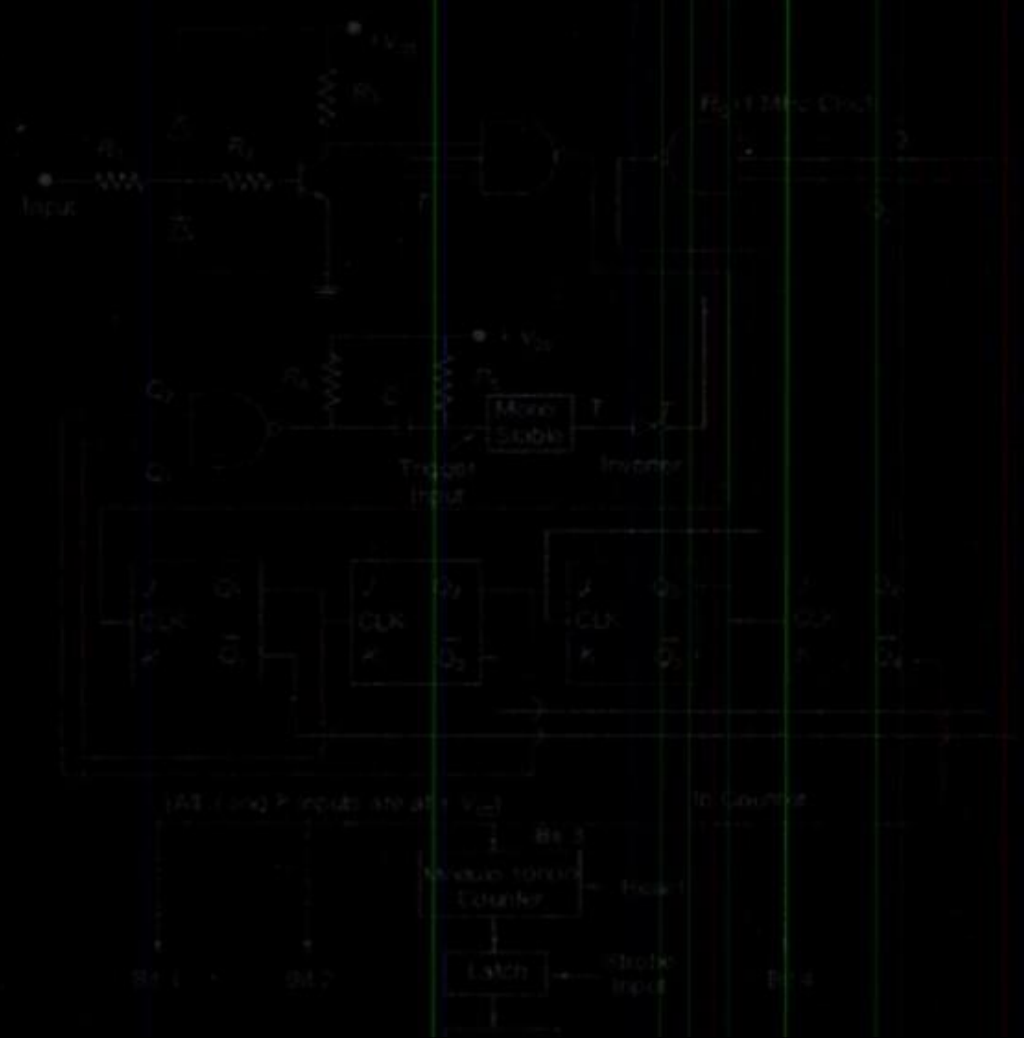
Third Edition

# Electronic Instrumentation



# Qualities of Measurements

*Chapter* **1**

## INTRODUCTION 1.1

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

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

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

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

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

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

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

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

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

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

For the 6th reading

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

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

## TYPES OF STATIC ERROR 1.5

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

### 1.5.1 Gross Errors

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

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

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

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

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

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

#### (i) Instrumental Errors

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

Instrumental errors can be avoided by

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

#### (ii) Environmental Errors

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

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

#### (iii) Observational Errors

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

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

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

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

### 1.7.2 Dynamic Response of a First Order Instrument

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

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

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

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

or

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

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

$K = b_0/a_0$ = static sensitivity

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

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

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

### 1.7.3 Dynamic Response of Second Order Instrument

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

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

The above equations can be reduced as

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

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

*Solution* The average deviation is calculated as follows

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

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

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

Therefore, the average deviation = 0.232.

### 1.8.4 Standard Deviation

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

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

where $\sigma$ = standard deviation

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

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

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

*Solution*

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

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

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

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

Therefore, the standard deviation is 0.27.

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

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

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

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

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

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

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

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

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

*Solution* The magnitude of the limiting error for the voltmeter is

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

The limiting error at 70 V is

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

The magnitude of limiting error of the ammeter is

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

The limiting error at 80 mA is

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

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

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

## STANDARD 1.9

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

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

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

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

### 1.9.1 International Standards

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

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

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

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

1 International ohm = 1.00049 Absolute ohm

1 International ampere = 0.99985 Absolute ampere

### 1.9.3 Secondary Standards

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

### 1.9.4 Working Standards

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

## ELECTRICAL STANDARDS 1.10

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

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

### 1.10.1 Absolute Ampere

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

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

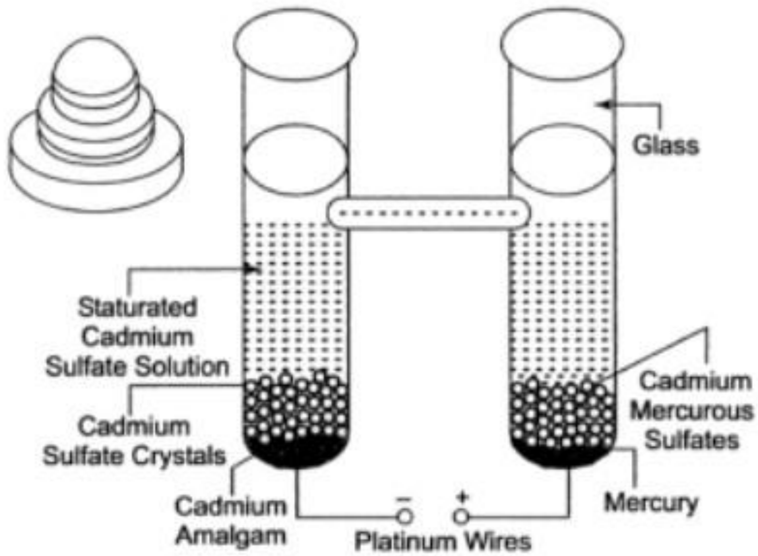



Fig 1.1 Voltage Standard

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

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

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

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