
ELECTRICAL AND ELECTRONIC MEASUREMENTS

Chapter 1 FUNDAMENTALS OF MEASUREMENTS

Detailed Chapter Notes for Engineering Students

Includes diagrams, tables, 15 MCQs with answer key and 10 broad questions

Poly Notes Hub

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1.1 Purpose of Measurement and Significance of Measurement

What is measurement?

Measurement is the process of finding the magnitude of an unknown quantity, called the **measurand**, by comparing it with a standard of the same kind. The result of every measurement has two parts: a **numerical value** and a **unit**. For example, the statement “the current is 5 A” tells us that the measured current is five times the standard unit of current, the ampere.

An **instrument** is a device used to determine the present value of the quantity under measurement. Electrical and electronic instruments measure quantities such as voltage, current, resistance, power, energy, frequency, phase and time, either directly or after converting them into a convenient electrical form.

Fundamental requirements of a measurement

For a measurement to be meaningful and repeatable, the following requirements must be satisfied:

- The **standard** used for comparison must be accurately defined, internationally accepted (SI system) and available for verification.
- The **apparatus** or instrument used must be based on a proven (verifiable) principle and must itself be traceable to a standard.
- The **method** of comparison must be provable, i.e. any other competent person using the same method should obtain the same result.

Methods of measurement

Basis	Direct method	Indirect method
Principle	The unknown quantity is compared directly with a standard or measured on a calibrated instrument.	The quantity is obtained by measuring other related quantities and calculating the result from a known relation.
Accuracy	Generally limited only by the instrument.	Errors of all the individual measurements add up in the final result.
Examples	Current with an ammeter; voltage with a voltmeter; length with a scale.	Power from $P = VI$ (voltmeter and ammeter); resistance from $R = V/I$; speed from distance and time.

Generalised measurement system

Most modern measurement systems can be represented by five functional blocks, shown in Fig. 1.1. Not every instrument contains all the blocks; a simple pointer-type ammeter, for instance, combines several of them in one moving system.

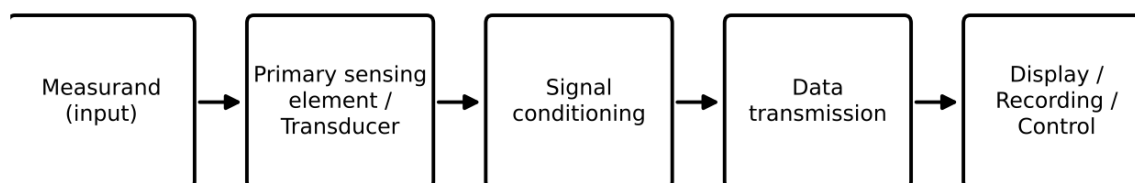


Fig. 1.1 Block diagram of a generalised measurement system

- **Primary sensing element (detector):** comes in direct contact with the measurand and gives an output that depends on it. Example: a thermocouple junction, a shunt resistor, a strain gauge.
- **Transducer:** converts the sensed physical quantity into a usable signal, usually electrical. Example: a thermocouple converts temperature into an e.m.f.
- **Signal conditioning:** amplifies, filters, linearises, modulates or converts the signal (for example analog-to-digital conversion) so that it is suitable for the next stage.
- **Data transmission:** carries the conditioned signal from the measuring point to the display point through cables, wireless links or telemetry.
- **Data presentation:** shows the result to the observer through an indicator, recorder, digital display or feeds it to a controller.

Purpose of measurement

Measurement is carried out for the following main purposes:

- **Monitoring** a process or operation, such as the voltage, frequency and load of a generating station.
- **Control** of processes: the measured value is fed back and compared with the desired value (for example, motor speed control).
- **Experimental analysis** in engineering design, to verify theory, to find the characteristics of a device and to collect data for improvement.
- **Testing and quality control** of products, to check that they meet the specified ratings and tolerances.
- **Protection and safety:** relays and trip circuits operate on measured quantities such as over-current and over-voltage.
- **Commercial purposes** such as billing of electrical energy by energy meters.
- **Fault diagnosis and maintenance**, by comparing measured values with normal values.
- **Research and development** of new devices, materials and systems.

Significance of measurement

Measurement is the basis of all science and engineering. A quantity that cannot be measured cannot be specified, designed, controlled or improved. Accurate measurement gives confidence in the performance, safety and economy of a system. In electrical engineering, it makes interchangeability of equipment, fair trade of energy and reliable operation of the grid possible.

Field	Role of measurement	Example
Power systems	Monitoring, protection, billing	Energy meters, CT/PT-fed relays
Industry	Process control and quality assurance	Temperature and speed control in a plant
Electronics	Design, testing and fault finding	Oscilloscope, multimeter, signal generator
Research	Collecting reliable data and validating models	Laboratory bridges and data loggers
Healthcare	Diagnosis and monitoring	ECG, blood pressure and temperature measurement

SI units of common electrical quantities

Quantity	SI unit	Symbol	Typical instrument
Current	ampere	A	Ammeter
Voltage (e.m.f.)	volt	V	Voltmeter
Resistance	ohm	Ω	Ohmmeter, bridge
Power	watt	W	Wattmeter
Energy	joule (kWh in practice)	J	Energy meter
Frequency	hertz	Hz	Frequency meter
Capacitance	farad	F	LCR meter, bridge
Inductance	henry	H	LCR meter, bridge
Magnetic flux	weber	Wb	Fluxmeter
Temperature	kelvin	K	Thermocouple, RTD

1.2 Definitions and Brief Explanations of Basic Terms

The performance of an instrument is described by a set of standard terms. The student must be clear about the meaning of each of them, because they are used throughout the subject.

1.2.1 Range

The **range** of an instrument is the region between the minimum and the maximum values of the quantity which the instrument can measure. It is stated as lower range value (LRV) to upper range value (URV). The algebraic difference between the two is called the **span**.

$$\text{Span} = \text{Upper range value} - \text{Lower range value}$$

- A voltmeter marked 0–300 V has a range of 0 to 300 V and a span of 300 V.
- A zero-centre ammeter marked –5 A to +5 A has a span of 10 A.
- A multi-range instrument has several ranges, selected by a range switch or by shunts and multipliers.

1.2.2 Sensitivity

Sensitivity is the ratio of the change in the output (or deflection) of the instrument to the change in the input (measurand) which causes it.

$$\text{Sensitivity, } S = \Delta\theta / \Delta x \text{ (e.g. mm per ampere, or degrees per volt)}$$

The reciprocal of sensitivity is called the **inverse sensitivity** or **scale factor** (units of measurand per scale division). A highly sensitive instrument shows a large deflection for a small input. For a moving-coil voltmeter, sensitivity is often expressed in **ohms per volt**, which equals $1 / (\text{full-scale deflection current})$, and a higher value means that the meter loads the circuit less.

Example 1.1

A pointer moves through 20 mm when the current changes by 4 A. Sensitivity $S = 20 / 4 = 5 \text{ mm/A}$ and inverse sensitivity = 0.2 A/mm.

1.2.3 True Value and Indicated Value

Term	Meaning
True value	The exact value of the quantity at the time of measurement. It can never be known exactly because no measurement is perfect, so in practice the <i>conventional true value</i> (the value given by a standard of much higher accuracy) is taken as the true value.
Indicated value	The value shown (read) by the instrument under test, i.e. the instrument reading. It differs from the true value by the error of the instrument and of the observer.

1.2.4 Errors

The **error** of a measurement is the difference between the indicated (measured) value and the true value. If A_m is the measured value and A_t the true value, then:

$$\text{Absolute error, } \delta A = A_m - A_t$$

$$\text{Relative error, } \varepsilon_r = \delta A / A_t \quad \text{Percentage error} = (\delta A / A_t) \times 100$$

$$\text{Correction} = - (\text{Error}) = A_t - A_m$$

The error may be positive (the instrument reads high) or negative (the instrument reads low). Errors are classified later in Section 1.3.4 as gross, systematic and random errors.

Example 1.2

A voltmeter reads 112 V when the true value is 110 V. Absolute error = +2 V; relative error = $2/110 = 0.0182$, i.e. **1.82 %**; correction = -2 V.

Limiting errors (guarantee errors)

Manufacturers do not claim that an instrument has no error; they guarantee that the error will not exceed a stated limit. This limit is called the **limiting error** or **guarantee error**. It is normally specified as a percentage of the **full-scale deflection (FSD)**, and sometimes as a percentage of the reading.

When the limiting error is given as a percentage of full scale, it is a fixed amount in units of the measurand, so the **relative error becomes larger when readings are small**. This is why a meter should be used so that the pointer deflects in the upper part of the scale.

Example 1.3

A 0-100 V voltmeter has a guaranteed accuracy of $\pm 1\%$ of FSD. Limiting error = ± 1 V at every point of the scale. The relative limiting error at various readings is given below.

Reading (V)	20	40	60	80	100
Limiting error (V)	± 1	± 1	± 1	± 1	± 1
Relative error (%)	± 5.00	± 2.50	± 1.67	± 1.25	± 1.00

Limiting error of combined quantities. When a result is calculated from several measured quantities, their limiting errors combine as follows:

Relation	Limiting error of the result
Sum or difference: $X = x_1 \pm x_2$	Absolute errors add: $\pm(\delta x_1 + \delta x_2)$
Product or quotient: $X = x_1 \cdot x_2$ or x_1/x_2	Relative errors add: $\pm(\epsilon_1 + \epsilon_2)$
Power: $X = x^n$	Relative error is n times: $\pm n \cdot \epsilon$

Example 1.4

- Two resistors $R_1 = 100 \Omega \pm 5 \%$ and $R_2 = 200 \Omega \pm 10 \%$ are connected in series. Errors are $\pm 5 \Omega$ and $\pm 20 \Omega$. Total $R = 300 \Omega$ with limiting error $\pm 25 \Omega$, i.e. **$\pm 8.33 \%$** .
- Resistance is found as $R = V/I$ with $V = 100 \text{ V} \pm 0.5 \%$ and $I = 10 \text{ A} \pm 1 \%$. Limiting error in $R = \pm(0.5 + 1) = \pm 1.5 \%$.

1.2.5 Resolution

Resolution is the smallest change in the measured quantity that the instrument can detect and show. In an analog instrument it is limited by the smallest scale division which the observer can read (including estimation between divisions). In a digital instrument it is the value of the least significant digit.

Example 1.5

A $3\frac{1}{2}$ -digit digital multimeter can display a maximum of 1999. On its 2 V range the least count is 0.001 V, so the resolution is **1 mV**. Resolution is not the same as accuracy; a meter can display small steps and still be inaccurate.

1.2.6 Accuracy

Accuracy is the closeness with which an instrument reading approaches the true value of the quantity being measured. It tells how small the error is. It may be stated in three ways:

- As a **percentage of full-scale reading**, e.g. $\pm 1 \%$ of FSD (most analog instruments).
- As a **percentage of the true value (reading)**, e.g. $\pm 0.5 \%$ of reading (most digital instruments).
- As an **absolute value** in units of the measurand, e.g. $\pm 0.2 \text{ A}$.

$$\% \text{ Accuracy} = 100 - \% \text{ Error}$$

1.2.7 Precision

Precision is a measure of the reproducibility or consistency of the measurements, i.e. how closely repeated readings of the same quantity agree with each other under the same conditions. A precise instrument gives nearly the same reading every time, but that reading may be far from the true value if there is a constant (systematic) error. Precision depends on the random errors and the number of significant figures to which the reading can be taken.

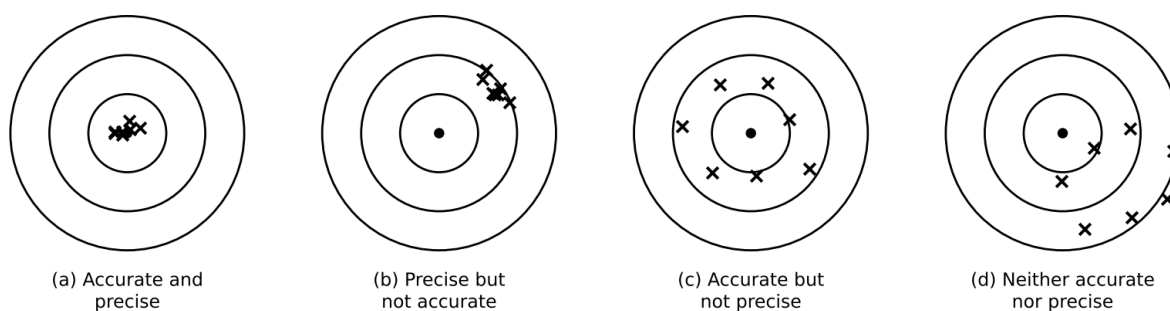


Fig. 1.3 Accuracy and precision illustrated on a target (centre = true value)

Accuracy	Precision
Closeness of the reading to the true value.	Closeness of repeated readings to each other.
Affected by systematic errors.	Affected by random errors.
Can be improved by calibration.	Cannot be improved by calibration; it depends on the design of the instrument.
Needs the true value (a standard) for assessment.	Can be assessed without knowing the true value.
An accurate instrument may or may not be precise.	A precise instrument may or may not be accurate.

1.2.8 Instrument Efficiency

The **efficiency of an instrument** expresses how much of the measuring signal is obtained for the power that the instrument itself draws from the circuit. It is defined as the ratio of the full-scale reading of the instrument to the power consumed by the instrument at full-scale reading.

$$\text{Instrument efficiency} = \text{Full-scale reading} / \text{Power consumed at full-scale}$$

The unit depends on the quantity measured (V/W for a voltmeter, A/W for an ammeter). An instrument with a high efficiency draws very little power from the circuit under test, so it disturbs the circuit less (small **loading effect**) and gives results closer to the true value. This is why high-resistance voltmeters and low-resistance ammeters are preferred.

Example 1.6

A 0–100 V voltmeter consumes 0.5 W at full scale. Efficiency = $100 / 0.5 = 200 \text{ V/W}$.

Summary of terms

Term	One-line definition	Expression
Range / span	Limits of measurement / URV – LRV	Span = URV – LRV
Sensitivity	Output change per unit input change	$S = \Delta\theta / \Delta x$
Error	Measured value – true value	$\delta A = A_m - A_t$
Limiting error	Maximum error guaranteed by the maker	$\pm(\% \text{ of FSD}) \times \text{FSD}$
Resolution	Smallest detectable change	Value of least count
Accuracy	Closeness to the true value	100 – % error
Precision	Closeness of repeated readings	Spread of readings
Efficiency	Full-scale reading per unit power used	$\text{Reading}_{\text{FS}} / \text{Power}_{\text{FS}}$

1.3 Classification of Instrument Systems

Instruments may be classified in several ways depending on the point of view: the method of obtaining the result, the manner in which the result is expressed, the nature of the display and the behaviour of the instrument with time. Fig. 1.4 summarises the classifications covered in this chapter.

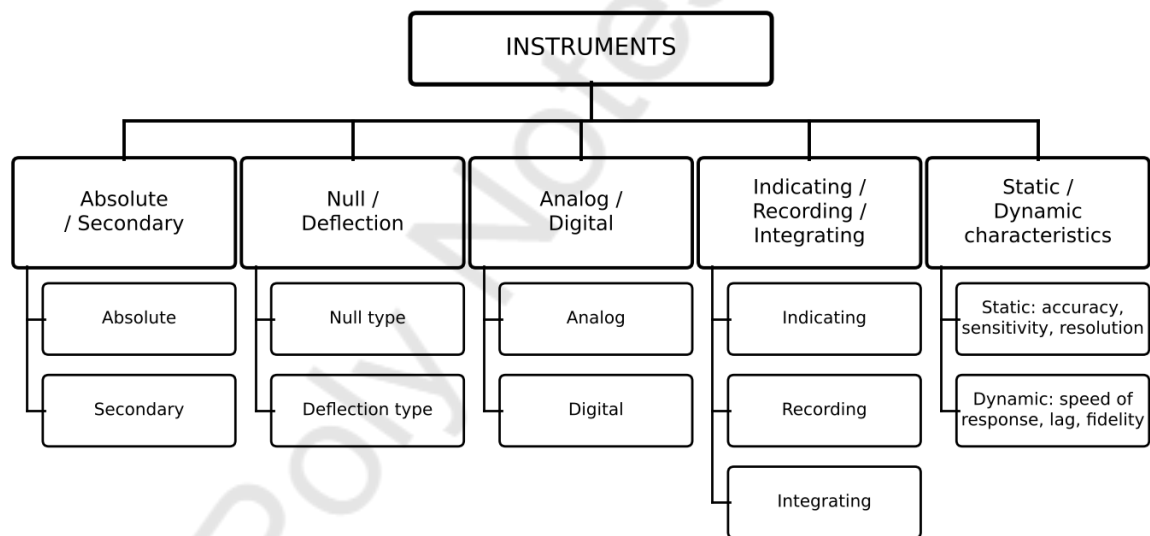


Fig. 1.4 Classification of instruments

1.3.1 Null and Deflection Type Instruments

Deflection type instruments. In these instruments the measurand produces a physical effect, such as a force or torque, which moves a pointer over a scale. The pointer stops where the effect of the measurand is balanced by an opposing effect built into the instrument (for example, a spring). The **magnitude of the pointer deflection** is taken as the measure of the quantity. Examples are the PMMC ammeter and voltmeter, moving-iron instruments and the dynamometer wattmeter.

Null type instruments. In these instruments the unknown quantity is balanced against a known quantity that can be varied, until a sensitive **null detector** (for example a galvanometer) shows zero. At balance, the unknown is calculated from the known value and the circuit constants.

Examples are the Wheatstone bridge, the AC bridges, the potentiometer and the beam balance.

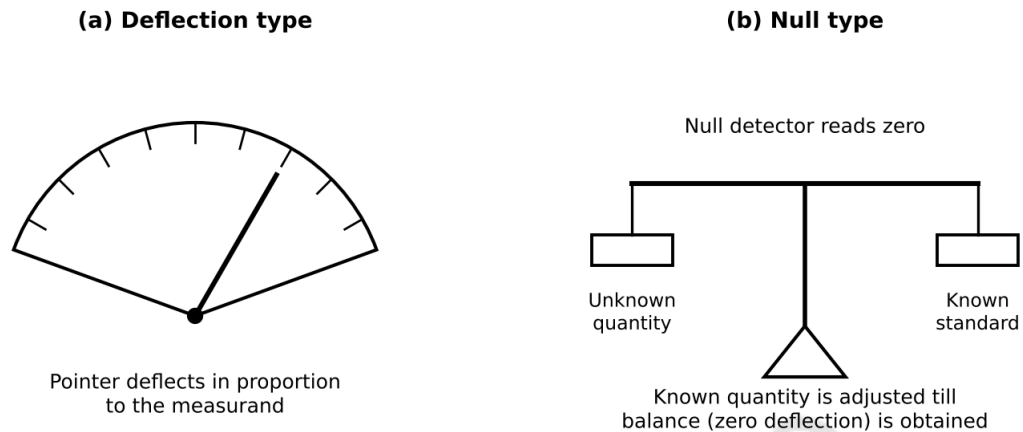


Fig. 1.2 Deflection and null type instruments

Basis	Deflection type	Null type
Principle	Pointer deflection is proportional to the measurand.	A known quantity is adjusted until the detector reads zero.
Accuracy	Lower; depends on calibration of the scale and the spring.	Higher; depends on the accuracy of the standard and the sensitivity of the detector.
Sensitivity	Moderate.	Very high near balance.
Power drawn from source	Takes some power to deflect the pointer (loading effect).	At balance draws no power from the source under measurement.
Speed of reading	Fast; direct reading.	Slow; balancing is required.
Cost and skill	Cheaper and simple to use.	Costlier and needs more skill.
Examples	PMMC and moving-iron meters, dynamometer wattmeter.	Wheatstone bridge, Schering bridge, potentiometer.

1.3.2 Absolute and Secondary Instruments

Absolute instruments give the value of the quantity directly in terms of the constants of the instrument and its deflection, without comparison with any other instrument. They need no calibration. They are used mainly in standard laboratories, e.g. the tangent galvanometer (current from the earth's field, coil dimensions and deflection) and the Rayleigh current balance.

Secondary instruments are calibrated by comparing them with an absolute instrument or with another secondary instrument that has already been calibrated. Their deflection has meaning only after calibration. Almost all industrial and laboratory instruments are secondary instruments, such as ammeters, voltmeters, wattmeters and energy meters.

Basis	Absolute instruments	Secondary instruments
Calibration	Not required.	Must be calibrated against a standard.
Reading	Obtained from instrument constants and deflection.	Obtained directly from the calibrated scale.
Use	Standardising laboratories.	Day-to-day measurement in industry and laboratories.

Basis	Absolute instruments	Secondary instruments
Speed and convenience	Slow, needs calculation.	Quick and convenient.
Examples	Tangent galvanometer, Rayleigh current balance.	Ammeter, voltmeter, wattmeter, energy meter.

1.3.3 Analog and Digital Instruments

Analog instruments give an output that varies continuously with the measurand; the pointer can take any position on the scale and the observer reads the value from the scale. **Digital instruments** give the output as discrete numerical digits on a display. Inside a digital instrument, the conditioned analog signal is converted into digital form by an **analog-to-digital converter (ADC)**, processed and then shown on an LED, LCD or other display.

Basis	Analog instruments	Digital instruments
Output	Continuous pointer movement over a scale.	Discrete numerical display.
Reading errors	Parallax and interpolation errors are possible.	No parallax; reading is direct and unambiguous.
Resolution	Limited by scale divisions.	High; set by the number of digits.
Accuracy	Typically 0.5 % to 2 % of FSD.	Can be 0.01 % of reading or better.
Speed of reading	Slower to read; hard to follow rapid changes.	Fast; suited to automatic measurement.
Interfacing	Difficult to connect to computers.	Easy interfacing with computers and data loggers.
Power and cost	Usually needs no power for sensing; cheap.	Needs a power supply; cost is higher.
Trend viewing	Easy to see trends and peaks at a glance.	Trend is harder to see on a numeric display.
Examples	PMMC voltmeter, moving-iron ammeter.	Digital multimeter, digital frequency counter.

1.3.4 Static and Dynamic Characteristics, Types of Errors

(a) Static characteristics

Static characteristics describe the performance of an instrument when the measurand is constant or changes very slowly, so that the instrument has reached a steady state. They are obtained by calibration.

Characteristic	Meaning
Accuracy and precision	Closeness to the true value and closeness of repeated readings (Section 1.2).
Sensitivity and resolution	Output change per unit input; smallest detectable change (Section 1.2).
Linearity	Closeness of the actual input-output curve to the ideal straight line. Non-linearity is given as the maximum deviation, usually as a percentage of FSD.
Hysteresis	Difference in output for the same input when the input is approached from below (increasing) and from above (decreasing). It is caused by friction and by elastic and magnetic properties of the materials.
Dead zone (dead band)	The largest change in input which produces no change in output.

Characteristic	Meaning
Threshold	The minimum input required to produce a detectable output when starting from zero.
Drift	Slow change in output with time even though the input is constant, caused by temperature changes, ageing and component instability. Types: zero drift and sensitivity (span) drift.
Repeatability	Agreement of repeated readings for the same input, same observer, same instrument and conditions, over a short time.
Reproducibility	Agreement of readings when the conditions are changed (different time, place, observer or instrument).
Stability and reliability	Ability to keep its performance over a long time; probability of working properly for a stated period.
Backlash	Lost motion in mechanical parts (gears, linkages) so that the output does not change at once when the input direction is reversed.
Loading effect	Change in the quantity being measured because of the instrument connected to it.

Input-output relation. An ideal instrument has a linear characteristic, $\text{output} = \text{sensitivity} \times \text{input}$. In practice, non-linearity, hysteresis and drift make the actual relation differ from the ideal one, as shown in Fig. 1.6.

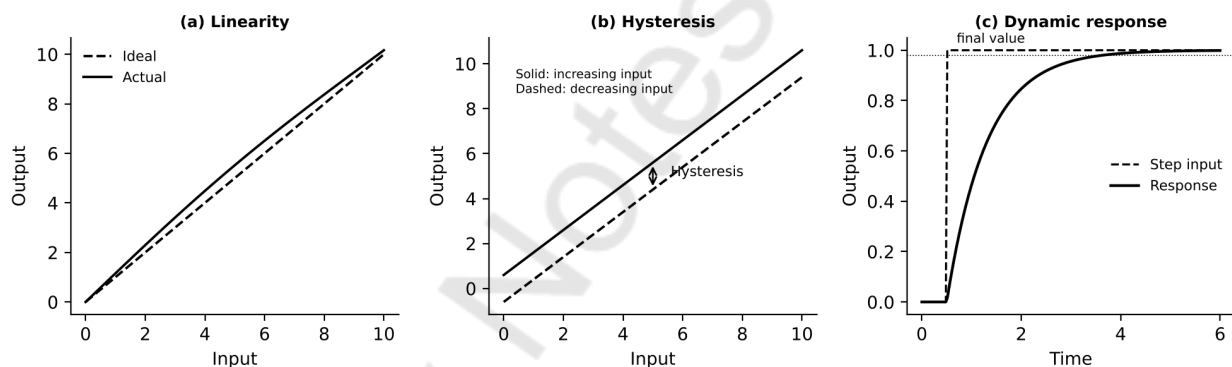


Fig. 1.6 Static and dynamic characteristics

(b) Dynamic characteristics

The measurand often changes with time. **Dynamic characteristics** describe how well the instrument follows these changes. When the input changes suddenly (a step), the output of a real instrument cannot change instantly; it takes time to settle at the new value, as in Fig. 1.6(c).

- **Speed of response (response time):** how quickly the instrument reacts to a change in the measurand.
- **Measuring lag:** delay in the response of the instrument to a change in the measurand. It may be a *retardation lag* (response starts at once but slowly) or a *time delay* (response begins after a dead time).
- **Fidelity:** the degree to which the instrument faithfully reproduces the changes in the measurand without distortion.
- **Dynamic error:** the difference between the true value of the quantity changing with time and the value indicated by the instrument, when the static error is assumed to be zero.
- **Time constant, rise time and settling time:** numerical measures of the speed of response (below).

For a simple (first-order) instrument, the response to a step input of final value A is:

$$y(t) = A (1 - e^{-t/\tau})$$

where τ is the **time constant**. After $t = \tau$ the output reaches 63.2 % of its final value, and after about 4τ it has reached about 98 %. A smaller time constant means a faster instrument. Pointer instruments with moving parts behave as second-order systems, and their response depends on the damping (Section 1.5.1).

Basis	Static characteristics	Dynamic characteristics
Applies to	Steady or very slowly varying input.	Rapidly varying input.
Examples	Accuracy, sensitivity, linearity, hysteresis, drift.	Speed of response, measuring lag, fidelity, dynamic error.
Found by	Calibration with constant inputs.	Applying step, ramp or sinusoidal inputs.

(c) Types of errors

No measurement is free from error. Knowing the types and causes of errors helps in reducing them. Errors are broadly classified into three groups, as shown in Fig. 1.7.

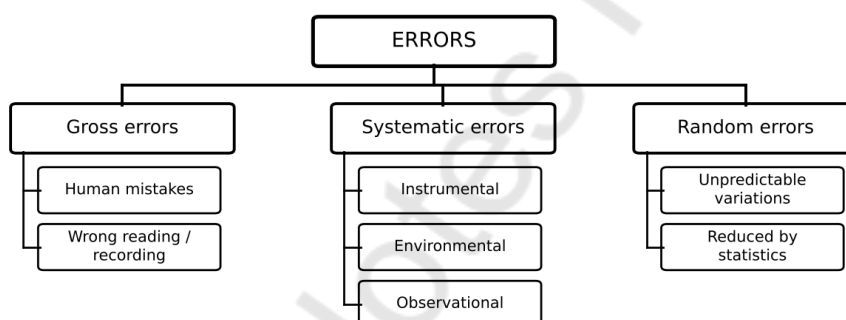


Fig. 1.7 Types of errors in measurement

Type	Causes	Examples	How to reduce
Gross errors	Human mistakes in reading, recording or calculating; wrong instrument selection.	Misreading 52 as 25; using a wrong range; forgetting the multiplying factor.	Take care, repeat readings, take several readings by different persons.
Systematic errors (instrumental)	Shortcomings of the instrument: friction, worn parts, weak springs, wrong zero, poor calibration, loading effect.	Zero error; ageing of a spring; a voltmeter drawing current from the circuit.	Calibrate, apply corrections, use better instruments, set zero before use.
Systematic errors (environmental)	Changes in the surroundings: temperature, humidity, pressure, dust, external magnetic or electric fields.	Resistance change with temperature; stray magnetic field affecting a meter.	Control the environment, use shielding, apply temperature compensation.
Systematic errors (observational)	Faults of the observer: parallax, wrong estimation of fractions of a division.	Reading the scale from an angle.	Use mirror scale and knife-edge pointer; look perpendicular to the scale.

Type	Causes	Examples	How to reduce
Random errors	Small unpredictable variations from unknown causes; they remain even after systematic errors are removed.	Slight scatter in repeated readings of the same quantity.	Take many readings and use statistical analysis (the average).

Statistical treatment of random errors. For n readings $x_1, x_2, \dots, x_n$:

- Arithmetic mean: $\bar{x} = (x_1 + x_2 + \dots + x_n) / n$, which is the best estimate of the true value.
- Deviation of each reading: $d = x - \bar{x}$ (the algebraic sum of deviations is zero).
- Standard deviation: $\sigma = \sqrt{(\sum d^2 / n)}$ for large n , or $\sqrt{(\sum d^2 / (n - 1))}$ for a small number of readings.
- Probable error: $r = 0.6745 \sigma$.

Remember

- Accuracy is affected mainly by **systematic** errors, precision by **random** errors, and gross errors are avoided by **care** of the observer.
- Static errors are errors that remain when the input is steady; dynamic errors arise when the input changes with time.

1.4 Calibration of Instruments: Necessity and Procedure

Calibration is the process of comparing the readings of an instrument (the *unit under test*) with those of a standard of known and higher accuracy, in order to find the error of the instrument and, where possible, to correct it. The result is usually a calibration table or a **calibration curve** that relates the indicated value to the true value.

Necessity of calibration

- Instruments change with time because of ageing, wear, friction, weakening of springs, mechanical shock and component drift, so the error must be checked regularly.
- To make sure that the instrument reads within its guaranteed accuracy and to find the correction to be applied.
- To maintain **traceability**: the reading can be related, through an unbroken chain of comparisons, to national and international standards.
- To obtain the **reliable, comparable** results needed for quality control, billing and legal use.
- To ensure safety of equipment and personnel, because wrong measurements can lead to wrong decisions.
- After repair, replacement of parts or exposure to abnormal conditions (shock, overload, temperature) the instrument must be re-checked.
- Calibration is also required for new instruments, before they are put into service, and when the instrument is used in a new environment.

Hierarchy of standards (traceability)

Measurement standards are arranged in a chain so that the accuracy of every instrument can be traced back to the definition of the unit. The accuracy decreases down the chain. In India the national primary standards are maintained at the CSIR-National Physical Laboratory (NPL), New Delhi.

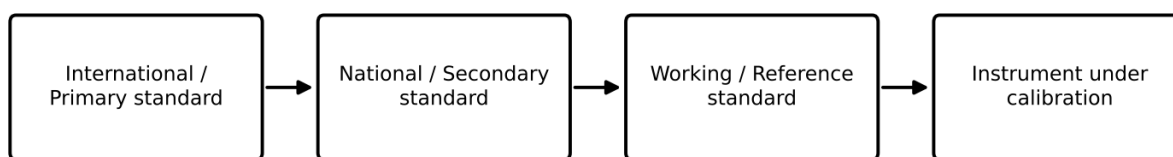


Fig. 1.5 Traceability chain in calibration (accuracy reduces down the chain)

Level of standard	Maintained at	Purpose
International standard	International bureau of weights and measures	Defines the unit; not for ordinary use.
Primary (national) standard	National laboratories such as NPL	Calibrates secondary standards; not available for general use.
Secondary standard	Accredited calibration laboratories and industry	Calibrates working standards.
Working standard	Laboratories and workshops	Used for regular calibration of ordinary instruments.

As a general rule, the standard used for calibration should be several times (commonly 4 to 10 times) more accurate than the instrument being calibrated.

Procedure of calibration

1. **Identify** the instrument, its range and its rated accuracy; check it visually for damage, and note the ambient conditions (temperature, humidity).
2. **Select the standard:** a reference instrument or source of higher accuracy (traceable to a national standard) and of suitable range.
3. **Prepare** the instrument: allow it to warm up where necessary, set the mechanical zero and place it in its normal working position.
4. **Connect** the instrument under test and the standard so that both receive the same input (for an ammeter, in series; for a voltmeter, in parallel), as in Fig. 1.9.
5. **Apply** input values in steps over the full range (for example 0, 20, 40, 60, 80, 100 % of range), first in increasing order (upscale) and then in decreasing order (downscale) to reveal hysteresis.
6. **Record** the reading of the instrument under test and the reading of the standard at every step.
7. **Calculate** the error (indicated – standard) and the correction (standard – indicated) at each point, and the percentage error with respect to full scale.
8. **Plot** the calibration curve (error or correction against reading) and compare the maximum error with the guaranteed limit.
9. **Adjust** (zero, span or gain) if the error exceeds the limit; repeat the calibration after adjustment.
10. **Document** the results in a calibration certificate and label the instrument with the date of calibration and the date when the next calibration is due.

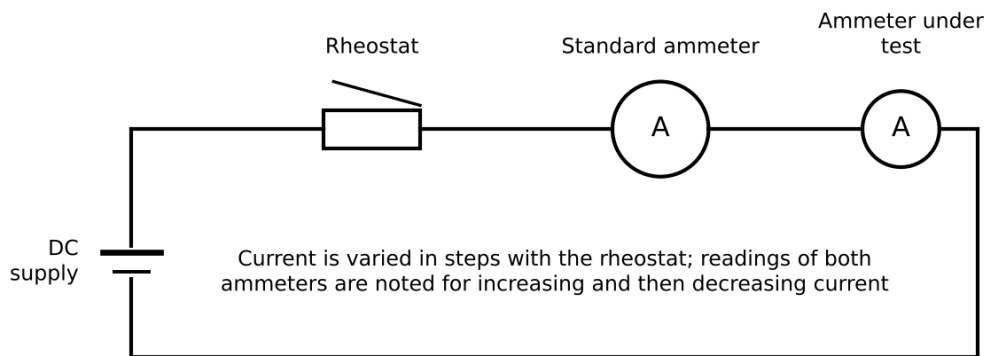


Fig. 1.9 Calibration of an ammeter by direct comparison

Sample calibration record of a 0–100 V voltmeter against a standard voltmeter:

Standard value (V)	Indicated value (V)	Error (V)	Correction (V)	Error (% of FSD)
20	20.5	+0.5	–0.5	+0.5
40	40.8	+0.8	–0.8	+0.8
60	60.9	+0.9	–0.9	+0.9
80	80.6	+0.6	–0.6	+0.6
100	100.4	+0.4	–0.4	+0.4

The maximum error is +0.9 V (0.9 % of FSD), which is within a guaranteed accuracy of ± 1 % of FSD, so the instrument is acceptable. The correction curve can be used to correct any reading taken with this meter.

Calibration interval. The period between two calibrations depends on the type of instrument, how often and how severely it is used, its stability, the accuracy required and the manufacturer's recommendation. Instruments used for critical or legal measurements are calibrated more frequently.

Method	Description
Direct comparison	The instrument is compared with a standard instrument of the same type, both receiving the same input (Fig. 1.9).
Indirect comparison	The instrument is calibrated against a standard source or a standard of a different kind, for example a standard resistor with a standard voltage source, or a calibrator.

1.5 Classification of Measuring Instruments

According to the way in which the information is presented, measuring instruments are classified as **indicating**, **recording** and **integrating** instruments.

Indicating instruments

An **indicating instrument** shows the instantaneous value of the quantity being measured by the position of a pointer on a scale, or by a digital display. It gives no permanent record. Examples are ammeters, voltmeters, wattmeters, frequency meters, power-factor meters and digital multimeters.

Recording instruments

A **recording instrument** gives a continuous permanent record of the variation of the quantity with time. A pen or stylus draws a trace on a moving chart, or the values are stored in memory. Examples are strip-chart recorders, X-Y plotters, ECG machines, oscillographs and digital data loggers. They are used where the history of a quantity is needed, for example the load curve of a substation or the temperature of a furnace.

Integrating instruments

An **integrating instrument** measures the total quantity delivered over a period of time, i.e. the time integral of the measured quantity. They add up (integrate) the power over time to give energy. Examples are the energy meter (kWh meter), ampere-hour meter, water-flow totaliser and the odometer of a vehicle.

Basis	Indicating	Recording	Integrating
Output	Instantaneous value on a scale or display.	Continuous graph or stored data against time.	Total accumulated quantity over time.
Record kept?	No.	Yes, permanent.	Yes, as a running total.
Quantity measured	Voltage, current, power, etc.	Variation of voltage, current, temperature, etc.	Energy (kWh), charge (Ah), total flow.
Examples	Ammeter, voltmeter, wattmeter.	Strip-chart recorder, data logger, ECG.	Energy meter, ampere-hour meter.
Typical use	Everyday observation and testing.	Analysis, trend study and fault investigation.	Billing and totalising.

1.5.1 Essential Requirements of Indicating Instruments

The pointer of an indicating instrument is moved by the measured quantity and must settle at a definite position which is a reliable measure of that quantity. For this, every indicating instrument must have three essential systems, each producing a torque (or force) on the moving system:

- a **deflecting system** producing the deflecting torque T_d ,
- a **controlling system** producing the controlling torque T_c , and
- a **damping system** producing the damping torque T_{damp} .

(i) Deflecting system

The deflecting system produces a torque proportional to the quantity being measured, which moves the pointer from its zero position. The torque is produced by one of several effects: magnetic effect (moving-coil and moving-iron instruments), electrodynamic effect (dynamometer), electrostatic effect (electrostatic voltmeters), thermal effect (hot-wire instruments) and induction effect (energy meters).

(ii) Controlling system

The controlling system performs two jobs: it produces a **controlling torque** which opposes the deflecting torque and increases as the pointer deflects, so that the pointer stops at a definite position for each value of the measurand; and it brings the pointer back to zero when the measured quantity is removed. Without it the pointer would swing to the end of the scale for any input. In the steady (final) position:

$$T_d = T_c$$

Basis	Spring control	Gravity control
Method	One or two hair-springs (phosphor bronze) attached to the moving system.	A small adjustable weight attached to the moving system.
Controlling torque	$T_c = K\theta$ (proportional to deflection, K = spring constant).	$T_c = W \cdot l \cdot \sin \theta$ (not proportional to deflection).
Scale	Uniform scale is possible (when $T_d \propto \text{current}$).	Scale is not uniform; it is cramped near zero.
Effect of temperature and ageing	Spring may weaken and change with temperature.	Not affected by temperature or ageing.
Mounting	Can be used in any position.	Instrument must be kept vertical (level); it cannot be used in portable meters.
Use	Most portable and panel instruments.	Some switchboard instruments and some old types.

(iii) Damping system

When the deflecting torque is applied, the moving system tends to overshoot the final position and oscillate about it because of its inertia. The **damping system** produces a torque which acts opposite to the motion of the moving system, and so stops the oscillations and brings the pointer quickly to rest at its final position. It does not affect the final steady deflection, because the damping torque is zero when the moving system is at rest.

Depending on the amount of damping, the response may be **under-damped** (the pointer overshoots and oscillates before settling), **critically damped** (the pointer reaches the final position in the shortest time without overshoot) or **over-damped** (the pointer creeps slowly to the final position). In practice the instrument is designed to be slightly under-damped, close to critical damping.

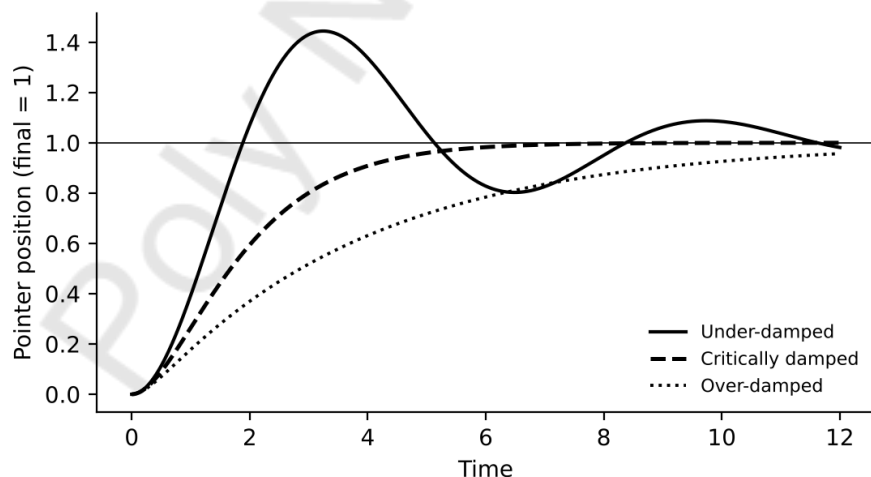


Fig. 1.8 Effect of damping on the pointer movement

Method of damping	Principle	Remarks
Air-friction damping	A light aluminium vane or piston attached to the moving system moves in a closed air chamber; air resistance opposes the motion.	Simple and cheap; used in moving-iron and some other instruments.
Fluid-friction damping	A disc attached to the spindle moves in oil; viscous friction of the liquid opposes the motion.	Effective, but the instrument must be kept upright and oil may leak.

Method of damping	Principle	Remarks
Eddy-current damping	A metal disc or former moves in the field of a permanent magnet; the eddy currents induced produce a braking torque.	Most efficient; used in PMMC instruments and energy meters. Not suitable where the magnet would disturb the operating field.

Other essential requirements

- The instrument should have **high accuracy** and **high sensitivity**.
- It should consume **very little power**; the ammeter resistance should be low and the voltmeter resistance high, to reduce loading.
- The **friction** in the pivots and bearings must be low, and the moving system should be **light but strong** so that the torque to weight ratio is high.
- The scale should be **uniform or easily readable** and should have clear markings; a mirror scale and knife-edge pointer reduce parallax.
- The instrument should be **well damped** so that the pointer settles quickly.
- It should be unaffected by **temperature, humidity, stray magnetic fields** and mechanical vibration, and should be adequately shielded.
- The **insulation** should be adequate for safety, and the construction robust and reliable.
- The instrument should be **cheap, durable** and need little maintenance.

Quick Revision: Formulas and Key Facts

- Span = URV – LRV; Sensitivity = $\Delta \text{output} / \Delta \text{input}$.
- Error = measured – true; Correction = – error; % error = error / true $\times$ 100.
- Limiting error (% of FSD) is fixed in value, so relative error = (limiting error / reading) $\times$ 100.
- Sum/difference: absolute errors add. Product/quotient: relative errors add. Power n: relative error $\times$ n.
- Instrument efficiency = full-scale reading / power consumed at full scale.
- First-order response: 63.2 % after one time constant.
- At steady deflection $T_d = T_c$; three torques: deflecting, controlling, damping.

Practice Section A: Multiple Choice Questions

Choose the correct option. The answer key with brief reasons is given at the end of this section.

- Q1.** The process of comparing an unknown quantity with a standard of the same kind is called
- (A) Calibration
 - (B) Measurement
 - (C) Control
 - (D) Sensitivity
- Q2.** The algebraic difference between the upper and lower range values of an instrument is called its
- (A) Span
 - (B) Resolution
 - (C) Threshold
 - (D) Accuracy
- Q3.** The pointer of an ammeter moves 30 mm when the current changes by 6 A. Its sensitivity is
- (A) 0.2 mm/A
 - (B) 36 mm/A
 - (C) 5 mm/A
 - (D) 180 mm/A
- Q4.** A 0–200 V voltmeter has a guaranteed accuracy of $\pm 1\%$ of full-scale deflection. The limiting error at a reading of 100 V is
- (A) $\pm 1\%$
 - (B) $\pm 0.5\%$
 - (C) $\pm 4\%$
 - (D) $\pm 2\%$
- Q5.** The closeness of agreement among repeated measurements of the same quantity is called
- (A) Accuracy
 - (B) Precision
 - (C) Resolution
 - (D) Range
- Q6.** A $3\frac{1}{2}$ -digit digital voltmeter on its 2 V range has a resolution of
- (A) 0.1 V
 - (B) 10 mV
 - (C) 1 mV
 - (D) 0.1 mV
- Q7.** Which of the following is a null type instrument?
- (A) Potentiometer
 - (B) PMMC ammeter
 - (C) Moving-iron voltmeter
 - (D) Dynamometer wattmeter
- Q8.** An example of an absolute instrument is the
- (A) Energy meter
 - (B) Voltmeter
 - (C) Wattmeter
 - (D) Tangent galvanometer

Q9. Which of the following is NOT a static characteristic of an instrument?

- (A) Hysteresis
- (B) Linearity
- (C) Speed of response
- (D) Dead zone

Q10. Error caused by reading a scale from an angle (parallax) is a

- (A) Random error
- (B) Observational error
- (C) Environmental error
- (D) Gross error

Q11. Calibration of an instrument is necessary to

- (A) Increase its range
- (B) Reduce its cost
- (C) Increase its sensitivity
- (D) Find and correct its error by comparison with a standard

Q12. An energy meter (kWh meter) is an example of an

- (A) Integrating instrument
- (B) Recording instrument
- (C) Null type instrument
- (D) Absolute instrument

Q13. The torque which brings the pointer quickly to rest without oscillations is the

- (A) Deflecting torque
- (B) Controlling torque
- (C) Damping torque
- (D) Gravity torque

Q14. At the final steady position of the pointer of an indicating instrument

- (A) Deflecting torque is greater than controlling torque
- (B) Deflecting torque equals controlling torque
- (C) Deflecting torque is less than controlling torque
- (D) Damping torque is maximum

Q15. For a first-order instrument, the output reaches about what percentage of its final value after one time constant?

- (A) 63.2 %
- (B) 36.8 %
- (C) 50 %
- (D) 98 %

Answer Key

Q	Ans	Reason	Q	Ans	Reason
1	B	Definition of measurement.	9	C	Speed of response is dynamic.
2	A	Span = URV – LRV.	10	B	Parallax arises from the observer.
3	C	$S = 30/6 = 5 \text{ mm/A}$.	11	D	Calibration compares with a standard and gives the correction.
4	D	Limiting error = 2 V; $2/100 = 2 \%$.	12	A	It totals energy over time.
5	B	Precision means repeatability of readings.	13	C	Damping torque stops oscillations.
6	C	Maximum count 1999, so 2 V / 2000 gives 1 mV.	14	B	Steady deflection needs $T_d = T_c$.
7	A	Balance is obtained at zero detector reading.	15	A	$y = A(1 - e^{-1}) = 0.632 A$.
8	D	It gives the value from its own constants, no calibration.			

Practice Section B: Broad Questions

Answer in detail, using neat diagrams, tables and formulae wherever necessary.

- Q1.** Define measurement. Explain the purpose and significance of measurement. Draw and explain the block diagram of a generalised measurement system.
- Q2.** Define and explain with examples: (a) range and span, (b) sensitivity, (c) true value and indicated value, (d) resolution, (e) instrument efficiency.
- Q3.** Distinguish between accuracy and precision with the help of a target diagram. What is meant by the limiting error of an instrument? Explain with an example.
- Q4.** A 0-150 V voltmeter has a guaranteed accuracy of $\pm 1.5\%$ of full-scale deflection. Calculate the limiting error in volts and the relative limiting error when the meter reads 50 V, 100 V and 150 V. What conclusion do you draw about the selection of the range of an instrument? Also find the limiting error of a resistance calculated as $R = V/I$ when $V = 100 \text{ V} \pm 1\%$ and $I = 5 \text{ A} \pm 2\%$.
- Q5.** What are null type and deflection type instruments? Compare them in a table and give two examples of each.
- Q6.** Differentiate (a) absolute and secondary instruments, and (b) analog and digital instruments, with suitable examples.
- Q7.** Explain the static characteristics of an instrument: linearity, hysteresis, dead zone, threshold, drift, repeatability and reproducibility. Sketch the relevant characteristics.
- Q8.** Explain the dynamic characteristics of an instrument. Classify the errors in measurement and describe the causes of each type and the methods to reduce them.
- Q9.** What is calibration? State the necessity of calibration. Describe the procedure of calibrating an ammeter by direct comparison, and explain the traceability chain of standards.
- Q10.** Classify measuring instruments into indicating, recording and integrating types with examples. What are the essential requirements of an indicating instrument? Explain the deflecting, controlling and damping systems, with the methods of damping.

End of Chapter 1: Fundamentals of Measurements