Electronics Engineering

Electronic Measurements and Instrumentation

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Electronic Measurements and Instrumentation

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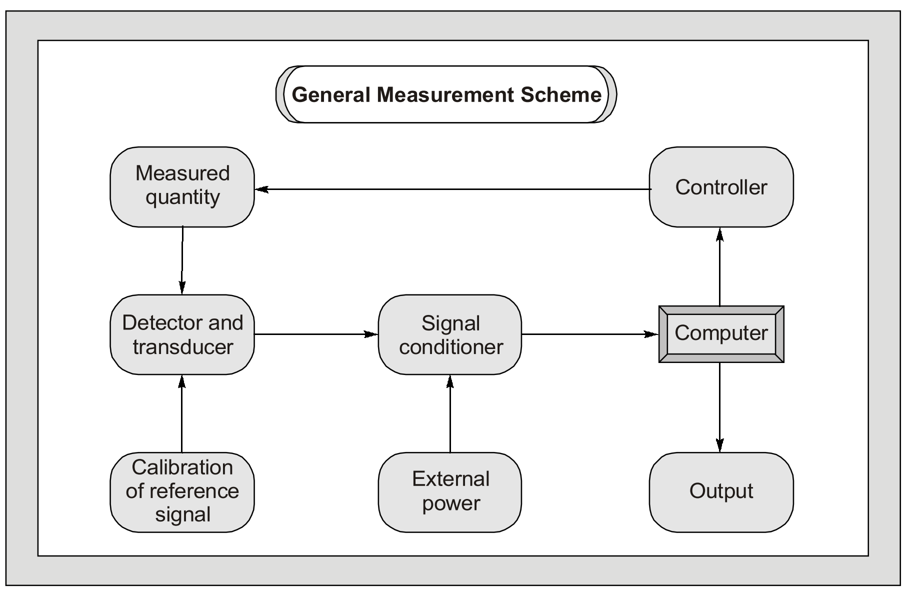
Introduction to Electronic Measurements and Instrumentation

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.

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CHAPTER 1

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

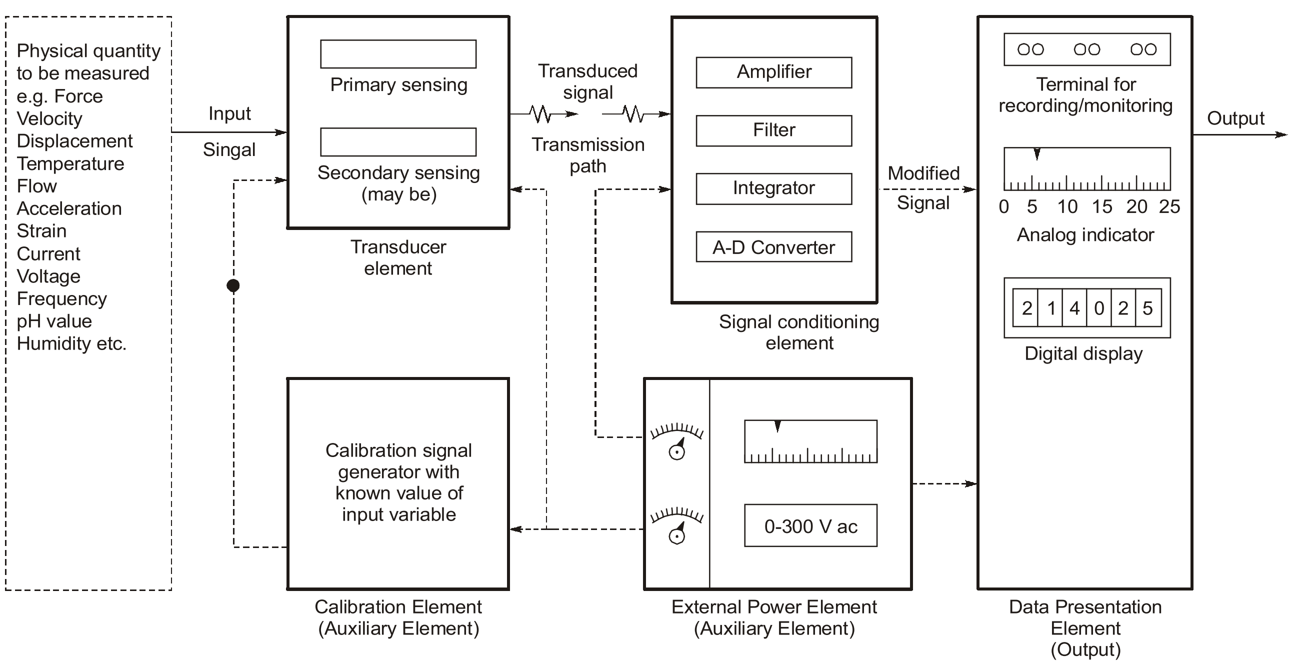


Figure-1.1

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

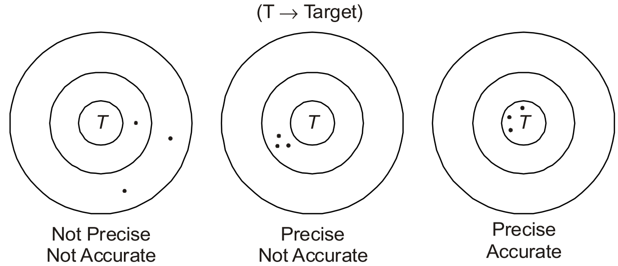
Accuracy

- 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.

(T → Target)



- 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 Ω (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 Ω. Calculate the voltage drop across the resistor to the appropriate number of significant figures.

Solution:

Current, $I = 4.37 A$ (3 significant figures)

Resistance, $R = 31.27\Omega$ (4 significant figures)

Voltage drop, $V = IR = 4.37 \times 31.27 = 136.6499$ 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 ⇒ More precised than other two.
⇒ 0.00248 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.

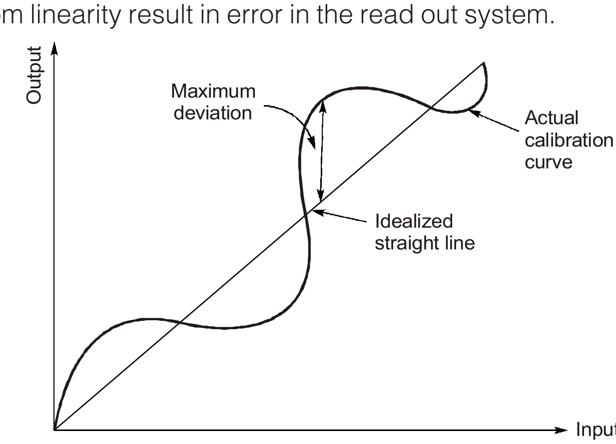


***Figure*-1.2 :** *Linearity w.r.t. actual calibration curve and idealized straight line*

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

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.
  It's 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.

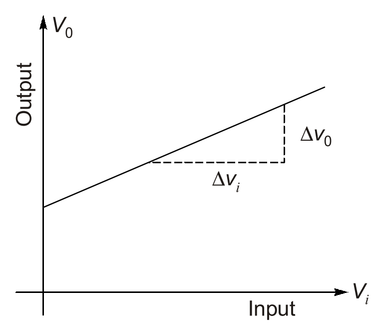


***Figure*-1.3 :** *Sensitivity*

$$\text{Static Sensitivity} = \frac{\text{Small change in output}}{\text{Small change in input}} = \frac{\Delta V_0}{\Delta V_i}$$

- The sensitivity 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

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

(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 it's 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 it's design, the material used and the work manship 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 Ω with a limiting error of ±10 Ω. The magnitude of the resistance will be between the limits

$$R = 200 \pm 10\ \Omega$$

or $$R \geq 190\ \Omega$$

and $$R \leq 210\ \Omega$$

Hence, the manufacturer guarantees that the value of the resistor lies between 190 Ω and 210 Ω.

Absolute (Relative) Limiting Error

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

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

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

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

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

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

Here, $\boxed{\frac{1}{1+\varepsilon_r} = \text{Correction factor}}$

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

Example - 1.5 A resistance has nominal value of 50 Ω. When it is measured it's actual value is found to be 60 Ω. Find the percentage limiting error.

Solution:

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

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

Example - 1.6 The measured value of a resistor is 100 Ω and it's relative error is ±10% then, it's true value and the range is

Solution:

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

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)

$$\text{Span} = 4000 - 400 = 600°\text{ C}$$

∴ $\text{Dead zone} = 0.125\% \text{ of span} = \frac{0.125}{100} \times 600 = 0.75°\text{C}$

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, $x_1 = a \pm \varepsilon_{r1}$

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

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

∴ $x = x_1 + x_2 + x_3$

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

$$\boxed{\varepsilon_x = \pm\left(\frac{a}{a+b+c} \cdot \varepsilon_{r1} + \frac{b}{a+b+c} \cdot \varepsilon_{r2} + \frac{c}{a+b+c}\varepsilon_{r3}\right)}$$

(ε_x = worst possible error)

Example - 1.8 Three resistances $R_1 = 10 \pm 2\%$, $R_2 = 20 \pm 5\%$, $R_3 = 50 \pm 3\%$ are connected in series. Find the % limiting error for the series combination.

Solution:

$$\varepsilon_R = \pm\left(\frac{10}{10+20+50}\times 2+\frac{20}{10+20+50}\times 5+\frac{50}{10+20+50}\times 3\right)$$

or, $$\varepsilon_R = \pm 3.375\%$$

$$\boxed{\%\text{ Limiting error} = \pm 3.375\%}$$

Given, $$R_T = 10 + 20 + 50 = 80\Omega$$

$$\boxed{R_{\text{measured}} = 80 \pm 3.375\%}$$

2. Multiplication or Division Terms

Let, $$x = \frac{x_1 x_2}{x_3} \text{ or } \frac{x_2 x_3}{x_1} \text{ or } x_1 x_2 x_3 \text{ or } \frac{x_1}{x_1 x_3}$$

Then, relative limiting error is

$$\boxed{\varepsilon_x = \pm(\varepsilon_{r1} + \varepsilon_{r1} + \varepsilon_{r3})}$$

NOTE

When, $$x = \frac{x_1 x_2}{x_2 + x_3} \text{ or } \frac{x_1}{x_2 + x_3} \text{ or } \frac{x_1 x_2}{x_2 - x_1}$$

Then, multiplication or division form is not applicable for finding relative limiting error.

Example - 1.9 In the measurement of unknown resistance by using a wheat stone bridge if $P = 20 \pm 5\%$, $Q = 50 \pm 3\%$ and $S = 30 \pm 2\%$. Find the value of the unknown resistance R and it's limiting error.

Solution:

Limiting error, $$\varepsilon_R = \pm(5 + 3 + 2) = \pm 10\%$$

$$R = \frac{P}{Q}\cdot S = \frac{20}{50}\times 30 = 12\,\Omega$$

So, unknown resistance, $$R = 12 \pm 10\%$$

3. Power of a Factor

Let, $$x = x_1^m \cdot x_2^n \cdot x_3^p \text{ or } \frac{x_1^m x_2^n}{x_3^p} \text{ or } \frac{x_1^m}{x_1^n x_3^p}$$

Then, Relative limiting error is $\varepsilon_r = \pm(m\,\varepsilon_{r1} + n\,\varepsilon_{r2} + p\,\varepsilon_{r3})$

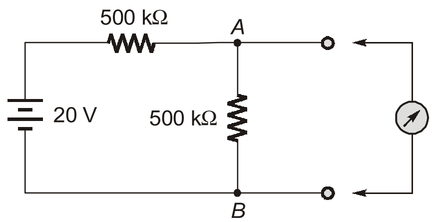
NOTE

When x is of the form $\dfrac{x_1^m}{x_2^n + x_3^p}$ or $\dfrac{x_1^m + x_2^n}{x_3^p}$

then, above method is not applicable for finding relative limiting 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:
(i) arithmetic mean
(ii) average deviation
(iii) standard deviation, treating the data as finite
(iv) 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 Ω with an error of ± 1 part in 10,000.
CD is a non-reactive resistor R_3 = 833 ± 0.25 Ω in series with no-loss capacitor C = 1.43 ± 0.001 μF.
DA is a non-reactive resistor R_2 = 16800 ± 1 part in 10,000.
The supply frequency is 50 ± 0.1 Hz. The bridge is balanced. Determine *L* and *R* of the coil and the limits or error. The balance conditions are:

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

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

Student's Assignments 1 Answers

1. 10 V, 8 V, 5.45 V, 2.86 V

2. (i) 147.53 Ω (ii) 0.218 Ω
(iii) 0.298 Ω (iv) 0.283 Ω

3. L = 21 ± 0.145 Hz and R = 2480 ± 29.5 Ω

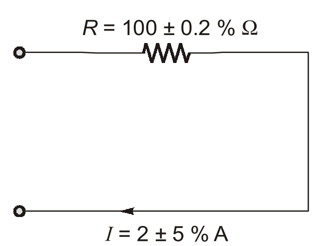
Student's Assignments 2

Q.1 Which of the following error is likely to occur in bridge method of measurement?
1. Residual error
2. Frequency and waveform error
3. 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 ±3% of full scale (at 25°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

Q.18 Permanent magnets used in instruments are hard core materials because
(a) they have broad hysteresis loop
(b) their energy density is high
(c) they have a high $(BH)_{max}$ product
(d) 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 = ± 3% of full scale which corresponds to ± 9 V.
So, range of reading for

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

3. (c)

$$P = I^2R$$
$$\in_I = 5\%$$
$$\in_r = 2\%$$
$$\in_p = 2\in_I + \in_R = 2 \times 5 + 0.2 = 10.2$$

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)

$$R_1 = 10^4 \pm 5\% \ \Omega$$
$$= 10^4 + \frac{5}{100} \times 10^4$$
$$= 10^4 \pm 500 \ \Omega$$
$$R_2 = 5000 \pm 10\% \ \Omega$$
$$= 5000 \pm \frac{10}{100} \times 5000$$
$$= 5000 \pm 500 \ \Omega$$
$$\therefore \quad R = R_1 + R_2 = 15000 \pm 1000 \ \Omega$$
$$\therefore \quad \text{Tolerance limit} = \frac{1000}{15000} \times 100$$
$$= 6.666\% \approx 6.67\%$$

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)

$$W_1 = (100 \pm 1) W$$
$$W_2 = (-50 \pm 0.5) W$$
$$\therefore \quad W_1 + W_2 = 50 \pm \frac{1.5}{50} \times 100$$
$$= \pm 50 \pm 3\%$$

Hence, uncertainly in measurement of power

$$= \pm 3\%$$

9. (c)

$$R = R_1 + R_2$$
$$\frac{\partial R}{R_1} = 1 \quad \text{and} \quad \frac{\partial R}{R_2} = 1$$
$$\sigma_{R1} = 5 \ \Omega$$
$$\sigma_{R2} = 15 \ \Omega$$
$$\sigma_R = \sqrt{\left(\frac{\partial R}{R_1}\right)^2 (\sigma_{R1})^2 + \left(\frac{\partial R}{R_2}\right)^2 (\sigma_{R2})^2}$$
$$= \sqrt{1(5)^2 + (15)^2} = 15.8 \ \Omega$$

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