 11.28 Phasor diagram showing the relationship between various quantities of an energy meter

The alternating flux ϕ_{se} will induce EMF E_{sc} in the aluminum disc lagging ϕ_{sc} by 90°. Similarly EMF induced by ϕ_{sh} in the disc will be E_{sh}. E_{sh} will lag ϕ_{sh} by 90°. E_{sc} will circulate eddy current i_{se} in the disc.

Similarly, E_{sh} will circulate eddy current i_{sh} in the disc.

Two opposite torques will be developed due to the interaction of ϕ_{sh} with i_{sc} and ϕ_{se} with i_{sh}. From Fig. 11.28, it is noted that the angle between ϕ_{sh} and i_{sc} is ϕ and the angle between ϕ_{sc} and i_{sh} is $(180 – \phi)$.

$$T_d \propto \left[\phi_{sh}\, i_{se} \cos\phi - \phi_{se}\, i_{sh} \cos(180^\circ - \phi)\right]$$

$$T_d \propto \left[\phi_{sh}\, i_{se} \cos\phi + \phi_{se}\, i_{sh} \cos\phi\right]$$

Now, ϕ_{sh} is proportional to V, i_{sc} is proportional to I, and i_{sh} is proportional to V, and ϕ_{se} is proportional to I.

Therefore, $$T_d \propto \left[VI\cos\phi + VI\cos\phi\right]$$

or, $$T_d \propto VI\cos\phi$$

Thus, the deflecting torque is proportional to the power consumed. For a particular period of time, if power consumed is recorded, the recorded value will give the measure of energy consumed.

The brake magnet produces a braking torque, T_b. When the aluminum disc revolves due to T_d, the magnetic flux of the brake magnet induces eddy current in the disc. The more the speed of the disc the more is the magnitude of the induced eddy current. By Lenz's law, EMF a opposite torque T_b is developed which controls the speed of the disc due to T_d. At a steady speed, $T_d = T_b$

and $$T_b \,\alpha\, N$$

This shows that the revolutions of the disc is the measure of power consumed and $\int_0^t N\,dt = \int_0^t P\,dt$ = Energy consumed.

The revolution made by the aluminium disc per hour when the load is 1kW is called the meter constant. When we say meter constant is 1200, it means 1200 revolutions of the aluminium disc will indicate the consumption of 1 unit of electricity, i.e., 1 kWh of electricity.

One defect in energy meters, known as creeping, show that aluminium disc rotates even when there is no load connected and only the voltage coil is excited.

To prevent any creeping, two small holes on two opposite sides of the spindle is made on the aluminium disc.

Example 11.6 The meter constant of an energy meter is 1200. The meter disc makes 210 revolutions in one minute when a current of 50 A flows through the load. The supply voltage is 230 V. Calculate the percentage error of the meter. Assume unity power factor load.

Solution:

Meter constant = 1200

$$\text{Energy consumed in 1 minute} = \frac{V\ I\ \text{Cos}\phi}{1000} \times \text{time}$$

$$= \frac{230 \times 50 \times 1}{1000} \times \frac{1}{60}\ \text{kWh}$$

$$= 0.191\ \text{kWh}$$

As per meter constant, energy registered in

$$\text{One minute} = \frac{210}{1200} = 0.17\ \text{kWh}$$

$$\text{Percentage error} = \frac{\text{energy registered} - \text{actual energy consumed}}{\text{actual energy consumed}}$$

$$\text{Percentage error} = \frac{(0.175 - 0.191)}{0.191} \times 100$$

$$= -8.3\ \text{per cent}$$

The minus sign indicates that the meter is running slow.

11.12 INSTRUMENT TRANSFORMERS

We have studied earlier that a low-range ammeter can be used to measure a high value of current by using shunts. Similarly, the measuring range of a voltmeter can be extended by using multipliers. However, there are some limitations to the use of shunts and multipliers for measurement of high current and high voltage, respectively by using low-range ammeters and voltmeters.

For measurement of high current and high voltage, voltmeters and ammeters of higher ranges are not used. Instead, for such measurement current transformers (CT) and potential transformers (PT) are used along with low-range ammeters and voltmeters. Generally ammeters of range 0–5 A and voltmeter of range 0–110 V are used.

Fig. 11.29 shows the use of CT and PT in the measurement of current and voltage of higher values. High-voltage and high-current measurements in on electrical power generation and a distribution system are done by installing CTs and PTs near the high-voltage and high-current lines and the output of CTs and PTs are connected to the ammeters and voltmeters of lower rating at the control station. In Fig. 11.29 is shown a power generation and transmission lines. Output of the generator which generates electricity at 11000 V is stepped up at high voltage, say 220 kV by using a step-up transformer and then connected to a long transmission line as shown. Current and potential transformers have been shown connected to the system. Output of the PT is connected to a 0–110 V voltmeter whereas the output of the CT is connected to a 0–5 A ammeter.

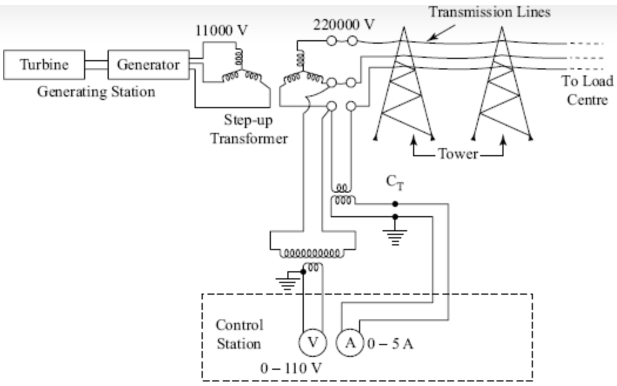


Figure 11.29 Use of CT and PT for measurement of high current and high voltage

Advantages of CT and PT: The advantages of using CT and PT for measurement of high value of current and voltage in preference to directly using ammeters and voltmeters of higher ratings (through shunts and multipliers) are mentioned below.

1. If we had to use ammeters and voltmeters directly on the high-voltage lines, the instruments would have had to be insulated heavily, and hence their physical size would be very big. Morever, it would be dangerous to bring high-voltage lines inside the control station. In case of any leakage of currents, the operator using these instruments may get a fatal electrical shock. Thus, the safety of the operator would be at stake.
2. With the help of standard instruments of low range, large current and voltage can be measured. Instrument transformers can either be of single range or of multirange.
3. From the output of the CT and PT, connections can also be taken to the current coil and pressure coil of a wattmeter for the measurement of power. Similarly, connections can be taken for the frequency meter also. Thus, several instruments can be connected to a single set of instrument transformers.
4. Instruments of moderate size and standards can be used for measurement.

It may be noted from Fig. 11.29 that the secondaries of CT and PT have been earthed. This is because, in case of open circuiting of the secondary by the operator, or by other reason the operator may get a severe shock if there is some leakage. That is why it is a warning to the operator as to not to open the secondary winding of a CT or a PT with their primaries connected to the lines.

We will now discuss in some details of current and potential transformers.

11.12.1 Current Transformers

A current transformer has very few turns in its primary. The secondary will have a large number of turns. The secondary winding is

The turns ratio, $$n = \frac{\text{number of turns in the secondary winding}}{\text{number of turns in the primary winding}} = \frac{N_2}{N_1}$$

The nominal ratio, $$K_n = \frac{\text{rated current of primary winding}}{\text{rated current of the secondary winding}} = \frac{I_1(\text{rated})}{I_2(\text{rated})}$$

The transformation ratio, $$K = \frac{\text{primary winding current}}{\text{secondary winding current}} = \frac{I_1}{I_2}$$

Since the output current is measured on a 0–5 A ammeter, the current flowing through the primary winding, which is being measured, can be calculated by multiplying the ammeter reading by the turns ratio.

For example, if the primary winding current limit is upto 1000 A, the turns ratio of the CT is 200. For a reading on the ammeter of 2 A, we will calculate the primary current as 2 A × 200 = 400 A. The reading of the ammeter has to be multiplied by the turns ratio factor to get the value of line current.

It may be noted that turns ratio is the ratio of turns of the secondary and primary windings and the transformation ratio is the ratio of current of the primary and secondary windings, If $I_1 N_1 = I_2 N_2$

then $$\frac{N_2}{N_1} = \frac{I_1}{I_2}$$

i.e., Turns ratio = Transformation ratio.

If, however, the turns ratio is not equal to the transformation ratio, it will introduce considerable error in the measurement. The difference between the nominal ratio, i.e., $\frac{I_1(\text{rated})}{I_2(\text{rated})}$ and the actual transformation ratio $\frac{I_1}{I_2}$ is called ratio error.

Again, if the secondary winding current and primary winding current are not opposing each other at 180°, an error is introduced, which is called phase angle error.

The ratio error and phase angle error in a CT, their causes, and means to reduce these errors are explained now.

For this, let us draw the complete phasor diagram of a CT which is similar to a two-winding transformer.

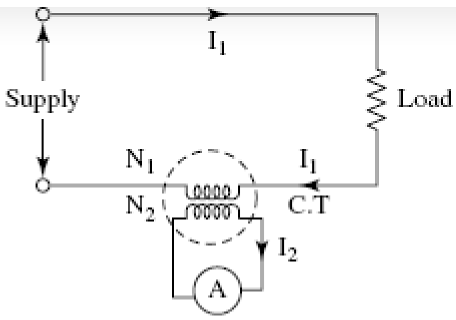


Figure 11.30 Measurement of line current using a CT and a low-range ammeter

Calculation of ratio error and phase angle error of a CT: In Fig. 11.30 is shown a CT connected with the circuit where high current, I_1 is flowing through the load. The primary circuit current of the CT is equal to I_1. The secondary circuit current of the CT is I_2 The turn ratio $\frac{N_2}{N_1} = \frac{I_1}{I_2}$

or,

$$I_1 = \left(\frac{N_2}{N_1}\right) I_2$$

Thus, by multiplying the reading of the ammeter connected to the secondary circuit of the CT by the turn ratio, i.e., $\frac{N_2}{N_1}$, we can get the value of current flowing through the load circuit. The ammeter is rated at 0–5 A. With this arrangement, i.e., having a CT and low-value ammeter, we are able to measure high current flowing through a circuit.

However, due to the no-load component of the primary current of a transformer, the actual transformation ratio deviates somewhat from the rated or nominal ratio of currents of the primary and secondary and also of their turn ratio. As we know, a transformer will draw some small amount of current at no load which has two components, viz the magnetizing component of the no-load current, I_m which produces the flux in the core and the loss component, I_c of the primary current, I_0 which corresponds to the losses in the core of the transformer. For the purpose of analysis, we will draw the simplified phasor diagram of a transformer having the core flux, φ as the reference axis as shown in Fig. 11.31.

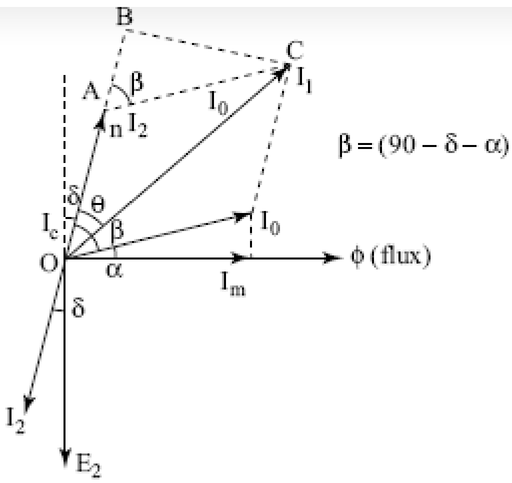


Figure 11.31 Simplified phasor diagram of a CT

Actually, nI_2 must be equal to I_1 as in Fig. 11.31. However, due to the presence of the no-load current, I_0, I_1 is somewhat away from nI_2. (Note that in Fig. 11.31, for clarity I_0 has been shown enlarged. Infact, I_0 is only 3 to 5 per cent of I_1.)

The vector sum of nI_2 and I_0 will give the value of I_1 as shown. In the figure, OC is equal to I_1. We extend nI_2 as shown by the dotted line. We draw a perpendicular from C on this extended line to meet at point B. OA is equal to nI_2 and ac is equal to I_0. The vertical line drawn downwards in E_2. E_2 lags the flux, ϕ by 90°.

Current flowing through the secondary winding due to E_2 is I_2. I_2 lags E_2 by an angle δ.

The angle between nI_2 and I_1 is θ.

The angle θ actually is very small, and hence OC can be considered equal to OB.

Therefore $$I_1^2 = OC^2 = OB^2 = (OA + AB)^2 = (nI_2 + I_0 \cos\beta)^2$$

or, $$I_1 = nI_2 + I_0 \cos\beta$$

or, $$I_1 = nI_2 + I_0 \cos[90 - (\delta + \alpha)]$$

$$= nI_2 + I_0 \sin(\delta + d)$$

Actual transformation ratio, $$K = \frac{I_1}{I_2} = n + \frac{I_0}{I_2}\sin(\delta + \alpha)$$

$$= n + \frac{I_0}{I_2}[\sin\delta\cos\alpha + \cos\delta\sin\alpha]$$

$$= n + \frac{I_m \sin\delta + I_c \cos\delta}{I_2} \qquad [\therefore\ I_0 \cos\alpha = I_m \text{ and } I_0 \sin\alpha = I_c]$$

Ratio error of the current transformer

= Nominal ratio – Actual ratio

Since, $$\frac{I_1(\text{rated})}{I_2(\text{rated})} = \frac{N_2}{N_1} = n,$$

$$\text{Percentage ratio error} = \frac{\text{nominal ratio} - \text{actual ratio}}{\text{actual ratio}} \times 100$$

$$= -\left(\frac{I_m \sin\delta + I_c \cos\delta}{I_2}\right) \times 100$$

It is seen from Fig. 11.31 that the there exists an angle of phase difference of θ between I_1 and nI_2. Idealy nI_2 and I_1 should not have any phase angle between them.

We have seen that there exists a difference between the actual transformation ratio and the turns ratio of a CT. This largely depends upon the loss component of the no-load current, i.e., I_c. The transformer phase angle depends upon the magnetizing component of the no-load current, i.e., I_m. By proper design, the magnitude of I_c and I_m are kept low to maintain the ratio error and phase angle error to the minimum.

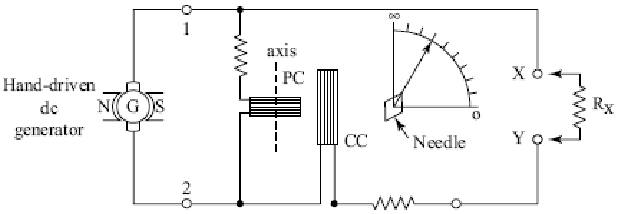


Figure 11.32 Principle of operation of an insulation tester illustrated

11.12.2 Potential Transformers

Potential transformers are similar to two winding transformers except that the secondary volt-ampere loading is very low. The primary winding is the high voltage winding which is connected across the lines whose voltage is to be measured. The secondary winding is normally rated at 110 V and is connected across a voltmeter or the pressure coil of a wattmeter. For details on potential transformer the students may refer to any advance book on measurement and instrumentation.

11.13 MEGGER AND MEASUREMENT OF INSULATION RESISTANCE

The insulation resistance of any cable or electrical system is very high. To measure such high resistance we use an instrument called megger. The resistance measure is of the order of mega ohms (× 10^6 Ω). The basic constructional details of a megger is explained below.

A megger consists of two coils placed at 90° with each other as shown in Fig. 11.32. One is called the current coil CC and the other is called the pressure coil PC. A magnetic needle is placed in the magnetic field created by the two coils. A pointer is connected to the generated by rotating the generator by hand with the help of a handle provided of the purpose.

R_X is the resistance of the insulation which is to be measured. The hand-driven dc generator provides a constant dc voltage. When dc supply is available, current flows through the pressure coil. The magnetic needle along with the pointer gets aligned with the axis of the pressure coil PC indicating infinite resistance ∞, as shown. On the other hand, when resistance measurement terminals X and Y are closed, current will flow through the current coil CC. The needle and pointer will move in the clockwise direction and align with the magnetic field created by the current coil. The pointer will move to O position on the seak. When R_X is connected for measurement and its value is comparatively low (current high) the torque produced due to coil CC is higher than torque produced by coil PC. The position of the pointer will be towords 0Ωside on the scale. When the value of R_X is high, very low current will flow through the coil CC, and hence the needle will align towords the coil PC and indicate resistance towards infinity.

11.14 MULTIMETER AND MEASUREMENT OF RESISTANCE

A single instrument is used to measure three quantities, viz current (i.e., Amperes), voltage (i.e., Volts), and resistance (i.e., Ohms). Multimeters are, therefore, also called AVO meters. Multimeters are available as analog type, electronic type, or digital type.

An analog multimeter is basically a permanent magnet moving coil galvanometer, For measurement of current, a selector switch is operated in the current measurement mode. As shown in Fig. 11.33 (a),

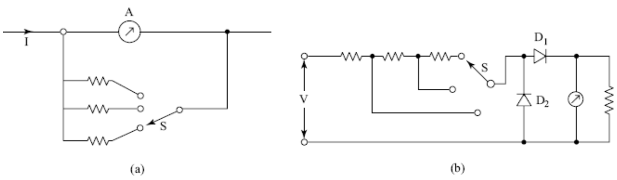


Figure 11.33 (a) Multi-range ammeter; (b) multi-range voltmeter

a number of low-value resistors, called shunts, are connected in parallel with the instrument through a range selection selector switch. The required range can be selected by moving the selector switch to a particular position as shown in Fig. 11.33 (a).

The use of the multimeter as a multi-range voltmeter has been shown in Fig. 11.33 (b). The rectifier diode D_1 conducts during the positive half cycle of the input waveform and causes the meter to give deflection according to the average value of the half cycle. Diode D_2 prevents a reverse voltage appearing across the diode D_1 during the negative half cycle of the input voltage. The calibration of the scale is such that the same scale is used for both dc and ac

$\frac{I_m}{\sqrt{2}}$

The rms value of the half-rectified wave = $\frac{I_m}{\pi}$. The rms value of the half-rectified wave is $\frac{I_m}{\pi} \div \frac{I_m}{\sqrt{2}}$ 0.45 times the rms value of the full sine wave voltage. In order to have the same deflection on dc and corresponding ac voltage range, the value of the multiplier (resistance to be connected in series with the voltmeter) for the ac range must be reduced accordingly.

For multi-range resistance measurement, the basic circuit is similar to an ohm meter and is shown in Fig. 11.34.

When R_X is zero, i.e., the terminals A and B are shorted, meter current is 0. When R_X is open, i.e., when R_X is infinity, current finds path through the meter only. By adjusting R we can get full deflection. Thus, the scale of the meter will have a zero mark on the left-hand side and on infinity mark on the right-hand side. Electronic multimeters use circuitry using field effect transistors and bipolar junction transistors, fixed and variable resistors, and a deflecting-type permanent-magnet moving-coil instrument.

In digital multimeters, the result of measurement is displayed at discrete intervals in the form of numerals in the decimal system. Digital meters provide readings in the form of numbers, and hence there is less chance of meter reading error and error due to parallax. The speed of taking the reading is also increased. Digital multimeters have gained popularity due to use of ICs. The size, power requirement, and cost have been reduced drastically.

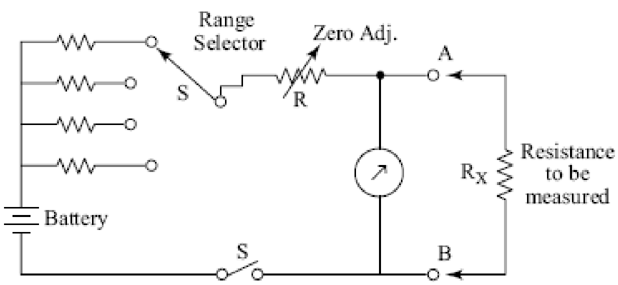


Figure 11.34 Measurement of resistance by a multimeter

Example 11.7 A pmmc-type instrument has a 4 cm × 3 cm size coil wound on its aluminium drum. The number of turns of the coil is 100. The magnetic field has a flux density fo 0.2 wb/m^2. The control spring provides a control torque of 1×10^{-6} Nm/degree of deflection of the moving coil. Calculate the value of current flowing through the coil when it is deflected by an angle of 48°.

Solution:

Area of the coil = 0.04 × 0.03 m^2

–4 2

or Td = $2.4 \times 10^{-2} \times I$ Nm

Control torque produced by the spring when elongated at 48°, $T_c = 1 \times 10^{-6} \times 48$ Nm.

For steady deflection, $T_d = T_c$.

Equating, $2.4 \times 10^{-2} \times I = 48 \times 10^{-6}$

or, $$I = \frac{48 \times 10^{-6}}{2.4 \times 10^{-2}} = 20 \times 10^{-4} \text{ A}$$
$$= 2 \times 10^{-3} \text{ A}$$

or, $$I = 2 \text{ mA}$$

Example 11.8 In a moving iron instrument a current of 5 A produces a deflection of 60°. What will be the deflection when a current of 2 A is flowing through the coil of the instrument? Assume that the instrument is spring controlled.

Solution:

We know that for a moving iron instrument deflecting torque is proportional to the square of the current flowing through the coil.

Therefore, $T_c \; \alpha \; I^2$

When spring controlled, the control torque is proportional to the angle of deflection.

Therefore, $T_c \; \alpha \; \theta$.

For steady deflection, $T_d = T_c$.

Thus, $T_d \; \alpha \; I^2$ and $T_c \; \alpha \; \theta$

Equating, $\theta \; \alpha \; I^2$

Now $\theta_1 \; \alpha \; I_1^2$

and $\theta_2 \; \alpha \; I_2^2$

So $$\frac{\theta_2}{\theta_1} = \left(\frac{I_2}{I_1}\right)^2$$

or, $$\theta = \theta_1 \left(\frac{I_2}{I_1}\right)^2$$

Substituting values $$\theta_2 = 60\left(\frac{2}{5}\right)^2 = 60 \times (0.4)^2$$
$$= 9.6°$$

Example 11.9 The meter constant of a single-phase energy meter is 1200. When a load of 6 kW is switched on, the disc of the meter

Actual energy consumed = 6 kW × 1 minute = $\frac{6\times1}{60}$ kWh = 0.1 kWh. Meter constant is 1200. This means for 1 kWh of energy consumed, the disc of the meter makes 1200 revolutions.

The reading of the meter corresponding to 136 revolutions = $\frac{136}{60}$ × 1 kWh = 0.113 kWh.

$$\text{Percentage Error} = \frac{(\text{Meter reading} - \text{Actual energy consumed})\times100}{\text{Actual energy consumed}}$$
$$= \frac{(0.113-0.1)\times100}{0.1} = \frac{0.013\times100}{0.1} = 13 \text{ per cent}$$

Example 11.10 A moving-coil-type instrument has an internal resistance of 25 Ohms. The instrument gives full scale deflection when a current of 100 mA flows through it. The same instrument is to be used as an ammeter of range 0–30 A and as a voltmeter of range 0–300 V. Show how this can be done.

Solution:

The connection of a multiplier, i.e., a high resistance in series with the instrument is required to use it as a voltmeter. For using the instrument as an ammeter of higher range, a shunt resistance is to be connected in parallel as shown.

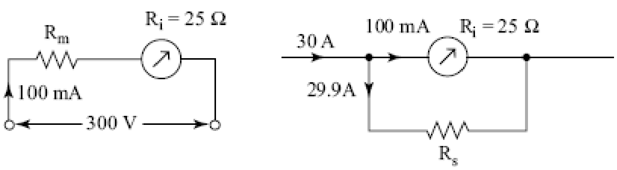


Figure 11.35

From Fig. 11.35 (a),

$$\frac{300}{R_m + R_i} = 100\text{ mA} = 0.1\text{ A}$$
$$R_m + R_i = \frac{300}{0.1} = 3000$$
$$R_m = 3000 - R_i = 3000 - 25$$
$$= 2975\ \Omega$$

or, $$= R_s = \frac{2.5}{29.9} = 0.0836\ \Omega$$

11.15 REVIEW QUESTIONS

A. Short Answer Type Questions

1. Distinguish between the following three types of measuring instruments:

   (i) deflecting type; (ii) recording type; and (iii) integrating type.

2. Define a transducer, where does it find place in the instrumentation and measurement system? Give one example.
3. Draw a block diagram showing basic instrumentation and measurement system elements.
4. Distinguish between analog and digital instruments.
5. Distinguish between active and passive instruments.
6. How do you define the static characteristics of measuring instruments?
7. Define the following:

   (i) accuracy; (ii) sensitivity; (iii) precision; and (iv) resolution.

8. Distinguish between accuracy and sensitivity of an instrument.
9. What is meant by loading effect of a measuring instrument?
10. Explain the difference between linear and nonlinear systems.
11. What are the dynamic characteristics of a measuring instrument?
12. Explain various measurement errors which are likely to occur while using deflecting type.
13. Explain the difference between a galvanometer and a milliammeter.
14. Why should we have high torque by weight ratio of the moving system of an instrument low?
15. Explain the constructional details and principle of the working of a permanent-magnet moving-coil instrument.
16. Explain the function of deflecting torque, control torque, and damping torque of a moving coil instrument.
17. Explain eddy current damping and air friction damping.
18. Explain the equation for deflecting torque of a pmmc instrument.
19. Explain why the pmmc-type instrument have a linear scale while moving iron instrument have square scale?
20. What are the sources of error in pmmc-type instruments? Explain them.
21. Where do we use shunts and multipliers?
22. How do we extend the range of ammeters and voltmeters?
23. Distinguish between a pmmc-type ammeter and a voltmeter.
24. Explain the working principle of attraction-type moving iron instruments.
25. Distinguish between an attraction-type and a repulsion-type moving-iron instrument.
26. Draw the constructional details and explain the working

28. Can we use a moving-iron instrument for both ac and dc measurements?
29. Explain the constructional details of a dynamometer-type instrument.
30. What are the sources of error in dynamometer-type instruments?
31. Prove that power in an ac circuit is equal to VI cosφ.
32. Explain how a wattmeter reading will be equal to VI cosφ.
33. Explain how error in measurement may occur due to the connections of current coil and pressure coil of a wattmeter.
34. Explain the constructional details and working principal of a single-phase induction-type energy meter.
35. What do you mean by creeping of an energy meter? How can creeping be eliminated?
36. Explain the use CT_S and PT_S.
37. State the advantages of CT and PT.
38. What is meant by ratio error and phase angle error of a current transformer?
39. Explain the basic principle of working of a multimeter.
40. Show how a megger is used for measurement of insulation resistance.

B. Numerical Problems

41. A PMMC-type instrument gives a full-scale deflection of 1 mA and has an internal resistance of 100 Ω. Calculate the values of shunts required to extend the range of the instrument to 0–100 mA and 0–500 mA.

[Ans 1.01 Ω; 0.02 Ω]

42. Calculate the value of multiplier resistance so that an instrument of internal resistance of 100Ωand full-scale deflection current of 1 mA can be converted into a 0–100 V range voltmeter.

[Ans R_m = 99,900 Ω]

43. A PMMC-type instrument gives a full-scale deflection of 100 mA when a potential difference across the terminal is 1 V. How can this instrument be used to measure upto 100 V?

[Ans Connecting a series resistance of 990 Ω]

C. Multiple Choice Questions

1. 1. For measurement of direct current we may use
   1. a moving-iron-type ammeter
   2. a galvanometer
   3. a permanent-magnet moving-coil-type ammeter
   4. a hot-wire-type ammeter.
2. In permanent-magnet wiring-coil-type instruments expression for deflecting torque can be written as
   1. $T_d \alpha\ I^2$

4. $T_d \alpha \frac{1}{I^2}$.

3. Damping of deflecting-type instruments is done to
    1. reduce the oscillations of the pointer in the final deflected position
    2. make the moving system go slow
    3. make the moving system move fast
    4. reduce the angle of deflection of the pointer on the graduated acate.
4. For which of the following instruments the calibrated scale is linear?
    1. Repulsion-type moving-iron instruments
    2. Attraction-type moving-iron instruments
    3. Permanent-magnet moving-coil instruments
    4. Dynamometer-type instruments.
5. The extension of range of an ammeter and a voltmeter can be made respectively by
    1. using multiplier and shunt
    2. using shunt and multiplier
    3. using series capacitor and a series inductor
    4. reducing the spring tension of the deflecting system.
6. To increase the sensitivity of a deflecting-type instrument
    1. torque–weight ratio of the moving system should be high
    2. torque–weight ratio of the moving system should be low
    3. it should be lightly damped
    4. the control torque must be reduced.
7. A permanent-magnet moving-coil instrument cannot be used for ac measurement because on ac the deflecting system will
    1. not respond to the quick alternating torques and will stay in its initial position
    2. respond to ac signal but will not move because of inertia
    3. get burnt out
    4. give incorrect reading.
8. In a moving-iron-type instrument the current flowing throgh the coil, I and the torque developed T_d are related as
    1. $T_d \alpha I$
    2. $T_d \alpha \frac{1}{I}$
    3. $T_d \alpha I^2$
    4. $T_d \alpha \frac{1}{I_{a^2}}$.
9. Wattmeters are of
    1. permanent-magnet moving-coil type
    2. dynamometer type
    3. moving-iron type
    4. hot-wire type.
10. Basic difference between an ammeter and a voltmeter is that
    1. an ammeter is a low-resistance instrument while a voltmeter is a high-resistance instrument

4. a voltmeter is connected in series with a circuit while an ammeter is connected in parallel.

11. Three-phase power P in terms of line and phase voltages and currents and power factor can be expressed as
    1. $P = V_{ph} I_{ph} \cos\phi$
    2. $P = \sqrt{3} V_L I_L \cos\phi$
    3. $P = \sqrt{3} V_{ph} I_{ph} \cos\phi$
    4. $P = 3V_L I_L \cos\phi$.
12. For measurement of electrical energy, we may use a
    1. wattmeter
    2. kWh meter
    3. multimeter
    4. voltmeter, ammeter, and a power factor meter.
13. The following could be one of the errors in an energy meter
    1. clamping
    2. clipping
    3. creeping
    4. clogging.
14. The energy meter installed near the main switch in residences and other locations is
    1. an indicating- or deflecting-type instrument
    2. an integrating-type instrument
    3. a recording-type instrument
    4. an absolute instrument.
15. A voltmeter has a uniform scale with 100 divisions, the full scale reading is 100 V and can be read up to 1/10 of a scale diviation with a fair degree of certainty. Its resolution is
    1. 0.1 V
    2. 0.2 V
    3. 0.01 V
    4. 0.02 V.
16. The deflection in moving-iron instruments is proportional to
    1. square of the rms value of the current
    2. rms value of the current
    3. square of the maximum value of current
    4. maximum value of the current.
17. We can distinguish between a moving-iron-type and a moving-coil-type instrument by working at their
    1. pointer
    2. graduated scale
    3. size
    4. all the items as in (a), (b), and (c).
18. In a moving iron instrument 8 A current causes a deflection of the needle over the scale by 60°. For a deflection of 15°, the current required will be
    1. 2_A
    2. 4_A
    3. 16_A
    4. 0.5_A.
19. A voltmeter must have very high internal resistance so that
    1. its accuracy is high
    2. its resolution is high
    3. it draws a very small amount of current
    4. it creates a high loading effect on the circuit.
20. An instrument with a measurement range of 0–100 V with

3. 0.01 per cent
4. 10 per cent.

Answers to Multiple Choice Questions

1. (c)
2. (b)
3. (a)
4. (c)
5. (b)
6. (a)
7. (a)
8. (c)
9. (b)
10. (a)
11. (b)
12. (b)
13. (c)
14. (b)
15. (a)
16. (a)
17. (b)
18. (b)
19. (c)
20. (d)