

# Electronics Engineering

## Electronic Measurements and Instrumentation

Comprehensive Theory

*with* Solved Examples and Practice Questions



**MADE EASY**  
Publications



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### **Electronic Measurements and Instrumentation**

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# Contents

## Electronic Measurements and Instrumentation

### Chapter 1

#### Introduction to Measurements ..... 2

|   |    |
|---|----|
| 1.1 Measurements and its Significance.....                                | 2  |
| 1.2 Basic Block Diagram of Measurement System.....                        | 2  |
| 1.3 Static Characteristics of Instrument<br>and Measurement Systems.....  | 3  |
| 1.4 Dynamic Characteristics of Instrument<br>and Measurement Systems..... | 6  |
| 1.5 Errors in Measurements and their Analysis .....                       | 7  |
| 1.6 Types of Errors.....  | 11 |
| 1.7 Statistical Treatment of Data .....                                   | 12 |
| 1.8 Standard and their Classifications .....                              | 19 |
| 1.9 Important Prefixes and Their Symbol .....                             | 21 |
| <i>Student's Assignments-1</i> .....                                      | 22 |
| <i>Student's Assignments-2</i> .....                                      | 22 |

### Chapter 2

#### Electromechanical Indicating Instruments.....25

|  |    |
|--|----|
| 2.1 Introduction.....  | 25 |
| 2.2 Deflection and Null Type Instruments .....               | 26 |
| 2.3 Torques in Electromechanical Indicating Instruments..... | 28 |
| 2.4 Types of Damping .....                                   | 30 |
| 2.5 Permanent Magnet Moving Coil (PMMC) Instruments ....     | 32 |
| 2.6 Errors in PMMC Meters .....                              | 43 |
| 2.7 Moving Iron (M.I.) Instruments .....                     | 45 |
| 2.8 General Torque Equation of Moving Iron Instruments ....  | 45 |
| 2.9 Errors in Moving Iron Instruments.....                   | 47 |

|   |    |
|---|----|
| 2.10 Electrodynamicometer Type Instruments .....              | 57 |
| 2.11 Applications of Electrodynamicometer Type Instruments... | 59 |
| 2.12 Rectifier Type Instruments (or Rectifier Meters) .....   | 72 |
| <i>Student's Assignments-1</i> .....                          | 77 |
| <i>Student's Assignments-2</i> .....                          | 78 |

### Chapter 3

#### Measurement of Power and Energy .....82

|   |     |
|---|-----|
| 3.1 Introduction.....                         | 82  |
| 3.2 Measurement of Power in DC Circuits ..... | 82  |
| 3.3 Measurement of Power in AC Circuit .....  | 83  |
| 3.4 Power in Poly Phase Systems.....          | 97  |
| 3.5 Measurement of Energy .....               | 99  |
| <i>Student's Assignments-1</i> .....          | 106 |
| <i>Student's Assignments-2</i> .....          | 106 |

### Chapter 4

#### Measurement of Resistance and DC Bridge ..... 109

|  |     |
|--|-----|
| 4.1 Resistors .....  | 109 |
| 4.2 Methods of Reducing Residual Inductance<br>and Capacitance in Resistors..... | 110 |
| 4.3 Measurement of Low Resistance .....  | 112 |
| 4.4 Measurement of Medium Resistance.....  | 121 |
| 4.5 Important Definitions .....  | 127 |
| 4.6 Measurement of High Resistance .....   | 132 |
| <i>Student's Assignments-1</i> .....   | 136 |
| <i>Student's Assignments-2</i> .....   | 137 |

## Chapter 5

### A.C. Bridges .....139

|  |     |
|--|-----|
| 5.1 Introduction to Bridge Measurement & A.C. Bridges..... | 139 |
| 5.2 Measurement of Inductance .....                        | 146 |
| 5.3 Measurement of Capacitance .....                       | 161 |
| 5.4 Wagner Earthing Device .....                           | 164 |
| 5.5 Measurement of Frequency (Wein's Bridge).....          | 168 |
| 5.6 Special Bridge Circuit .....                           | 171 |
| <i>Student's Assignments-1</i> .....                       | 173 |
| <i>Student's Assignments-2</i> .....                       | 174 |

## Chapter 6

### Digital Instrumentation and Signals Analyzers.....177

|   |     |
|---|-----|
| 6.1 Digital Voltmeters (DVM) .....        | 177 |
| 6.2 Electronic Counters.....              | 182 |
| 6.3 Conventional Electronic Counters..... | 182 |
| 6.4 Digital Phase Meter.....              | 188 |
| 6.5 Signals Analysis .....                | 189 |
| 6.6 Harmonic Distortion Analyzer .....    | 192 |
| 6.7 Spectrum Analyzer .....               | 194 |
| <i>Student's Assignments-1</i> .....      | 195 |
| <i>Student's Assignments-2</i> .....      | 196 |

## Chapter 7

### Cathode Ray Oscilloscope (CRO) .....199

|  |     |
|--|-----|
| 7.1 Basics of CRO (Cathode Ray Oscilloscope) ..... | 199 |
| 7.2 Advantages of CRO .....                        | 199 |
| 7.3 Cathode Ray Tube (CRT).....                    | 201 |
| 7.4 Deflection Sensitivity of CRO .....            | 204 |
| 7.5 Graticule.....                                 | 205 |
| 7.6 Relation Between Bandwidth and Rise Time.....  | 206 |
| 7.7 Lissajous Pattern .....                        | 208 |
| 7.8 Phase Angle From the Lissajous Pattern .....   | 212 |
| 7.9 Special CRO.....                               | 214 |
| 7.10 Probes of CRO .....                           | 214 |
| <i>Student's Assignments-1</i> .....               | 215 |
| <i>Student's Assignments-2</i> .....               | 216 |

## Chapter 8

### Transducers .....218

|  |     |
|--|-----|
| 8.1 Introduction.....                                  | 218 |
| 8.2 Active and Passive Transducers .....               | 219 |
| 8.3 Analog Transducers.....                            | 219 |
| 8.4 Measurement of Displacement using Transducers .... | 220 |
| 8.5. Strain Gauges.....                                | 227 |
| 8.6 Piezo-electric Transducers.....                    | 232 |
| 8.7 Inductive Transducers .....                        | 235 |
| 8.8 Capacitive Transducers .....                       | 236 |
| 8.9 Photoelectric Transducer .....                     | 237 |
| 8.10 Measurement of Temperature .....                  | 239 |
| 8.11 Measurement of Pressure .....                     | 249 |
| 8.12 Measurement of Flow .....                         | 255 |
| 8.13 Measurement of Sound.....                         | 259 |
| 8.14 Measurement of Angular Displacement .....         | 260 |
| <i>Student's Assignments-1</i> .....                   | 263 |
| <i>Student's Assignments-2</i> .....                   | 263 |

## Chapter 9

### Miscellaneous .....266

|  |     |
|--|-----|
| 9.1 Potentiometer.....                   | 266 |
| 9.2 Quality Factor Meter (Q Meter) ..... | 271 |
| 9.3 Flux Meter.....                      | 276 |
| 9.4 Data Acquisition System .....        | 277 |
| 9.5 Telemetry.....                       | 280 |
| <i>Student's Assignments-1</i> .....     | 281 |
| <i>Student's Assignments-2</i> .....     | 281 |

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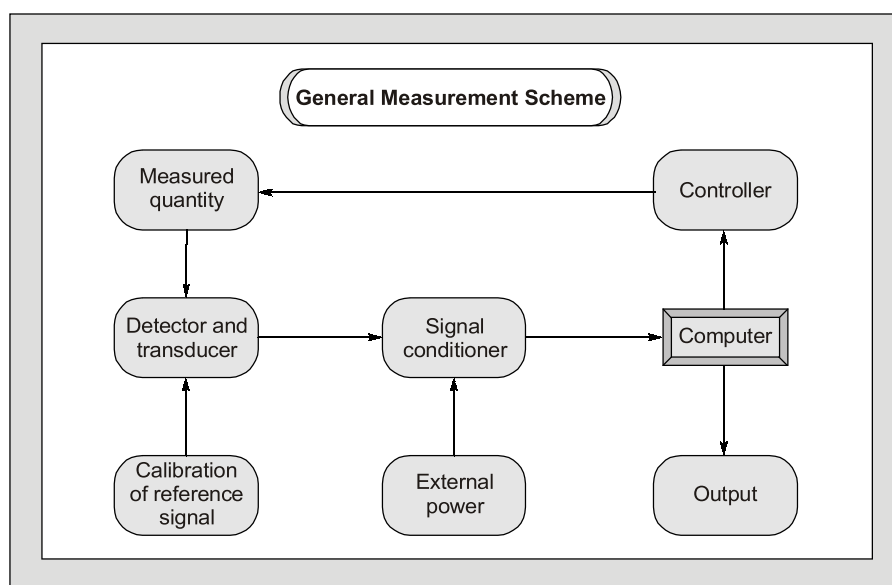
# Introduction to Electronic Measurements and Instrumentation

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Measurement and instrumentation systems have wide applications such as measurement of electrical and physical quantities like current, voltage, power, temperature, pressure, displacement etc.

The reason for measurement arises when one wants to generate data for design or when one wants to propose a theory based on a set of measurement and instrumentation for commerce.

The measurement and instrumentation systems can also be used to locate things or events. Like employees present in a building, the epicenter of an earthquake. Sometimes, measurement systems are made a part of control system. One can observe the change in the field of measurement and instrumentation due to the introduction of new standards, and sensors.



This course on instrumentation and measurement is intended to make the engineers familiar about the art of modern instrumentation and measurement systems. It is well suited for classroom courses of engineering as well as for various competitive examinations.

Equal importance has been provided to both theory as well as problems with illustrative examples after every topic. It has been tried to cover every topic so that even a beginner understands it easily to excel in the subject of measurement and instrumentation.

# Introduction to Measurements

## 1.1 Measurements and it's Significance

The measurement of a given quantity is essentially an act or the result of comparison between the quantity (whose magnitude is unknown) and a predefined standard. Measurement is the process by which one can convert physical parameters to meaningful numbers. The measuring process is one in which the property of an object or system under consideration is compared to an accepted standard unit, a standard defined for that particular property. For the result of the measurement to be meaningful, the standard used for comparison purposes must be accurately defined and should be commonly accepted. Also, the apparatus used and the method adopted must be provable. The importance of measurement is simply expressed in the following statement of the famous physicist "Lord Kelvin":

*"I often say that when you can measure what you are speaking about and can express it in numbers, you know something about it; when you can't express it in numbers your knowledge is of a meager and unsatisfactory kind."*

## 1.2 Basic Block Diagram of Measurement System

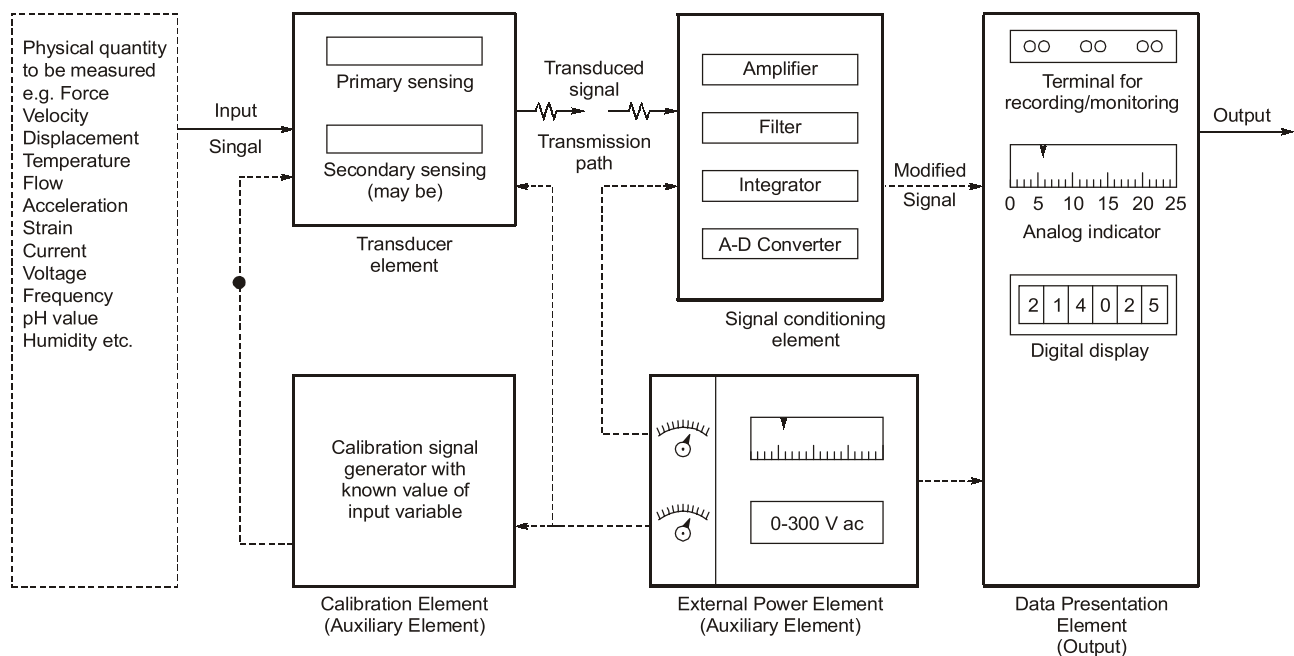


Figure-1.1

## Method of Measurement

### Direct Measurement

- In this method, the measured or the unknown quantity is directly compared against a standard.
- This method of measurement sometimes produces human errors and hence gives inaccurate results.

### Indirect Measurement

- This method of measurement is more accurate and more sensitive.
- These are more preferred over direct measurement.

## Calibration

The calibration of all instruments is important since it affords the opportunity to check the instrument against a known standard and subsequently to find errors and accuracy. Calibration procedures involve a comparison of the particular instrument with a primary standard or, a secondary standard or, an instrument of known accuracy.

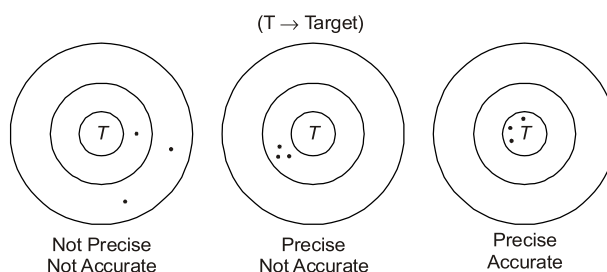
## 1.3 Static Characteristics of Instrument and Measurement Systems

### Accuracy

- It is the closeness with which an instrument reading approaches the true value of the quantity being measured.
- The accuracy can be specified in terms of inaccuracy or limits of error.
- The best way to conceive the idea of accuracy is to specify it in terms of the true value of the quantity being measured.
- The accuracy of a measurement means conformity to truth.

### Precision

- It is a measure of the reproducibility of the measurements i.e. given a fixed value of a variable, precision is a measure of the degree to which successive measurements differ from one another.
- The term “Precise” means clearly or sharply defined.
- Precision is used in measurements to describe the consistency or the reproducibility of results.
- Precision instruments are not guaranteed for accuracy.



- Precision depends upon number of significant figures
- The more significant figures, then the precision is more
- Significant figures convey actual information regarding the magnitude and the measurement precision of a quantity.

**Example:** 302 A (Number of significant figures = 3)  
302.10 V (Number of significant figures = 5)  
0.000030  $\Omega$  (Number of significant figures = 6)

**Example - 1.1**

In calculating voltage drop, a current of 4.37 A is recorded in a resistance of 31.27  $\Omega$ . Calculate the voltage drop across the resistor to the appropriate number of significant figures.

**Solution:**

Current,  $I = 4.37 \text{ A}$  (3 significant figures)  
 Resistance,  $R = 31.27 \Omega$  (4 significant figures)  
 Voltage drop,  $V = IR = 4.37 \times 31.27 = 136.6499 \text{ volt}$  (7 significant figures)  
 Since number of significant figures used in multiplication is 3.  
 So answer can be written only to a maximum of three significant figures i.e.  $V = 137$

**NOTE:** 248 volt; 248.0 volt  $\Rightarrow$  More precised than other two.  
 $\Rightarrow 0.00248 \text{ MV}$

**Example - 1.2**

A reading is recorded as 23.90°C. The reading has

- (a) three significant figures (b) five significant figures  
 (c) four significant figures (d) none of these

**Solution: (c)****Example - 1.3**

Assertion (A): A precision instrument is always accurate.

Reason (R): A precision instrument is one where the degree of reproducibility of the measurements is very good.

- (a) Both A and R are true and R is the correct explanation of A  
 (b) Both A and R are true but R is NOT the correct explanation of A  
 (c) A is true but R is false  
 (d) A is false but R is true

**Solution: (d)**

Precision instruments are not guaranteed for accuracy. Refer to definition of precision.

**Linearity**

- If the output is proportional to input then, it is called linear.
- Non-linear behaviour of an instrument doesn't essentially lead to inaccuracy.
- Most of the time it is necessary that measurement system component should have linear characteristics. For example, the resistance used in a potentiometer should vary linearly with displacement of the sliding contact in order that the displacement is directly proportional to the sliding contact voltage. Any departure from linearity result in error in the read out system.

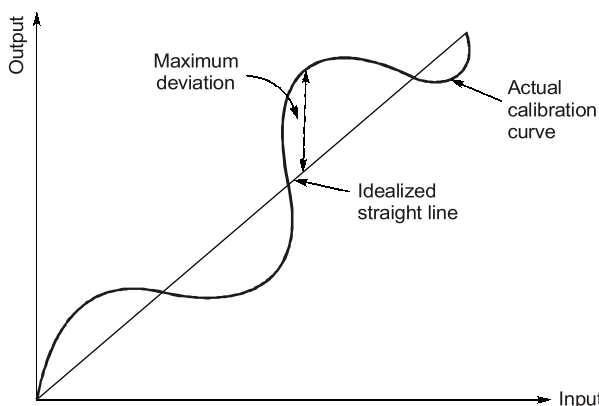


Figure-1.2: Linearity w.r.t. actual calibration curve and idealized straight line



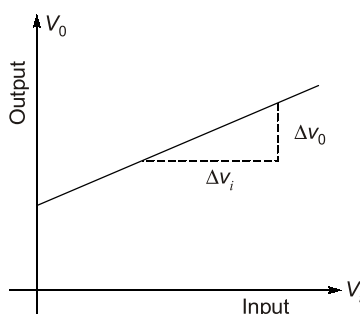
$$\text{N.L.} = \frac{\text{Maximum deviation of output from the idealized straight line}}{\text{Actual reading}} \times 100 ; \text{N.L.} = \frac{\text{Maximum deviation of output from the idealized straight line}}{\text{Full scale deflection}} \times 100$$

### Reproducibility

It is the degree of closeness with which a given value may be repeatedly measured. It may be specified in terms of units for a given period of time.

### Static Sensitivity

- The “static sensitivity” of an instrument is the ratio of the magnitude of the output signal or response to the magnitude of input signal or the quantity being measured. Its units are mm/μA; per volts etc. depending upon type of input and output.
- Sometimes the static sensitivity is expressed as the ratio of the magnitude of the measured quantity to the magnitude of the response.



**Figure-1.3 : Sensitivity**

$$\text{Static Sensitivity} = \frac{\text{Small change in output}}{\text{Small change in input}} = \frac{\Delta V_o}{\Delta V_i}$$

- The sensitivity of an instrument should be high and therefore, instrument should not have a range greatly exceeding the value to be measured.

$$\text{Deflection Factor} = \frac{1}{(\text{Static Sensitivity})}$$

### Resolution or Discrimination

The small measurable input change that can be measured by the instrument is called resolution or discrimination.

### Threshold

If the input is slowly increased from some arbitrary (non-zero) input value, it will again be found that output doesn't change at all until a certain increment is exceeded. i.e. threshold is defined as smallest measurable input.

#### Example - 1.4

A digital voltmeter has a read-out range from 0 to 9,999 counts. Determine the resolution of the instrument in volt when the full scale reading is 9.999 V.

**Solution:**

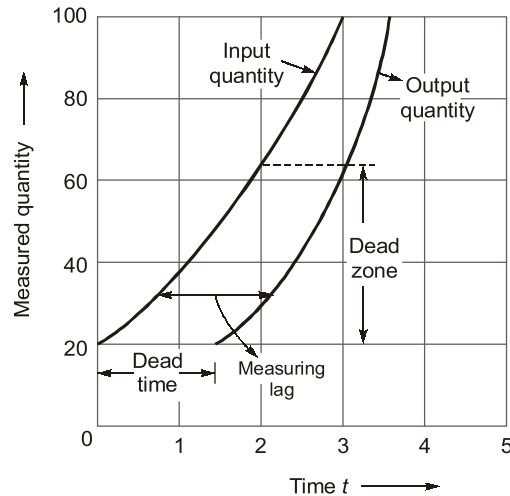
Resolution of instrument = 1 count in 9,999

$$\text{Resolution} = \frac{1}{9999} \text{ count} = \frac{1}{9999} \times 9.999 = 10^{-3} \text{ volt} = 1 \text{ mV}$$

**Dead Time**

Dead time is defined as the time required by a measurement system to begin to respond to a change in the measurand. Figure 1.4 shows the measured quantity (input) and its value as indicated by an instrument (output). Dead time infact, is the time before the instrument begins to responds after the measured quantity has been changed.

**Dead Zone:** Dead zone is the largest change of input quantity for which there is no output of the instrument.



**Figure-1.4:** Dead Zone and Dead Time

**Signal to Noise Ratio (S/N)**

- Noise is an unwanted signal superimposed upon the signal of interest thereby causing a deviation of the output from its expected value.
- The ratio of desired to the unwanted noise is called signal to noise ratio and is expressed as

$$\frac{S}{N} = \frac{\text{Signal Power}}{\text{Noise Power}}$$

- In any measurement system, it is desired to have a large signal-to-noise ratio. This can be achieved by increasing the signal level without increasing the noise level or decreasing the noise level with some suitable technique.

**Repeatability**

It is the repetition of reading of an instrument from a given set of reading.

**1.4 Dynamic Characteristics of Instrument and Measurement Systems**

The dynamic characteristics of an instrument are

- Speed of response:** It is the rapidity with which an instrument responds changes in the measured quantity.

- (ii) **Fidelity:** It is the degree to which an instrument indicates the changes in the measured variable without dynamic error (faithful reproduction).
- (iii) **Lag:** It is the retardation or delay in the response of an instrument to changes in the measured variable
- (iv) **Dynamic Error:** It is the difference between the true value of a quantity changing with time and the value indicated by the instrument, if no static error is assumed.

## 1.5 Errors in Measurements and their Analysis

Measurements done in a laboratory or at some other place always involve errors. No measurement is free from errors. If the precision of the equipment is adequate, no matter what its accuracy is, a discrepancy will always be observed between two measured results.

### True Value

The true value of quantity to be measured may be defined as the average of an infinite number of measured values when the average deviation due to various contributing factors tends to zero.

### Limiting Errors (Guarantee Errors)

The accuracy and precision of an instrument depends upon its design, the material used and the workmanship that goes into making the instrument. Components are guaranteed to be within a certain percentage of the rated value. Thus, the manufacturer has to specify the deviations from the "nominal value" of a particular quantity. The limits of these deviations from the specified value are defined as "**Limiting Errors**" or "**Guarantee Errors**".

For example, the magnitude of a resistor is  $200\ \Omega$  with a limiting error of  $\pm 10\ \Omega$ . The magnitude of the resistance will be between the limits

$$\begin{aligned} R &= 200 \pm 10\ \Omega \\ \text{or} \quad R &\geq 190\ \Omega \\ \text{and} \quad R &\leq 210\ \Omega \end{aligned}$$

Hence, the manufacturer guarantees that the value of the resistor lies between  $190\ \Omega$  and  $210\ \Omega$ .

### Absolute (Relative) Limiting Error

The relative (fractional) error is defined as the ratio of the error to the specified (nominal) magnitude of a quantity.

$$\text{Relative limiting error, } \epsilon_r = \left( \frac{\text{Measured value} - \text{True value}}{\text{True value}} \right) \times 100$$

$$\text{or, } \% \epsilon_r = \left( \frac{\text{Actual value} - \text{True value}}{\text{True Value}} \right) \times 100$$

$$\text{or, } \% \epsilon_r = \left( \frac{A_m - A_T}{A_T} \right) \times 100 \quad \begin{cases} A_m = \text{Measured value} \\ A_T = \text{True value} \end{cases}$$

$$\text{Now, } \% \epsilon_r = \frac{A_m - A_T}{A_T} \quad \text{or} \quad \frac{A_m}{A_T} = 1 + \epsilon_r \quad \text{or} \quad \frac{A_T}{A_m} = \frac{1}{1 + \epsilon_r}$$

$$A_T = \left( \frac{1}{1 + \epsilon_r} \right) A_m$$

Here,

$$\frac{1}{1 + \epsilon_r} = \text{Correction factor}$$

**NOTE:** Nominal value = True value and Actual value = Measured value

**Example - 1.5**

A resistance has nominal value of 50  $\Omega$ . When it is measured its actual value is found to be 60  $\Omega$ . Find the percentage limiting error.

**Solution:**

$$\% \text{ error, } \epsilon_r = \left( \frac{A_m - A_T}{A_T} \right) \times 100 = \left( \frac{60 - 50}{50} \right) \times 100 = 20\%$$

$$\% \text{ error} = 20\%$$

**Example - 1.6**

The measured value of a resistor is 100  $\Omega$  and its relative error is  $\pm 10\%$  then, its true value and the range is

**Solution:**

$$\epsilon_r = \pm 10\% \text{ of } 100 = \pm 10 \Omega$$

Range,

$$A_T = (100 - 10) \text{ to } (100 + 10) = 90 \Omega \text{ to } 110 \Omega$$

**Example - 1.7**

The dead zone in a certain pyrometer is 0.125 percent of span. The calibration is 400°C to 1000°C. What temperature change might occur before it is detected?

(a) 0.25°C

(b) -0.50°

(c) 1.25°C

(d) 0.75°C

**Solution: (d)**

$$\text{Span} = 1000 - 400 = 600^\circ \text{C}$$

$$\therefore \text{Dead zone} = 0.125\% \text{ of span} = \frac{0.125}{100} \times 600 = 0.75^\circ \text{C}$$

Hence, a change of 0.75°C must occur before it is detected.

## Combination of Quantities with Limiting Errors

When two or more quantities, each having a limiting error, are combined, it is advantageous to be able to compute the limiting error of the combination.

### 1. Sum or Difference of Two or more quantities

Let,

$$x_1 = a \pm \epsilon_{r1}$$

$$x_2 = b \pm \epsilon_{r2}$$

$$x_3 = c \pm \epsilon_{r3}$$

$\therefore$

$$x = x_1 + x_2 + x_3$$

or,

$$x = -x_1 - x_2 - x_3$$

So,

$$x = \pm (x_1 + x_2 + x_3)$$

Relative limiting error in  $x$  is given by

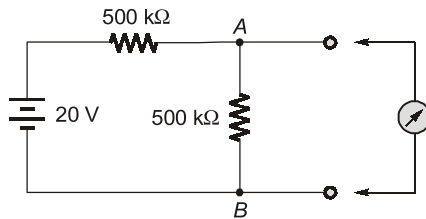
$$\epsilon_x = \pm \left( \frac{a}{a+b+c} \cdot \epsilon_{r1} + \frac{b}{a+b+c} \cdot \epsilon_{r2} + \frac{c}{a+b+c} \epsilon_{r3} \right)$$

( $\epsilon_x$  = worst possible error)

Student's  
Assignments

1

- Q.1** What is the true value of voltage across the 500 kΩ resistor connected between terminals A and B as shown in given figure? What would a voltmeter with a sensitivity of 20 kΩ/V read on the following ranges : 50, 15, 5 V when connected across terminals C and D?



- Q.2** The following values were obtained from the measurements of the value of a resistor: 147.2 Ω, 147.4 Ω, 147.9 Ω, 148.1 Ω, 147.1 Ω, 147.5 Ω, 147.6 Ω, 147.4 Ω, 147.6 Ω, and 147.5 Ω. Calculate:

- arithmetic mean
- average deviation
- standard deviation, treating the data as finite
- standard deviation, treating the data as population.

- Q.3** The four arms of a Hay's a.c. bridge are arranged as follows:

AB is a coil of unknown impedance.

BC is a non-inductance  $R_1 = 1000 \Omega$  with an error of  $\pm 1$  part in 10,000.

CD is a non-reactive resistor  $R_3 = 833 \pm 0.25 \Omega$  in series with no-loss capacitor  $C = 1.43 \pm 0.001 \mu\text{F}$ . DA is a non-reactive resistor  $R_2 = 16800 \pm 1$  part in 10,000.

The supply frequency is  $50 \pm 0.1 \text{ Hz}$ . The bridge is balanced. Determine  $L$  and  $R$  of the coil and the limits or error. The balance conditions are:

$$L = \left( \frac{CR_1R_3}{1 + \omega^2 C^2 R_3^2} \right) \text{ and}$$

$$R = \left( \frac{R_1R_2R_3C^2\omega^2}{1 + \omega^2 C^2 R_3^2} \right)$$

Student's  
Assignments

1

Answers

- 10 V, 8 V, 5.45 V, 2.86 V
- (i) 147.53 Ω (ii) 0.218 Ω  
(iii) 0.298 Ω (iv) 0.283 Ω
- $L = 21 \pm 0.145 \text{ Hz}$  and  $R = 2480 \pm 29.5 \Omega$

Student's  
Assignments

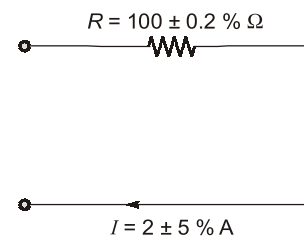
2

- Q.1** Which of the following error is likely to occur in bridge method of measurement?

- Residual error
  - Frequency and waveform error
  - Leakage and eddy current error
- (a) 1 only (b) 2 only  
(c) 1 and 2 only (d) 1, 2 and 3

- Q.2** A utility type voltmeter with an accuracy of  $\pm 3\%$  of full scale (at  $25^\circ\text{C}$ ) is used on 300 V scale to measure 230 V. What will be the possible percentage error and what range will the actual voltage fall within if the instrument reads 200 V?
- (a) 3.9%, 200 V (b) 3.9%, 191 - 209 V  
(c) 7.6%, 221 - 239 V (d) 7.6%, 200 V

- Q.3** In the circuit given in the figure, the limiting error in the power dissipation ' $I^2R$ ' in the resistor  $R$  is



- (a) 1.2% (b) 5.2%  
(c) 10.2% (d) 25.2%

- Q.4** A zero to 300 V voltmeter has a guaranteed accuracy of 1% full scale reading. The voltage measured by the instrument is 83 V. The percentage limiting error is

- (a) 0.95 (b) 1.81  
(c) 3.62 (d) 4.85

**Q.5** Torque developed by an electromagnet is given as

$$F = \mu^a B^b A^c$$

where,  $\mu$  = Permeability of air in the gap  
 $B$  = Flux density in the air gap  
 $A$  = Cross-sectional area of the gap

The values of  $a$ ,  $b$  and  $c$  are respectively

- (a) 1, 1 and 2 (b) -1, 1 and -2  
(c) 1, 2 and -1 (d) -1, 2 and 1

**Q.6** A resistor of 10 k $\Omega$  with 5% tolerance is connected in series with a 5 k $\Omega$  resistor of 10% tolerance. What is the tolerance limit of the series network?

- (a) 5% (b) 6.67%  
(c) 10% (d) 8.33%

**Q.7** Five Students made the following readings on a very accurate voltmeter which reads 2.13 V, 3.15 V, 2.97 V, 3.10 V and 2.99 V. What is the most probable value of the voltage?

- (a) 3.066 V (b) 3.12 V  
(c) 2.99 V (d) 2.97 V

**Q.8** The power in a 3-phase, 3-wire load is measured using two 100 W full scale wattmeters  $W_1$  and  $W_2$ .  $W_1$  is of accuracy class  $\pm 1\%$  and reads 100 W.  $W_2$  is of accuracy class  $\pm 0.5\%$  and reads -50 W. The uncertainty in the computation of total power will be

- (a)  $\pm 1.5\%$  (b)  $\pm 0.5\%$   
(c)  $\pm 4\%$  (d)  $\pm 3\%$

**Q.9** Two resistances  $100 \pm 5 \Omega$  and  $150 \pm 15 \Omega$  are connected in series. If the errors are specified as standard deviations, the resultant error will be

- (a)  $\pm 10 \Omega$  (b)  $\pm 10.5 \Omega$   
(c)  $\pm 15.8 \Omega$  (d)  $\pm 20 \Omega$

**Q.10** The measurement of a quantity

- (a) is an act of comparison of an unknown quantity with another quantity.  
(b) is an act of comparison of an unknown quantity with a known quantity whose accuracy may be known or may not be known.

- (c) is an act of comparison of an unknown quantity with a predefined acceptable standard which is accurately known.  
(d) none of the above

**Q.11** A null type of instrument as compared to a deflection type instrument has

- (a) a high accuracy (b) a lower sensitivity  
(c) a faster response (d) all of these

**Q.12** In measurement systems, which of the following are undesirable static characteristics?

- (a) Sensitivity and accuracy  
(b) Drift, static error and dead zone  
(c) Reproducibility and non-linearity  
(d) Drift, static error, dead zone and non-linearity

**Q.13** The mean deviation  $\bar{D}$  in terms of deviations from the mean value of  $n$  readings is

- (a)  $\frac{\sum |d|}{n}$  (b)  $\frac{\sum d}{n}$   
(c)  $\frac{\sqrt{\sum d^2}}{n}$  (d)  $\sqrt{\frac{\sum d^2}{n}}$

**Q.14** A set of reading has a wide range and therefore it has:

- (a) low precision (b) high precision  
(c) low accuracy (d) high accuracy

**Q.15** The following are the desirable dynamic characteristics of a measurement system :

- (a) fast response, fidelity, measuring lag and dynamic error  
(b) fast response and measuring lag  
(c) fidelity and measuring lag  
(d) fast response and fidelity

**Q.16** The material of wires used for making resistance standards is usually

- (a) Nichrome (b) Copper  
(c) Manganin (d) Phosphor Bronze

**Q.17** Fluid friction damping can be used in

- (a) horizontally mounted instruments  
(b) vertically mounted instruments  
(c) both in horizontally and vertically mounted instruments  
(d) none of these

- Q.18** Permanent magnets used in instruments are hard core materials because
- they have broad hysteresis loop
  - their energy density is high
  - they have a high  $(BH)_{\max}$  product
  - all of the above

**Answer Key:**

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

**Student's  
Assignments****2****Explanations****1. (d)**

The various errors occurring in bridge method of measurement are (which we will see in later chapters):

- ⇒ Frequency error
- ⇒ Waveform error
- ⇒ Eddy Current error
- ⇒ Leakage Current error
- ⇒ Residual error

**2. (b)**

Accuracy =  $\pm 3\%$  of full scale which corresponds to  $\pm 9$  V.

So, range of reading for

$$200 \text{ V} = (200 \pm 9) \text{ V} = 191 - 209 \text{ V}$$

**3. (c)**

$$P = I^2 R$$

$$\epsilon_I = 5\%$$

$$\epsilon_R = 0.2\%$$

$$\epsilon_P = 2\epsilon_I + \epsilon_R = 2 \times 5 + 0.2 = 10.2\%$$

**4. (c)**

$$1\% \text{ accuracy} = \frac{300 \times 1}{100} = 3 \text{ V}$$

$$\therefore \text{Percentage limiting error} = \frac{8}{83} \times 100 = 3.62\%$$

**5. (d)**

Force developed by an electromagnet is:

$$F = \frac{B^2 A}{\mu} = \mu^{-1} B^2 A^1$$

**6. (b)**

$$R_1 = 10^4 \pm 5\% \Omega$$

$$= 10^4 + \frac{5}{100} \times 10^4$$

$$= 10^4 \pm 500 \Omega$$

$$R_2 = 5000 \pm 10\% \Omega$$

$$= 5000 \pm \frac{10}{100} \times 5000$$

$$= 5000 \pm 500 \Omega$$

$$\therefore R = R_1 + R_2 = 15000 \pm 1000 \Omega$$

$$\therefore \text{Tolerance limit} = \frac{1000}{15000} \times 100$$

$$= 6.666\% \approx 6.67\%$$

**7. (a)**

Most probable value

$$= \left( \frac{3.12 + 3.15 + 2.97 + 3.1 + 2.99}{5} \right) = 3.066 \text{ V}$$

**8. (d)**

$$W_1 = (100 \pm 1) \text{ W}$$

$$W_2 = (-50 \pm 0.5) \text{ W}$$

$$\therefore W_1 + W_2 = 50 \pm \frac{1.5}{50} \times 100$$

$$= 50 \pm 3\%$$

Hence, uncertainty in measurement of power =  $\pm 3\%$

**9. (c)**

$$R = R_1 + R_2$$

$$\frac{\partial R}{\partial R_1} = 1 \quad \text{and} \quad \frac{\partial R}{\partial R_2} = 1$$

$$\sigma_{R1} = 5 \Omega$$

$$\sigma_{R2} = 15 \Omega$$

$$\sigma_R = \sqrt{\left( \frac{\partial R}{\partial R_1} \right)^2 (\sigma_{R1})^2 + \left( \frac{\partial R}{\partial R_2} \right)^2 (\sigma_{R2})^2}$$

$$= \sqrt{1(5)^2 + (15)^2} = 15.8 \Omega$$

