DI03000091: Electrical Instrumentation

GTU Course Presentation

July 25, 2026

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Lecture Agenda I

- Fundamental Concepts of Measurement
- The Direct Method of Measurement: Concepts & Examples
- Diagrammatic Model of Direct Measurement
- The Indirect Method of Measurement: Concepts & Examples
- Diagrammatic Model of Indirect (Transducer) Measurement
- Comparative Matrix: Direct vs. Indirect
- Engineering Selection Criteria & Case Studies
- Summary and Review Questions

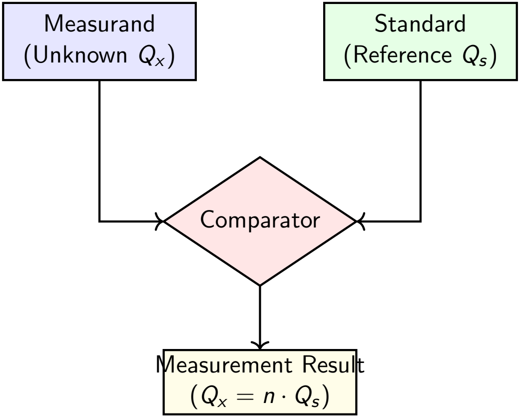
Introduction to Measurement Systems I

- Measurement is the quantitative comparison of an unknown physical quantity (measurand) with a predefined standard.
- The standard is a physical representation of the unit of measurement, established by international agreements.
- A reliable measurement system must minimize systematic and random errors while ensuring repeatability.
- Depending on how the comparison is executed, measurements are categorized into Direct and Indirect methods.
- Modern electrical instrumentation relies heavily on converting physical variables into electrical signals.

Direct Method of Measurement I

- Definition: The measurand is directly compared against a standard of the same physical quantity without intermediate translation.
- Mathematical Relation: $Q_{measured} = n \cdot Q_{standard}$, where n is the ratio determined by comparison.
- Example 1: Measuring length using a graduated steel scale (comparing length to a standard meter line).
- Example 2: Measuring unknown resistance R_x using a Wheatstone bridge where balance is achieved against known resistors.
- Example 3: Direct voltage comparison using a DC potentiometer against a standard Weston cadmium cell.

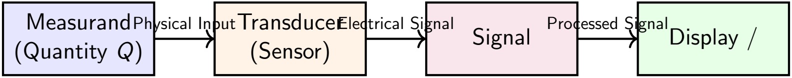
Direct Measurement Process Flow I



Indirect Method of Measurement I

- Definition: The measurand is converted into a different physical quantity that is easier to measure, process, or display.
- Mathematical Relation: $Q_{output} = f(Q_{measurand})$, where f represents the transfer function of the measurement system.
- This method is necessary when the measurand is inaccessible or cannot be directly compared to a standard of its own kind.
- Example 1: Measuring temperature using a thermocouple, which converts temperature difference into a thermoelectric EMF.
- Example 2: Measuring force or load using a strain gauge, where mechanical strain changes resistance, measured via a bridge circuit.

Indirect Measurement System Architecture I



Direct vs. Indirect Methods I

Feature	Direct Method	Indirect Meth
Comparison Type	Immediate comparison with a standard of the same physical unit.	Measurand cor other form (us cal) first.
Accuracy	Higher, as it avoids cumulative errors of multi-stage conversion.	Lower, as error across transduc ditioners.
Dynamic Response	Poor; typically limited to static or very slow steady-state parameters.	Excellent; ide speed, transie namic changes
Applications	Standards laboratories, calibration, simple manual dimensional checks.	Industrial auto mote sensing computerized a
Human Factor	High susceptibility to human parallax, estimation, and alignment errors.	Low; output is tized, logged, a automatically.

Engineering Selection Criteria I

- Measurand Accessibility: If a high-voltage conductor or chemical reactor is being measured, direct methods are too hazardous; indirect telemetry is required.
- Bandwidth and Frequency Response: For alternating or fluctuating signals, direct mechanical methods suffer from inertia; electronic indirect methods are mandatory.
- System loading effects: Indirect methods using active sensors can minimize energy extraction from the measured medium.
- Cost and complexity tradeoffs: Direct instrumentation has low capital cost but high operational overhead; indirect systems are complex but scale well.

Summary and Review Questions I

- Direct measurement compares the unknown parameter directly to a standard, providing high accuracy but limited dynamic range.
- Indirect measurement uses transducer stages to translate the measurand, offering compatibility with modern control systems.
- Review Question 1: Discuss why standard calibration systems utilize direct measurements whereas control loops use indirect measurements.
- Review Question 2: A thermistor measures temperature. Describe the sequence of energy transformations that make this an indirect measurement.

Agenda I

- Classification of Instruments: Absolute vs. Secondary
- Absolute Instruments: Working Principles & Examples
- Secondary Instruments: Characteristics & Types
- Indicating Instruments: Functional Mechanism and Torques
- Integrating Instruments: Deflection & Operation
- Recording Instruments: Continuous Measurement Systems
- Comparative Summary of Indicating, Integrating, and Recording Instruments

Classification of Instruments I

- Measuring instruments are broadly classified into two categories: Absolute and Secondary Instruments.
- Absolute (Primary) Instruments: Give the value of the quantity under measurement in terms of physical constants of the instrument itself and its deflection.
- No calibration is required for absolute instruments as they do not depend on comparison with other standards.
- Secondary Instruments: Calibrated such that their deflection directly indicates the electrical quantity on a pre-graduated scale.
- Secondary instruments require comparison with an absolute instrument or a pre-calibrated standard to verify accuracy.

Absolute Instruments: Tangent Galvanometer Principle I

Since $F(I) = \frac{\mu_0 NI}{2r}$, current $I = K \tan \theta$;

Secondary Instruments Overview I

- Secondary instruments are the standard tools used in daily engineering practice (e.g., Voltmeters, Ammeters, Wattmeters).
- They utilize the effects of electrical current (magnetic, thermal, electrostatic, chemical) to produce physical deflection.
- They must be calibrated before use to ensure that the scale readings map correctly to standard SI units.
- Depending on the nature of the measurement output, secondary instruments are categorized into: Indicating, Integrating, and Recording instruments.

Indicating Instruments: Essential Torques I

- Indicating instruments indicate the magnitude of an electrical quantity at the instant it is being measured.
- Deflecting Torque (T_d): Generated by the electrical quantity, causing the moving system (pointer) to deflect from zero.
- Controlling Torque (T_c): Opposes the deflecting torque and increases with deflection. Ensures the pointer stops at a unique position for a given input value. Achieved by spring or gravity control.
- Damping Torque (T_d or T_v): Dampens the oscillations of the pointer about its steady-state position to allow quick reading. Achieved by air, fluid, or eddy current damping.

Torque Balance in Indicating Instruments I

Deflection angle $\theta \propto$ Deflecting current I;

Integrating Instruments: Operational Principles I

- Integrating instruments measure and register the total quantity of electricity (ampere-hours) or total electrical energy (kilowatt-hours) consumed over a period.
- Unlike indicating instruments, they have no pointer/controlling torque; instead, they utilize a continuously rotating system.
- The speed of rotation of the moving element (e.g., aluminum disc) is made directly proportional to the rate of energy consumption (power).
- A train of gear wheels registers the total number of revolutions, displaying the total energy consumed in kWh.

Recording Instruments: Mechanism & Applications I

- Recording instruments continuously record the variation of an electrical quantity over a specified period.
- The moving system carries a stylus, pen, or ink-dropper that traces a path on a moving chart or paper strip.
- The chart is driven at a constant speed by a synchronous motor, spring-driven clockwork, or electronic stepper motor.
- Crucial for monitoring long-term system behavior, load curves in substations, temperature variations, and fault analysis.

Comparison of Indicating, Integrating, and Recording Instruments I

Parameter	Indicating	Integrating	Rec
Function	Shows value at the instant of measurement.	Sums up the total quantity over a period.	Rec cont time
Output	Dial pointer deflection.	Gear dial counter/register.	Styl log
Examples	Ammeter, Voltmeter, Wattmeter.	Energy Meter (kWh), Ampere-Hour Meter.	Stri Digi
Applications	Lab testing, real-time panels.	Billing consumers, energy audits.	Pow proc

Agenda I

- Functional block diagram of a generalised measurement system
- Primary sensing, variable conversion, and manipulation elements
- Data transmission and presentation elements
- Requirements of electromechanical indicating instruments
- Analysis of Deflecting Torque (T_d) and Controlling Torque (T_c)
- Analysis of Damping Torque (T_v) and response classifications
- Comparison: Spring Control vs. Gravity Control
- Overview of Damping Methods: Air Friction, Fluid Friction, and Eddy Current

Generalised Measurement System Architecture I

(Physical Input);
ode [block, right of=m, node distance=3.2cm] (pse) Primary Sensing Element;
ode [block, right of=pse, node distance=3.2cm] (vce) Variable Conversion Element;
ode [block, right of=vce, node distance=3.2cm] (vme) Variable Manipulation;
ode [block, below of=vme, node distance=2.2cm] (dte) Data Transmission;
ode [block, left of=dte, node distance=3.2cm] (dpe) Data Presentation;
ode [block, left of=dpe, node distance=3.2cm] (obs) Observer / User;

Generalised Measurement System Architecture II

line](m)--(pse);\pathline] (pse) – (vce);
line](vce)--(vme);\pathline] (vme) – (dte);
line](dte)--(dpe);\pathline] (dpe) – (obs);

Sensing and Conversion Elements I

- Primary Sensing Element: First block that receives energy from the measured medium. It produces an output depending on the measurand (e.g., a Bourdon tube converting pressure to displacement, or a resistance thermometer converting temperature to resistance changes).
- Variable Conversion Element: Converts the output of the primary sensing element (which may be electrical, mechanical, optical, etc.) into an alternative, more convenient form while maintaining the essential information content.
- For example, in an electronic balance, a strain gauge converts mechanical force to a change in electrical resistance. The wheatstone bridge then converts this resistance change into an electrical voltage signal.

Sensing and Conversion Elements II

- The conversion process must be linear, stable, and highly repeatable to avoid introducing systematic errors or calibration drifts into the measurement chain.

Manipulation, Transmission, and Presentation I

- Variable Manipulation Element: Operates on the converted signal to change its magnitude (e.g., amplification via operational amplifiers or attenuation via voltage dividers) without altering its physical nature.
- Data Transmission Element: Required when the presentation or control location is remote from the sensing location. Signals are transmitted via analog current loops (4-20 mA), optical fibers, digital fieldbuses, or wireless transceivers.
- Data Presentation Element: Provides the final interface to the human observer or feedback controller. This includes analog pointers, digital liquid crystal displays (LCDs), graphic recorders, or data-logging computer workstations.
- Modern systems integrate microcontrollers at the presentation stage for automatic scaling, unit conversion, temperature compensation, and digital communication.

Operating Forces in Indicating Instruments I

- Electromechanical indicating instruments require three distinct torques to function correctly: Deflecting (or operating) torque, Controlling (or restoring) torque, and Damping torque.
- Deflecting Torque (T_d): Causes the moving system (and pointer) to move from the zero position when the instrument is energized.
- Controlling Torque (T_c): Opposes the deflecting torque and ensures that the deflection is proportional to the magnitude of the quantity under measurement.
- Damping Torque (T_v): Prevents the pointer from oscillating around its final steady-state position, bringing it to rest quickly to allow rapid, accurate readings.
- In the steady-state condition, the deflecting torque is exactly balanced by the controlling torque: $T_d = T_c$ (at rest).

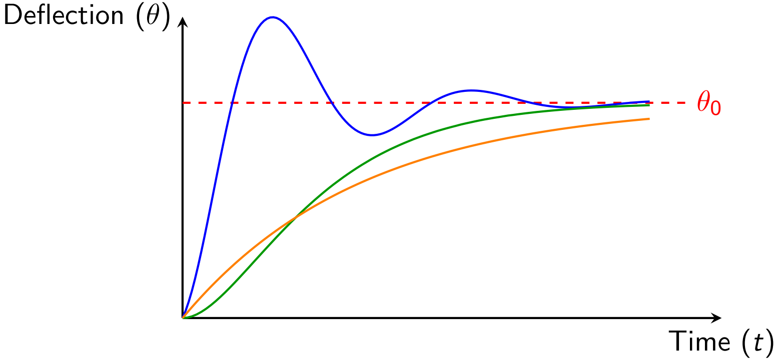
Deflecting and Controlling Torques I

- Deflecting Torque generation: T_d is produced using magnetic effects (PMMC), electromagnetic attraction/repulsion (Moving Iron), electrodynamic effects (Dynamometer), or thermal effects.
- Spring Control: Employs two spiral hairsprings wound in opposite directions to compensate for temperature. The restoring torque is directly proportional to deflection: $T_c = K \cdot \theta$ (where K is the spring constant).
- With Spring Control: At steady-state, $T_d = T_c$. Since $T_c = K\theta$, if $T_d \propto I$ (e.g., PMMC), the scale is linear: $\theta = \frac{G}{K} I$.
- Gravity Control: Uses a small adjustable control weight. The controlling torque is given by $T_c = m \cdot g \cdot d \cdot \sin\theta$, where m is mass, g is gravity, and d is the distance to the center of gravity.

Deflecting and Controlling Torques II

- With Gravity Control: At steady state, $T_d = T_c \propto \sin\theta$. This yields a non-linear, cramped scale at the lower end, and the instrument must be level.

Dynamic Response & Damping Curves I



Controlling Methods Comparison I

Feature	Spring Control	Gravity Co
Torque Equation	$T_c = K \cdot \theta$ (Linear)	$T_c = W \cdot$ linear)
Scale Uniformity	Uniform and linear scale	Non-uniform the beginnin
Mounting Position	Can be used in horizontal, vertical, or inclined positions	Must be m vertically to
Temperature Sensitivity	Subject to temperature errors (spring stiffness changes)	Not affected changes
Weight	Adds negligible mass to the moving system	Control weig tal weight a

Damping Methods in Practice I

- Air Friction Damping: Utilizes a light aluminum piston or vane moving in a closed chamber. Used in Moving Iron and Induction instruments where operating magnetic fields are weak.
- Fluid Friction Damping: Employs a vane submerged in a high-viscosity damping oil. Provides greater damping than air, but limited to vertically mounted panel-type electrostatic instruments.
- Eddy Current Damping: A thin aluminum or copper disc attached to the spindle rotates in the field of a permanent magnet. The induced eddy currents interact with the field to produce an opposing torque ($T_v \propto$ speed).

Damping Methods in Practice II

- Eddy current damping is the most efficient method and is widely used in Permanent Magnet Moving Coil (PMMC) and Hot-wire instruments due to its reliability and absence of friction.
- Summary: The select damping method is governed by the operating field strength of the instrument to avoid interference with the deflecting magnetic fields.

Lecture Agenda I

- Introduction to Range, Span, True Value, and Indicated Value
- Measurement Error and Correction: Mathematical definitions and relationships
- Sensitivity and Scale Factor: Formulation and physical meaning
- Repeatability vs. Reproducibility: Concepts of measurement consistency
- Precision vs. Accuracy: Understanding the distinct differences with diagrams
- Significant Figures: Rules and representation in scientific measurements

Range, Span, True Value, and Indicated Value I

- Range: Defines the limits between which the input or output of an instrument may vary. Expressed by stating the lower and upper limits (e.g., 0 V to 10 V, -50°C to 150°C).
- Span: The algebraic difference between the upper and lower limits of the range. For a range of -50°C to 150°C, the span is 150 - (-50) = 200°C.
- True Value: The actual, real value of the physical quantity under measurement. It is an ideal concept and cannot be measured with absolute certainty; it is typically represented by the mean of an infinite number of measurements or by a primary standard.
- Indicated Value: The value of the physical quantity registered or displayed by the measuring instrument directly, without any corrections applied.

Measurement Error and Correction I

- Absolute Error (e): Defined as the difference between the indicated value (A_m) and the true value (A_t). Formally: $e = A_m - A_t$.
- Absolute Correction (δ): The value that must be added algebraically to the indicated value to get the true value: $A_t = A_m + \delta$. Therefore, $\delta = -e = A_t - A_m$.
- Relative Error (e_r): The ratio of the absolute error to the true value, often expressed as a percentage: $e_r = \frac{A_m - A_t}{A_t} \times 100\%$.
- Static Error: The deviation of the indicated value from the true value when the measured quantity is static or varies very slowly with time.

Comparison Table: Error, Correction, and Relative Metrics I

Parameter	Symbol	Formula	Descri
Absolute Error	e	$e = A_m - A_t$	Discrep and tru
Absolute Correction	δ	$\delta = A_t - A_m$	Adjustr value t $A_m + \delta$
Relative Error	e_r	$e_r = \frac{e}{A_t}$	Fractio value, racy.
Percentage Relative Error	$\%e_r$	$\%e_r = \frac{A_m - A_t}{A_t} \times 100$	Relativ age of

Sensitivity and Scale Factor Representation I

$$S = \frac{dQ_o}{dQ_i} \approx \frac{\Delta Q_o}{\Delta Q_i};$$

ode[align=left, text width=5cm] at (3.5,0.8) **Scale Factor** (K):

Sensitivity and Scale Factor Representation II

$K = \frac{1}{S} = \frac{\Delta Q_i}{\Delta Q_o}$;

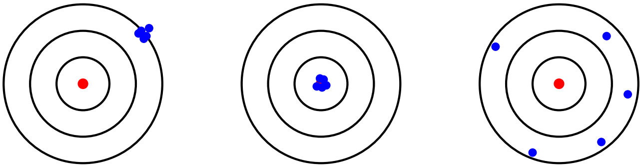
Repeatability versus Reproducibility I

- Repeatability: The closeness of agreement among consecutive measurements of the same quantity under the same conditions of measurement. Same operator, same instrument, same location, same environment, and repeated over a short period of time.
- Reproducibility: The closeness of agreement among measurements of the same quantity under changed conditions of measurement. This can involve different observers, different instruments, different locations, or different times.
- Key Contrast: Repeatability measures the short-term consistency (minimum variation), whereas reproducibility measures the long-term or system-wide consistency under varying conditions.

Repeatability versus Reproducibility II

- Both are statistical measures of precision and are typically quantified using standard deviation or variance of the measurement set.

Accuracy versus Precision Visualized I



Accuracy versus Precision Explained I

- Accuracy: The degree of closeness of a measured value to its true or accepted reference value. It is directly related to systematic error; smaller systematic errors lead to higher accuracy.
- Precision: The degree of agreement or reproducibility among a series of individual measurements of the same quantity. It represents the degree of repeatability and is related to random errors; smaller random errors lead to higher precision.
- Conformity: A component of precision, representing the ability of an instrument to produce the same reading under the same conditions. However, a highly conforming instrument can still be inaccurate if there is a constant systematic bias.
- Summary: An instrument can be highly precise but inaccurate (due to systematic calibration offset), but it cannot be verified as highly accurate without being reasonably precise.

Significant Figures and Reporting Measurements I

- Significant Figures: The number of meaningful digits in a measured value that carry real information about its precision. It includes all certain digits plus one first uncertain (estimated) digit.
- Rule of Representation: A measurement of 12.3 V indicates that the value is known to be between 12.25 V and 12.35 V (three significant figures). A measurement of 12.30 V indicates that it is between 12.295 V and 12.305 V (four significant figures).
- Propagation of Figures: In addition/subtraction, the result should have the same number of decimal places as the term with the fewest decimal places. In multiplication/division, the result should have the same number of significant figures as the term with the fewest significant figures.

Significant Figures and Reporting Measurements II

- Instrumentation Standard: When reporting instrument errors or uncertainties, they should typically be rounded to one or at most two significant figures, and the measured value rounded to match the decimal place of the uncertainty.

Agenda I

- Fundamental definition of measurement error
- Broad classification of errors: Gross, Systematic, and Random
- Gross Errors: Sources, practical examples, and prevention
- Systematic Errors: Instrumental, environmental, and observational sources
- Quantifying systematic errors: The voltmeter loading effect
- Random Errors: Indeterminate nature and statistical analysis
- Comparative summary of error types

- No measurement in electrical instrumentation can be made with absolute accuracy. The measured value will always deviate from the true value.
- Error is defined mathematically as the difference between the measured value (V_m) and the true value (V_t):
  Error $= V_m - V_t$.
- Static correction is defined as the negative of the error:
  Correction $= V_t - V_m$.
- To minimize uncertainty, engineers must understand the origin, nature, and mathematical characteristics of the different types of errors.

Classification of Measurement Errors I

(Human Mistakes); ode (sys) at (4,2) [minimum width=2.5cm]
Systematic Errors
(Determinate); ode (rand) at (8,2) [minimum width=2.5cm]
Random Errors
(Indeterminate); [-¿, thick] (root) – (gross); [-¿, thick] (root) – (sys); [-¿, thick] (root) – (rand); ode (inst) at (1.5,0) [fill=green!10, minimum width=2cm] Instrumental; ode (env) at (4,0) [fill=green!10, minimum width=2cm] Environmental; ode (obs) at (6.5,0) [fill=green!10, minimum width=2cm] Observational; [-¿, thick] (sys) – (inst); [-¿, thick] (sys) – (env); [-¿, thick] (sys) – (obs);

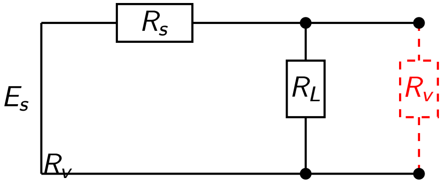
Gross Errors: Human Mistakes I

- Definition: Errors that occur primarily due to human oversights, lapses in concentration, or lack of care during measurement and recording.
- Common Sources: Misreading scale divisions (e.g. reading 22.5V as 25.2V), writing down an incorrect number in the logbook, or improper adjustment of instrument zero points.
- Physical Mistakes: Making incorrect electrical connections (e.g. connecting an ammeter in parallel with a load) or neglecting correction factors.
- Minimization: Gross errors cannot be modeled mathematically. They must be avoided by: taking extreme care, using automated data loggers, and taking multiple independent readings by different observers.

Systematic Errors: Instrumental Sources I

- Definition: Determinately directed errors that tend to occur consistently in one direction (always positive or always negative) under similar conditions.
- Instrumental Errors: Built-in deficiencies of the instrument caused by mechanical friction in the pivot bearings, wear of spring tension, or static calibration issues.
- Misuse of Instruments: Using an instrument outside its specified range or failing to set the pointer to zero prior to starting the measurement.
- Loading Effect: The error caused by the instrument altering the state of the circuit under measurement (e.g., a low-resistance voltmeter drawing significant current).

Systematic Errors: Voltmeter Loading Effect I



Systematic Errors: Environmental & Observational I

- Environmental Errors: Caused by external conditions affecting the instrument, such as ambient temperature changes, humidity variations, and stray magnetic/electrostatic fields.
- Temperature effects: Changes the resistance of copper coils inside analog meters, introducing systematic scale errors.
- Minimization of Environmental Errors: Using magnetic shielding, housing instruments in temperature-controlled chambers, and using compensation circuits.
- Observational Errors: Most commonly caused by parallax error, where the operator's line of sight is not perfectly perpendicular to the mirror-backed pointer scale.

Random Errors: Nature and Statistical Analysis I

- Definition: Residual errors that remain after all systematic errors have been minimized or corrected; they vary randomly in magnitude and direction.
- Origin: Caused by complex, unknown, or microscopic variations in the measuring system, such as thermal noise, high-frequency voltage fluctuations, or vibration.
- Statistical Treatment: Since they are indeterminate, they are analyzed using probability theory, assuming a Gaussian (Normal) Distribution.
- Key Metrics: Arithmetic Mean $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, Standard Deviation $\sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}$, and Variance σ^2.
- Minimization: Increasing the number of independent measurements and computing the arithmetic mean.

Comparison of Gross, Systematic, and Random Errors I

Parameter	Gross Errors	Systematic Errors	Ra
Cause	Human oversight, reading/writing mistakes	Instrumental calibration, environmental factors	Un ing
Predictability	Completely unpredictable	Predictable, follows definite laws	Sta ity
Minimization	Care, multiple observers, cross-checking	Calibration, compensation, shielding	Av rea an
Math Treatment	Cannot be treated mathematically	Corrected by formula or correction factor	Tre sta tio

Lecture Agenda I

- Functional elements of an instrumentation system
- Classification of measurement errors: Gross, Systematic, and Random
- Systematic errors: Instrumental, Environmental, and Observational
- Statistical analysis of random errors
- Methods of error minimization and calibration

Functional Elements of Instrumentation System I

Quantity; [-¿, thick] (2.2,0.6) – (3.2,0.6); [rounded corners, fill=blue!10] (3.2,0) rectangle (5.4,1.2);
ode[align=center] at (4.3,0.6) Primary
Sensing Element; [-¿, thick] (5.4,0.6) – (6.4,0.6); [rounded corners, fill=blue!10] (6.4,0) rectangle (8.6,1.2);
ode[align=center] at (7.5,0.6) Variable
Conversion; [-¿, thick] (8.6,0.6) – (9.6,0.6); [rounded corners, fill=blue!10] (9.6,0) rectangle (11.8,1.2);
ode[align=center] at (10.7,0.6) Signal
Processing; [-¿, thick] (10.7,0) – (10.7,-1.5); [rounded corners, fill=blue!10] (9.6,-2.7) rectangle (11.8,-1.5);
ode[align=center] at (10.7,-2.1) Data
Transmission; [-¿, thick] (9.6,-2.1) – (8.6,-2.1); [rounded corners, fill=blue!10] (6.4,-2.7) rectangle (8.6,-1.5);

Functional Elements of Instrumentation System II

ode[align=center] at (7.5,-2.1) Data
Presentation; [-¿, thick] (6.4,-2.1) – (5.4,-2.1); [rounded corners,
fill=blue!10] (3.2,-2.7) rectangle (5.4,-1.5);
ode[align=center] at (4.3,-2.1) Observer /

Recorder;

Understanding the Instrumentation System I

- An instrumentation system is designed to measure physical quantities and present them in a readable form.
- Each functional stage introduces potential errors due to non-ideal behavior of components.
- Primary Sensing Element: Interacts directly with the measurand; loading effects here cause loading errors.
- Variable Conversion & Processing: Converts sensor output (e.g., resistance change to voltage) and filters/amplifies; prone to noise, offset, and non-linearity.
- Data Transmission & Presentation: Transmits signal over distance; prone to attenuation and external electromagnetic interference (EMI).

Introduction to Measurement Errors I

- No measurement can be made with perfect accuracy. Understanding error is crucial for design and calibration.
- Error is defined as the deviation of the measured value from the true value of the physical quantity.
- Mathematical Expression: E = Am - At, where Am is the measured value and At is the true value.
- Absolute Error vs. Relative Error: Relative error is absolute error divided by the true value, often expressed as a percentage.
- Errors are broadly classified into three categories: Gross Errors, Systematic Errors, and Random Errors.

Classification of Measurement Errors I

Errors child node Gross Errors child node Systematic Errors child node Instrumental child node Environmental child node Observational child node Random Errors ;

Comparison of Error Types I

Parameter	Gross Errors	Systematic Errors	Random
Source	Human negligence and improper use.	Inherent equipment flaws or environmental factors.	Unknown tic envi variations
Behavior	Large, erratic, and unpredictable.	Constant in magnitude and sign under same conditions.	Small, fl and follo sian distri
Correction	Double-checking readings and proper care.	Calibration, zeroing, and hardware compensation.	Taking t metic mea datasets.

Systematic Errors: Instrumental, Environmental, Observational I

- Systematic errors are deterministic; they tend to bias the measurement in a specific direction.
- Instrumental Errors: Arise from inherent shortcomings in the instrument (e.g., friction in bearings, calibration drift, zero offset, or loading effects).
- Environmental Errors: Caused by external conditions affecting the instrument, such as temperature fluctuations, humidity changes, magnetic fields, and vibration.
- Observational Errors: Introduced by the observer (e.g., parallax error when reading an analog pointer, or misinterpreting scale graduations).
- Minimization: Controlled by calibrating instruments regularly, designing temperature-compensated circuits, and using digital readouts to eliminate parallax.

Random Errors & Statistical Analysis I

- Random errors remain after all systematic errors have been accounted for; they are caused by stochastic variations.
- They are unpredictable in magnitude and sign, but they follow a Normal (Gaussian) probability distribution.
- Arithmetic Mean: The best estimate of the true value for a finite set of readings (x_bar = sum(x_i)/n).
- Standard Deviation (sigma): Measures the precision and dispersion of the measurements; lower sigma implies higher precision.
- Limiting Errors (Guarantee Errors): The maximum limits of deviation specified by the manufacturer (e.g., an instrument specified as accurate to +/-1% of full scale).

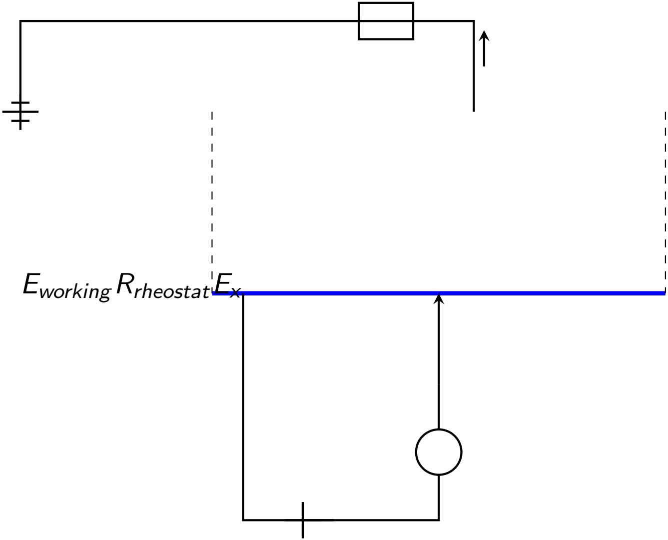
Methods for Error Minimization I

- Careful Design: Selection of high-precision, low-drift components and shielded wiring to prevent electromagnetic interference.
- Calibration: Comparing the instrument against a known standard of higher accuracy to establish correction factors.
- Environmental Control: Using temperature-controlled enclosures, vibration isolation tables, and magnetic shielding.
- Statistical Averaging: Recording multiple measurements and computing the mean to reduce the effect of random noise.
- Proper Operating Procedures: Ensuring correct sensor loading, impedance matching, and using automated data acquisition.

Agenda I

- Basic operating principle of a slide-wire DC potentiometer
- The standardization process using a Weston cadmium standard cell
- Construction and design details of Crompton's laboratory DC potentiometer
- Mathematical relationships, calibration steps, and resolution analysis
- Application: Precision measurement of low, medium, and high resistance
- Application: Calibration of analog voltmeters using a Volt-box
- Application: Calibration of ammeters using a standard shunt resistor
- Key sources of error: Thermal EMFs, contact resistance, and mitigation techniques

Basic Principle of DC Potentiometer I

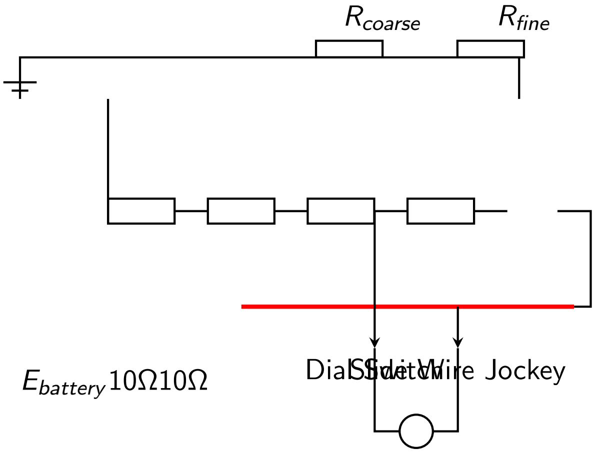


Standardization of DC Potentiometer I

- Standardization is the process of adjusting the current through the slide wire to a precise, known value to calibrate the scale drop per unit length.
- A Weston cadmium standard cell with a known EMF of 1.0186 V (at 20 degrees Celsius) is connected into the potentiometer circuit in opposition to the working battery.
- The sliding jockey is positioned at the exact graduation mark representing 1.0186 V (or 101.86 cm on a scale calibrated at 1 mV/cm).
- The coarse and fine rheostats in series with the working battery are adjusted until the galvanometer shows a null deflection (zero current).
- At the null point, the voltage drop across the selected portion of the slide wire is exactly equal to the standard cell EMF, securing calibration.

Standardization of DC Potentiometer II

- Important constraint: Once standardized, the working battery rheostat must not be altered during subsequent measurements of unknown voltages.


R_{coarse}
R_{fine}
$E_{battery}$ 10Ω10Ω
Dial Switch
Slide Wire Jockey

Working and Operation of Crompton's Potentiometer I

- The instrument utilizes 15 precision resistors connected in series with a slide wire. Each resistor and the slide wire have an equal resistance of 10 ohms.
- Working current is set to 10 mA (0.01 A) via the standardization process. Consequently, the voltage drop across each of the 15 resistors is exactly 0.1 V.
- The 10-ohm slide wire has a drop of 0.1 V across its entire length. It is divided into 100 equal scale divisions, giving a resolution of 1 mV per division.
- By utilizing a vernier scale on the slider, the resolution is further extended to 0.1 mV, facilitating highly precise readings.

Working and Operation of Crompton's Potentiometer II

- To measure an unknown voltage, balance is obtained by first switching the dial steps in 0.1 V increments, then moving the slide wire jockey.
- The measured voltage is calculated as: V_x = (Dial Switch Setting x 0.1 V) + (Slide Wire Division x 0.001 V) + (Vernier Division x 0.0001 V).

Resistance Range	Measurement Method	Potentiometer Set tails
Low Resistance ($< 1\ \Omega$)	Comparison with a Standard low resistance (S) connected in series.	Voltage drops $V_x =$ $V_s = IS$ are measure constant current I. $S \times (V_x/V_s)$.
Medium Resistance ($1\ \Omega$ to $100\ k\Omega$)	Substitution or voltage-ratio comparator method.	Potentiometer c voltage drops acros dard and unknown in a balanced bridge uration.
High Resistance ($> 100\ k\Omega$)	Loss of charge or guard circuit configurations.	Potentiometer n voltage drop across series standard shu tor sensing leakage

Calibration of Voltmeters and Ammeters I

- Voltmeters cannot be directly calibrated above 1.6 V due to the potentiometer's limited range. Instead, a precision Volt-box divider is used.
- The Volt-box steps down the high voltage by a known ratio (e.g., 100:1 or 10:1). The potentiometer measures this stepped-down voltage directly.
- Actual Voltage = Potentiometer Reading x Volt-box Multiplier. Voltmeter Error = Voltmeter Reading - Actual Voltage.
- Ammeter calibration uses a precision low-resistance standard shunt (S) connected in series with the ammeter under test.
- The potentiometer measures the voltage drop V_s across this shunt. The true current is then calculated as $I = V_s/S$.
- Ammeter Error = Ammeter Reading - Calculated True Current (I). A calibration curve is plotted across multiple current settings.

Multi-Range Potentiometer & Error Sources I

- Multi-range potentiometers employ shunt and series resistors (range switches like x1, x0.1, x0.01) to scale down current without changing input resistance.
- Thermo-electric EMFs: Junctions of dissimilar metals under temperature gradients generate parasitic voltages that distort low-voltage measurements.
- Mitigation of Thermal EMFs: Copper-copper terminals are used for critical connections, and reversing switches isolate the offset potentials.
- Contact Resistance: Friction and wear at the slider and dial switch terminals introduce variable resistance, requiring self-cleaning contact geometry.
- Insulation Leakage: Leakage currents from the working battery or external high-voltage circuits to the galvanometer path distort balance.

Multi-Range Potentiometer & Error Sources II

- Standard Cell Drift: The EMF of standard cells varies with temperature and exhibits long-term drift, necessitating periodic validation.

Summary and Comparison with Deflection Instruments I

- Null Balance Principle: DC Potentiometers work on the zero-current balance principle, eliminating current draw from the circuit under test.
- Infinite Input Impedance: Because zero current is drawn at balance, the potentiometer behaves as a voltmeter with infinite input impedance.
- Elimination of Loading Errors: Unlike deflection voltmeters, potentiometers do not distort the voltage of the source they measure.
- Primary Standards: Because of their high accuracy and stability, they are used as primary calibration standards in standards laboratories.

Summary and Comparison with Deflection Instruments II

- Dynamic Limitations: Potentiometers are manual, non-direct-reading instruments and cannot measure dynamic or high-frequency signals.
- Broad Utility: They remain fundamental for precision calibration of voltmeters, ammeters, wattmeters, and thermocouple instrumentation.

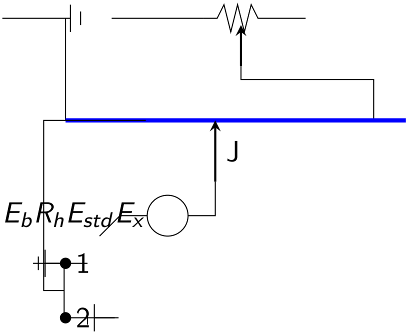
Lecture Agenda I

- Fundamental Working Principle of DC Potentiometers
- Circuit Construction: Slide-wire and Components
- The Standardization Process & Calibration
- Crompton's Laboratory-Type DC Potentiometer
- Comparison: Slide-wire vs. Dial-type Potentiometers
- Key Applications in Electrical Measurements
- Sources of Error and Best Measurement Practices

Fundamental Working Principle of DC Potentiometer I

- Based on the comparison of an unknown EMF with a known reference voltage drop along a slide wire.
- Zero loading error: Draws no current from the source under measurement at the balance point.
- A constant current flows through a slide wire of uniform cross-sectional area and resistance.
- The potential drop per unit length (voltage gradient, v) remains constant along the wire.
- Mathematical formulation at balance: $E_x = v \times l$, where l is the length corresponding to null deflection.
- Null indicator (Galvanometer) shows zero deflection when the potential drop equals the unknown EMF.

Basic DC Potentiometer Circuit Diagram I



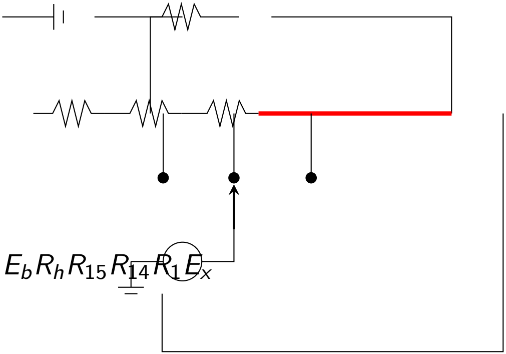
The Standardization Process I

- Standardization calibrates the slide wire scale in terms of absolute voltage.
- A highly stable reference cell (e.g., Weston Cadmium Cell, $E_{std} = 1.0186$ V) is connected.
- The sliding contact is positioned at the exact scale division matching the reference voltage.
- The regulating rheostat (R_h) is tuned until the galvanometer indicates a perfect null.
- This establishes the exact voltage gradient v (e.g., 0.1 V per meter or 1 mV per division) across the wire.
- Important: The working rheostat must not be changed once standardized to preserve the calibration.

Crompton's Laboratory DC Potentiometer I

- Developed to circumvent the impracticality of using extremely long slide wires in standard labs.
- Combines a dial switch of 15 series-connected resistors with a single short slide-wire segment.
- Each dial step and the slide wire have equal resistance (typically 10 ohms, representing a 0.1 V drop).
- Provides a total measurement range of 1.6 V (1.5 V across the dial steps + 0.1 V across the slide-wire).
- Includes coarse and fine sliding rheostats for highly precise current tuning during calibration.
- Achieves excellent resolution (down to 10 microvolts) within a very compact physical enclosure.

Crompton's Potentiometer Circuit Diagram I



Comparison: Slide-Wire vs. Dial-Type Potentiometer I

Parameter	Slide-wire Potentiometer	Dial-type (Crom Potentiometer
Resolution	Low (limited by wire length)	Extremely High (vi steps + slide wire)
Accuracy	Moderate (typically ±1 mV)	High (up to ±0.1 r better)
Mechanical Wear	High (sliding contacts run across the full wire)	Lower (sliding restric minor slide wire)
Instrument Size	Large and physically bulky	Compact, rack or b top laboratory box
Drift Sensitivity	High drift due to ambient temperature changes	Lower drift due temperature-stable resistors

Key Applications of DC Potentiometer I

- **Measurement of Unknown EMF**: Highly accurate determination of battery/cell voltages without loading.
- **Calibration of Voltmeters**: The voltmeter is connected in parallel with a known potential slide, which is verified by the potentiometer.
- **Calibration of Ammeters**: Done by measuring the potential drop across a highly accurate standard low resistance in series with the ammeter.
- **Measurement of Low Resistance**: By comparing the potential drops across the unknown resistor and a known standard resistor connected in series.
- **Calibration of Wattmeters**: Combined voltage and current calibration using volt ratio boxes and standard shunts.

Summary and Experimental Best Practices I

- DC Potentiometer is a fundamental null-balance instrument ensuring zero load error during balance.
- Standardization is a mandatory step before any measurement to fix the voltage gradient.
- Thermoelectric EMFs at contact points and thermal draft are the primary sources of measurement errors.
- Always shield the slide wire from direct heat sources and drafts to maintain consistent temperature.
- Do not keep the key pressed continuously; tap it briefly to prevent heating of resistors.
- Modern digital voltmeters have largely replaced laboratory potentiometers but rely on similar high-input-impedance nulling concepts.

Lecture Agenda I

- Limitations of Slide-Wire Potentiometers and the Need for Dial-Type Systems
- Fundamental Working Principle of Dial-Type Potentiometers
- Crompton's DC Potentiometer: Structure and Internal Design
- The Two-Dial Potentiometer Configuration
- Standardization / Calibration Procedure Using standard cells
- Measurement of Unknown Electromotive Force (EMF)
- Design Calculations, Current Calibration, and System Constraints
- Comparative Analysis: Slide-Wire vs. Two-Dial Systems

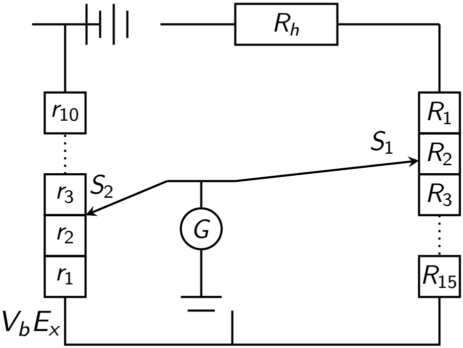
Limitations of Slide-Wire Potentiometers I

- Traditional slide-wire potentiometers require a very long wire (typically 10 meters) to achieve high resolution, making the instrument bulky and delicate.
- Continuous contact sliding along the resistance wire causes mechanical wear, leading to non-uniform cross-sectional area and subsequent calibration drift.
- Dust accumulation and thermal expansion introduce contact resistance and temperature-dependent measurement errors.
- The resolution is limited by the visual readability of the scale and the physical spacing of the slide-wire markings.
- Dial-type systems solve these problems by replacing the long slide-wire with series-connected precision resistors controlled by rotary switches.

Working Principle of Dial-Type Potentiometers I

- Dial-type potentiometers replace the continuous slide-wire with a series of precision-wound non-inductive resistors.
- A multi-position rotary switch (dial) allows selecting specific voltage steps, which provides step-wise coarse adjustment.
- To achieve high resolution, a second dial or a short slide-wire is connected in series to interpolate between the steps of the main dial.
- The total resistance of the potentiometer is kept constant, ensuring a stable working current from the supply battery.
- By maintaining constant current, the voltage drop across each resistor step remains highly stable and predictable.

Schematic of Crompton's 2-Dial Potentiometer I



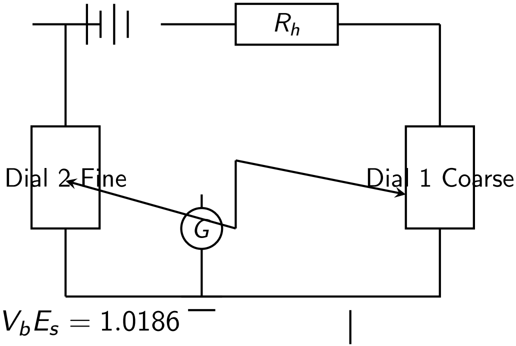
Dial 1: Coarse Control Analysis I

- Dial 1 typically consists of 15 precision non-inductive resistors connected in series, each having a resistance of exactly 10 Ohms.
- A standard working current of 10 mA is maintained through the potentiometer circuit during operation.
- The voltage drop across each individual resistor step is calculated as: $V_{step} = I_p * R_{step} = 10 \text{ mA} * 10 \text{ Ohms} = 0.1 \text{ V}$.
- The total voltage range covered by Dial 1 is from 0 V to 1.5 V, adjusted in discrete steps of 0.1 V.
- This dial provides the coarse adjustment, allowing the user to select the nearest lower 0.1 V step below the unknown voltage.

Dial 2: Fine Control Analysis I

- Dial 2 provides the fine adjustment, interpolating between the 0.1 V steps of Dial 1 to achieve high measurement resolution.
- In a two-dial potentiometer, Dial 2 replaces the sliding wire with a second rotary switch controlling smaller resistance steps.
- Typically, Dial 2 consists of 10 or 100 steps of 1 Ohm or 0.1 Ohm respectively, connected in series with Dial 1.
- With a 10 mA current and 10 steps of 1 Ohm, the voltage drop per step is $V\_fine = 10$ mA * 1 Ohm = 0.01 V (10 mV).
- This completely eliminates the sliding contact wear of traditional slide-wires and ensures high repeatability and calibration stability.

Standardization Setup and Procedure I



Comparison: Slide-Wire vs. 2-Dial Potentiometer I

Parameter	Slide-wire Potentiometer	2-Dial Potention
Resolution	Limited by wire length and scale readability.	High, discrete ste nate visual estimat
Mechanical Wear	High due to sliding along the entire wire.	Negligible, rotary with low contact r
Physical Size	Large, bulky (multiple meters of wire).	Compact, built int instrument casing.
Standardization	Done at a fixed point on slide-wire.	Precise calibration standard cell at exa
Calibration Drift	High, due to temperature and sliding wear.	Low, non-inductive resistors are stable

Mathematical Analysis & Key Design Formulas I

- Working Current Equation: I_p = V_b / (R_dial1 + R_dial2 + R_h), where V_b is the working battery voltage, R_dial1 & R_dial2 are dial resistances, and R_h is the rheostat resistance.
- Under standardized conditions, the current is adjusted to I_p = 10 mA. Thus, total potentiometer resistance for standard calibration is R_total = E_s / I_p.
- Measured Voltage Equation: E_x = (N_coarse * V_step1) + (N_fine * V_step2), where N_coarse and N_fine are the chosen dial steps, and V_step1 & V_step2 are the voltage drops per step.
- Resolution of the 2-dial system: delta_V = I_p * R_step2. For 10 mA current and 1 Ohm step, resolution is 10 mV. With a vernier or 0.1 Ohm step, it reaches 1 mV.

Mathematical Analysis & Key Design Formulas II

- Design constraint: To ensure constant load on the working battery, the sum (R_dial1 + R_dial2) must remain constant regardless of switch contact positions.

Agenda I

- Classification of Resistances (Low, Medium, High)
- Challenges in Measurement of Low Resistance
- Kelvin Double Bridge: Diagram, Theory, and Equations
- Wheatstone Bridge for Medium Resistance & Sensitivity Analysis
- High Resistance Challenges & Guard Circuit Solutions
- Loss of Charge Method & Megger for Insulation Testing

Classification of Resistances I

Class	Range	Typical Examples	Common Methods
Low	$< 1\ \Omega$	Armature windings, ammeter shunts, switch contact resistance	Kelvin Do tentiometer ohmmeter
Medium	$1\ \Omega$ to $0.1\ \mathrm{M}\Omega$	Relay coils, multipliers, heater elements, electronic components	Wheatstone Voltmeter tion methoc
High	$> 0.1\ \mathrm{M}\Omega$	Cable insulation, winding insulation of machines, vacuum tubes	Loss of Char (Mega-ohm cuit methoc

Challenges in Low Resistance Measurement I

- Low resistance is defined as resistance of 1 Ohm or less.
- The primary challenge is the contact resistance and lead resistance, which can be of the same order of magnitude as, or even greater than, the resistance being measured.
- Thermoelectric EMFs arising at the junctions of dissimilar metals under temperature gradients can introduce significant DC offset errors.
- To mitigate contact resistance, four-terminal resistors are used: two current terminals (C1, C2) carrying the main current and two potential terminals (P1, P2) for potential drop measurement.
- The potential terminals are positioned inside the current terminals so that contact voltage drop at current terminals is not included in the measurement.

Kelvin Double Bridge Circuit Diagram I

Kelvin Double Bridge Circuit Diagram II

$_box)at(1.5,4)(Unknown);ode[resistor](r_box)at(4,4)(Link);$

Kelvin Double Bridge Theory and Equations I

- The bridge utilizes a second set of ratio arms (p and q) to connect to the low resistance link 'r' at terminals B and C.
- The galvanometer connects the junction of P and Q (node A) to the junction of p and q (node B).
- Under balanced condition, no current flows through the galvanometer, indicating that the potential at A is equal to the potential at B.
- The balance equation including the link resistance 'r' is: $R = \frac{P}{Q}S + \frac{q \cdot r}{p+q+r}\left(\frac{P}{Q} - \frac{p}{q}\right)$.
- By adjusting the ratio arms such that $\frac{P}{Q} = \frac{p}{q}$, the term representing the link resistance error becomes zero.
- Thus, the balance equation reduces to the standard Wheatstone form: $R = \frac{P}{Q}S$, which is completely independent of the lead and link resistance.

Wheatstone Bridge Circuit Diagram I

$_arm)at(-1,1); ode[resistor, rotate =$

Wheatstone Bridge Sensitivity & Limitations I

- The standard balance equation for a Wheatstone bridge is: $R = S \cdot \frac{P}{Q}$.
- Bridge sensitivity (S_B) measures the galvanometer deflection per unit fractional change in the unknown resistance: $S_B = \frac{\theta}{\Delta R/R}$.
- For maximum sensitivity, the bridge arms should have equal values ($P = Q = R = S$), yielding the highest deflection for a small imbalance.
- Limitation 1 (Low Resistance): Bridge cannot measure low resistances because lead and contact resistance errors at connections are comparable to the unknown resistance.
- Limitation 2 (High Resistance): High resistances limit the current to extremely low values, which decreases the galvanometer's deflection sensitivity. Additionally, leakage currents bypass the bridge arms, introducing major errors.

High Resistance: Challenges & Guard Circuits I

- High resistance is defined as resistance exceeding 0.1 Mega-ohms ($10^5\ \Omega$).
- A major source of error in high resistance measurement is the leakage current flowing over the surface of the insulation, which bypasses the internal volume under test.
- To eliminate the leakage current error, a 'Guard Circuit' or 'Guard Terminal' is employed.
- The guard wire is wrapped around the insulation surface and connected directly back to the supply voltage terminal.
- This configuration ensures that any surface leakage current returns to the power supply without passing through the measuring galvanometer or micro-ammeter, isolating the true volume insulation resistance.

High Resistance Methods: Loss of Charge & Megger I

- Loss of Charge Method: A standard capacitor C is charged to voltage V and then discharged through the unknown high resistance R over a timed interval t.
- The remaining voltage is $v = Ve^{-t/RC}$, and the resistance is calculated as: $R = \frac{t}{C \ln(V/v)}$. Errors are reduced by measuring insulation leakage resistance separately.
- Megger (Mega-ohmmeter): A portable, hand-driven or battery-operated generator and meter used for field testing of insulation.
- The Megger uses a ratio-meter consisting of a deflecting (current) coil and a controlling (voltage) coil, mounted on a single moving element inside a magnetic field.

High Resistance Methods: Loss of Charge & Megger II

- The pointer deflection is directly proportional to the ratio of voltage to current ($V/I = R$), providing direct readings in Mega-ohms independent of the generator's exact rotational speed.

Lecture Agenda I

- Classification of Resistances (Low, Medium, High)
- Medium Resistance Measurement: The Wheatstone Bridge Circuit
- Limitations of Wheatstone Bridge for Low Resistance Measurements
- Low Resistance Measurement: Kelvin's Double Bridge Circuit and Equation
- High Resistance Measurement Challenges and the Megger Instrument
- Megger: Design, Principle of Operation, and Application in Insulation Testing
- Comparative Analysis of DC Bridges and Resistance Measurement Instruments

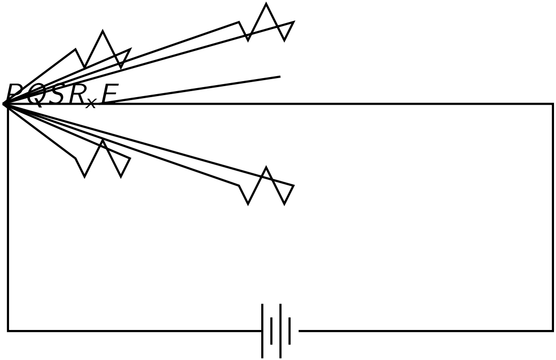
Wheatstone Bridge: Fundamentals and Balance Condition I

- DC bridges are widely used for the measurement of electrical resistance. They operate on the principle of null-detection to achieve high accuracy.
- Classification of Resistances: Low (¡ 1 Ohm), Medium (1 Ohm to 100 kOhm), High (¿ 100 kOhm). Wheatstone bridge is the standard method for medium resistance.
- The bridge consists of four resistance arms forming a closed loop, a DC source (battery), and a sensitive detector (galvanometer).
- At balance condition, the potential difference across the galvanometer is zero, meaning no current flows through it (Ig = 0).

Wheatstone Bridge: Fundamentals and Balance Condition II

- Balance equation: P * S = Q * R, where R is the unknown resistance. This simplifies to: R = S * (P / Q). The ratio P / Q is known as the ratio arm factor.

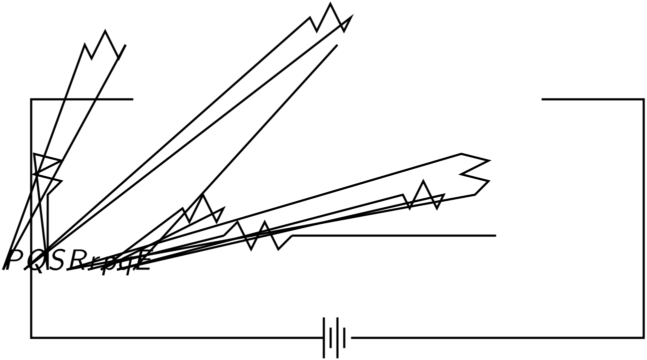
Wheatstone Bridge Circuit Schematic I



Limitations of Wheatstone Bridge for Low Resistance I

- When measuring low resistances (¡ 1 Ohm), the resistance of connection leads and contact resistances become significant.
- In a standard Wheatstone bridge, lead resistances are added directly to the unknown resistance R or standard resistance S.
- This introduces a substantial relative error since lead resistance (typically 0.001 to 0.1 Ohm) is comparable to the low resistance under measurement.
- Thermal EMFs at junctions also introduce measurement errors under high current conditions required for low resistance testing.
- Hence, modifications are required: Kelvin's Double Bridge separates the voltage terminals from current terminals to eliminate lead resistance errors.

Kelvin's Double Bridge Schematic I



Kelvin's Double Bridge: Mathematical Derivation I

- Kelvin's double bridge uses a second set of ratio arms (p and q) to connect the galvanometer to the appropriate point on the low-resistance link 'r'.
- Under balanced condition, the ratio of outer arms P/Q is made exactly equal to the ratio of inner arms p/q: $P/Q = p/q$.
- The balance equation derivation yields: $R = S * (P/Q) + q * r / (p + q + r) * (P/Q - p/q)$.
- Since we maintain $P/Q = p/q$, the second term containing the lead resistance 'r' becomes exactly zero: $(P/Q - p/q) = 0$.
- Thus, the balance equation simplifies to: $R = S * (P/Q)$. The effect of the lead resistance 'r' is completely eliminated, enabling high accuracy measurement down to micro-ohms.

High Resistance Measurement & Challenges I

- High resistance (typically ¿ 100 kOhm to several Giga-ohms) is encountered in motor/transformer winding insulation and underground cables.
- Challenge 1: Leakage Currents. Current flowing over the outer surface of insulation bypasses the meter, creating severe measurement errors.
- Challenge 2: Electrostatic Interference. High voltages used for measurements generate electrostatic charges that disrupt readings.
- Challenge 3: Polarization & Absorption. Solid insulation exhibits capacitive charging effects, requiring time for current to stabilize.
- To overcome leakage currents, a 'Guard Terminal' is employed to intercept surface leakage current and shunt it directly back to the source without passing through the measuring coil.

Megger: High Resistance and Insulation Tester I

- Megger is a portable, hand-operated or battery-driven instrument used to measure high insulation resistance directly in mega-ohms.
- It consists of a hand-driven permanent magnet DC generator (producing typically 500V, 1000V, or 2500V) and a special moving-coil meter.
- The meter mechanism uses a ratiometer consisting of two coils: a Control Coil (Pressure Coil) and a Deflecting Coil (Current Coil) mounted on the same spindle.
- No control springs are used. Instead, the control torque is provided electromagnetically by the control coil connected in parallel with the generator.
- Deflecting torque is produced by the current coil in series with the unknown resistance. The pointer position is proportional to the ratio of Voltage to Current (V/I), representing Resistance.

Comparison of DC Resistance Measurement Methods I

Parameter	Wheatstone Bridge	Kelvin Double Bridge	Megger
Range	Medium ($1\,\Omega$ to $100\,\mathrm{k}\Omega$)	Low ($0.1\,\mu\Omega$ to $1.0\,\Omega$)	High ($100\,\mathrm{k}\Omega$ to $100\,\mathrm{G}\Omega$)
Primary App.	General resistors, components	Ammeter shunts, bar conductors	Cable insulation, winding test
Accuracy	High (0.1% – 0.5%)	Very High (0.05% – 0.2%)	Moderate (1% – 5%)
Power Source	Low voltage battery (typically 1.5V to 9V)	High current low-voltage source	Built-in hand generator or battery

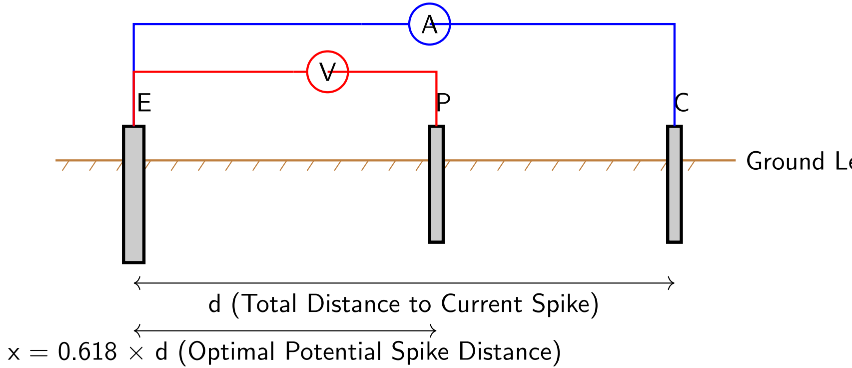
Agenda I

- Importance of Grounding & Earth Resistance Limits
- The Fall of Potential Method: Theoretical Basis
- Operating Principle of a Megger Earth Tester
- Need for Alternating Current (AC) in Soil Measurements
- Function of Current Reverser and Rotary Rectifier
- Internal Schematic & Circuit Configurations
- Table of Acceptable Earth Resistance Limits
- Step-by-Step Measurement Procedure
- Key Safety and Precision Guidelines

Importance of Grounding & Earth Resistance I

- Grounding provides a safe, low-impedance path to the earth for fault currents, preventing high voltages on exposed metallic enclosures.
- A low earth resistance ensures protective devices like fuses and circuit breakers operate rapidly during a phase-to-ground fault.
- Earth resistance depends on the electrode design, its depth, and soil resistivity (influenced by moisture, salts, and temperature).
- Periodic measurement of earth resistance is vital as soil conditions deteriorate and metallic electrodes corrode over time.

Fall of Potential Method I



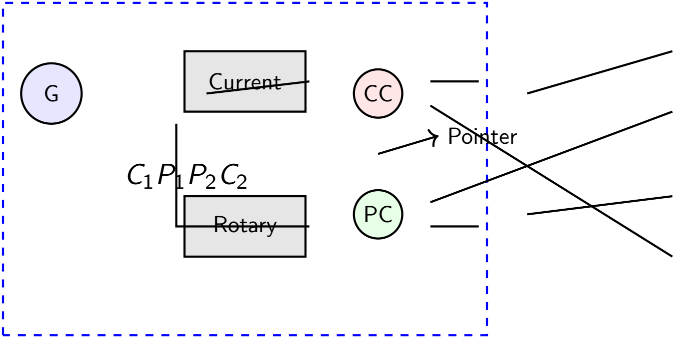
Earth Tester Construction Details I

- An Earth Tester is a specialized Megger integrating a hand-driven generator and a Permanent Magnet Moving Coil (PMMC) ratiometer.
- The ratiometer contains two coils: a Current Coil (CC) and a Potential Coil (PC), mounted at a fixed angle to each other on a common shaft.
- No control springs are used; the deflecting torque is proportional to the current, and the restoring torque is proportional to the voltage.
- This configuration directly measures the ratio V/I, allowing the pointer to indicate resistance R directly on a calibrated scale.

Role of AC in Earth Testing I

- Passing Direct Current (DC) through soil causes electrolytic polarization, which builds up a back-EMF at the electrode-soil boundary.
- Electrolytic back-EMF introduces severe errors, artificially increasing the measured earth resistance value.
- Using Alternating Current (AC) in the earth prevents polarization and cancels out the influence of stray DC currents in the ground.
- The instrument generator produces DC internally, which is converted to AC before entering the earth, and rectified back to DC for measurement.

Internal Schematic of Earth Tester I



Acceptable Earth Resistance Limits I

No.	Type of Electrical Installation	Max Earth
1	Large Generating Stations	
2	Major Power Substations (Extra High Voltage)	
3	Small/Medium Distribution Substations	
4	Industrial Plant Sub-panels	
5	Domestic/Residential Premises	
6	Earth Electrode at Transmission Tower Footings	

Step-by-Step Measurement Procedure I

- Step 1: Isolate the main earth electrode (E) under test from the rest of the electrical grid to ensure safety.
- Step 2: Place two auxiliary spikes, Potential Spike (P) and Current Spike (C), in the soil in a straight line relative to E.
- Step 3: Connect terminals P1 and C1 of the tester to the main electrode E, P2 to spike P, and C2 to spike C.
- Step 4: Rotate the generator handle at a steady speed (typically 140 to 160 rpm) to establish stable test currents.
- Step 5: Read the earth resistance directly from the calibrated analog scale or digital screen.

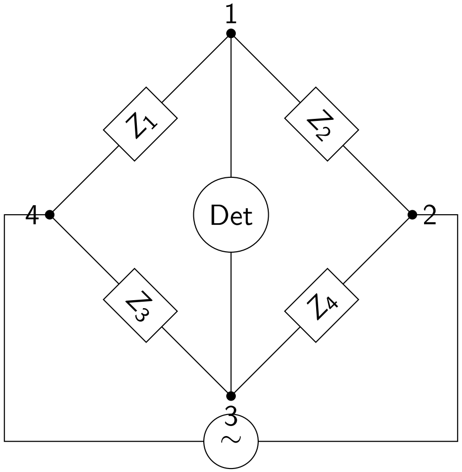
Measurement Guidelines & Precision Tips I

- Electrode Spacing: Ensure the distance between E and C is large enough to prevent their individual resistance zones from overlapping.
- Three-Terminal configuration: For general tests, terminals P1 and C1 are shorted at the instrument, requiring only 3 field wires.
- Soil Treatment: If earth resistance is excessively high, soil can be treated with moisture, coal, or salt to increase conductivity.
- Worst-case Testing: Perform tests during dry seasons when soil moisture is at its lowest to guarantee safety limits under all conditions.

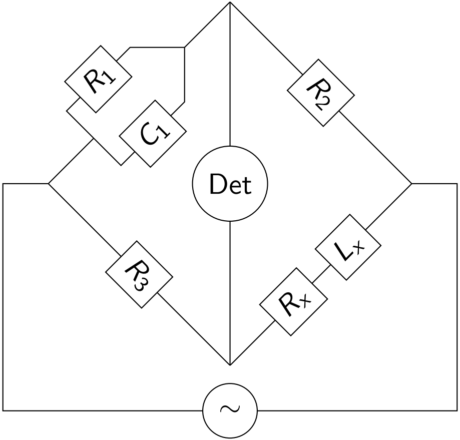
Agenda I

- General Principle of AC Bridges & Balance Equations
- Maxwell's Inductance-Capacitance Bridge
- Hay's Bridge for High-Q Inductors
- Anderson's Bridge for Low-Q Inductance
- Schering Bridge for Capacitance & Dissipation Factor
- Wien's Bridge for Frequency Measurement
- Comparative Summary & Practical Error Sources in AC Bridges

General Principle of AC Bridges I



Maxwell's Inductance-Capacitance Bridge I



Hay's Bridge for High-Q Inductors I

- Hay's bridge is a modification of Maxwell's L-C bridge, designed specifically for measuring high-Q inductors (Q ¿ 10).
- In contrast to Maxwell's bridge, the standard capacitor C_1 is connected in series with resistor R_1 rather than in parallel.
- Balance equations are frequency-dependent: L_x = (R_2 R_3 C_1) / (1 + (\{}omega R_1 C_1)2̂).
- The equivalent series resistance is given by: R_x = (\{}omega2̂ R_1 C_12̂ R_2 R_3) / (1 + (\{}omega R_1 C_1)2̂).
- For high-Q coils (Q ¿ 10), the term (\{}omega R_1 C_1)2̂ is less than 0.01, allowing the simplification L_x \{}approx R_2 R_3 C_1 with high accuracy.

Anderson's Bridge for Low-Q Inductance I

- Anderson's bridge is an advanced modification of Maxwell's bridge used to measure low-Q inductors (Q ¡ 1).
- It introduces a double-bridge node configuration, using a junction resistor r to link the detector to the standard capacitor C.
- This modification bypasses the need for high-value variable resistors that Maxwell's bridge requires to measure low-Q inductors.
- Balance Equations: $L_x = (C R_3 / R_4) * [r (R_2 + R_4) + R_2 R_4]$ and $R_x = (R_2 R_3) / R_4$.
- Key Advantage: Highly accurate measurement of low-Q coils using small, standard variable capacitor values.

Schering Bridge for Capacitance & Dissipation Factor I

- The Schering bridge is the industry standard for measuring capacitance, loss angle, and dielectric losses.
- The unknown capacitor is represented as C_x in series with its equivalent loss resistance R_x.
- Arm 1 contains a standard loss-free capacitor C_1, while Arm 4 contains a parallel resistor R_4 and capacitor C_4 configuration.
- Balance Equations: C_x = C_1 * (R_4 / R_3) and R_x = R_3 * (C_4 / C_1).
- The dissipation factor is defined as: D = \{}omega C_x R_x = \{}omega C_4 R_4. This value is key in evaluating dielectric insulation quality.

Wien's Bridge for Frequency Measurement I

- Wien's bridge is a frequency-selective bridge used to measure frequency, primarily in the audio range (20 Hz to 20 kHz).
- It features a series RC combination (R_1, C_1) in one arm and a parallel RC combination (R_2, C_2) in the adjacent arm.
- Balance Condition: The bridge is balanced at a specific frequency: f = 1 / (2 \{}pi \{}sqrt{R_1 R_2 C_1 C_2}).
- The ratio of the other two arms must satisfy: R_3 / R_4 = (R_1 / R_2) + (C_2 / C_1).
- Common Practical Setup: If R_1 = R_2 = R and C_1 = C_2 = C, the frequency simplifies to f = 1 / (2 \{}pi R C) and the resistance ratio is R_3 = 2 R_4.

Comparison and Selection of AC Bridges I

Bridge Name	Primary Parameter	Q/D Range	Key Balance Eq
Maxwell's L-C	Inductance (L_x)	Medium Q $(1 < Q < 10)$	$L_x = R_2 R_3 C_1$, R_x
Hay's Bridge	Inductance (L_x)	High Q $(Q > 10)$	$L_x \approx R_2 R_3 C_1$ $\frac{\omega^2 R_1 C_1^2 R_2 R_3}{1+(\omega R_1 C_1)^2}$
Anderson's Bridge	Inductance (L_x)	Low Q $(Q < 1)$	$L_x = \frac{CR_3}{R_4}[r(R_2+R$
Schering Bridge	Capacitance (C_x)	Low D $(D < 0.1)$	$C_x = C_1 \frac{R_4}{R_3}$, $R_x =$
Wien's Bridge	Frequency (f)	N/A	$f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$

Sources of Errors & Mitigation in AC Bridges I

- Stray Capacitance: Parasitic capacitances between components and ground alter high-frequency behavior, mitigated using a Wagner Ground Connection.
- Mutual Inductance: Magnetic coupling between coils can introduce errors, minimized by twisting lead wires and using toroidal magnetic shields.
- Resistor Frequency Errors: High-frequency skin effects and stray inductance change resistor values; non-inductive bifilar resistors are preferred.
- Wagner Earth Device: Connects two auxiliary impedance arms to ground, bringing detector potential to zero relative to ground without direct earthing.
- Shielding: Complete electrostatic and electromagnetic metallic enclosures around bridge arms isolate sensitive components from ambient noise.

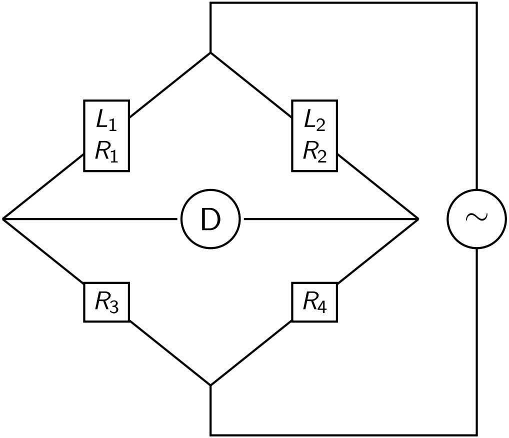
Lecture Agenda I

- AC Bridge Fundamentals & Balance Conditions
- Maxwell's Inductance Bridge (L-L configuration): Circuit & Equations
- Maxwell's Inductance-Capacitance Bridge (L-C configuration): Working Principle
- Derivation of Balance Equations for Maxwell's L-C Bridge
- Phasor Diagram of Maxwell's L-C Bridge
- Quality Factor (Q-factor) Limitations and Range of Measurement
- Comparative Analysis of L-L and L-C Bridges
- Key Practical Advantages and Practical Engineering Applications

Introduction to AC Bridges I

- AC bridges are electrical networks used to measure unknown impedances (inductance, capacitance, and resistance) by comparison with known standards.
- A standard AC bridge is a four-arm network supplied by an AC source (oscillator) and utilizes a detector sensitive to AC signals (headphones, electronic voltmeters, or tuned amplifiers).
- The bridge is said to be balanced when the detector current is zero, indicating that the potential at the detector terminals is equal in both magnitude and phase.
- General balance equation: $Z_1 Z_4 = Z_2 Z_3$, where Z represents complex impedance vectors of the four arms.
- To satisfy the complex equality, both real parts (magnitude balance) and imaginary parts (phase angle balance) must be balanced independently: $\theta_1 + \theta_4 = \theta_2 + \theta_3$.

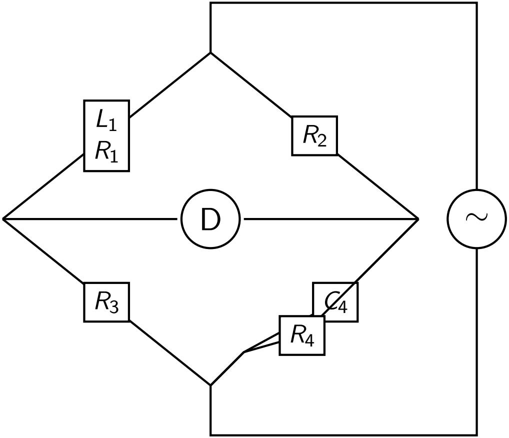
Maxwell's Inductance Bridge Circuit Diagram I



Maxwell's Inductance Bridge: Balance Derivation I

- In Maxwell's Inductance Bridge (L-L Bridge), the unknown self-inductance L_1 with resistance R_1 is compared with a standard variable inductor L_2 of resistance R_2.
- The impedance of Arm 1 is $Z_1 = R_1 + j\omega L_1$, and Arm 2 is $Z_2 = R_2 + j\omega L_2$. Arms 3 and 4 are pure non-inductive resistances: $Z_3 = R_3$ and $Z_4 = R_4$.
- Applying the general balance condition $Z_1 Z_4 = Z_2 Z_3$, we get: $(R_1 + j\omega L_1)R_4 = (R_2 + j\omega L_2)R_3$.
- Equating the real parts: $R_1 R_4 = R_2 R_3 \implies R_1 = \frac{R_2 R_3}{R_4}$. This gives the unknown resistance of the inductor.
- Equating the imaginary parts: $\omega L_1 R_4 = \omega L_2 R_3 \implies L_1 = L_2 \frac{R_3}{R_4}$. This yields the unknown inductance.
- Note that R_1 and L_1 are independent of the supply frequency ω, making the balance stable and frequency-independent.

Maxwell's Inductance-Capacitance Bridge Diagram I



Maxwell's L-C Bridge: Mathematical Derivation I

- In Maxwell's L-C Bridge (Inductance-Capacitance Bridge), the unknown inductance is measured by comparison with a standard variable capacitor C_4.
- Impedances of the arms: $Z_1 = R_1 + j\omega L_1$, $Z_2 = R_2$, $Z_3 = R_3$. The parallel combination in Arm 4 gives: $\frac{1}{Z_4} = \frac{1}{R_4} + j\omega C_4 \implies Z_4 = \frac{R_4}{1+j\omega C_4 R_4}$.
- Using balance condition: $Z_1 = Z_2 Z_3 / Z_4 \implies Z_1 = Z_2 Z_3 \left(\frac{1}{R_4} + j\omega C_4\right)$.
- Substituting Z_1: $R_1 + j\omega L_1 = \frac{R_2 R_3}{R_4} + j\omega C_4 R_2 R_3$.
- Equating the real parts yields the unknown series resistance: $R_1 = \frac{R_2 R_3}{R_4}$.
- Equating the imaginary parts yields the unknown inductance: $L_1 = R_2 R_3 C_4$.

Maxwell's L-C Bridge: Mathematical Derivation II

- Both equations are completely independent of frequency, which allows the use of arbitrary AC source waveforms without balance disruption.

Comparison: Maxwell's Inductance vs. L-C Bridge I

Parameter	**Maxwell's Inductance Bridge (L-L)**	**Maxwell's Bridge**
Standard Component	Variable Inductor (L_2)	Variable Cap (C_4)
Calibration	Tricky due to mutual coupling	Easier, sta capacitors are stable
Cost	High (variable inductors are expensive)	Low (standard c itors are cheape
Balance equations	$L_1 = L_2 \frac{R_3}{R_4}$ and $R_1 = R_2 \frac{R_3}{R_4}$	$L_1 = R_2 R_3 C$ $R_1 = \frac{R_2 R_3}{R_4}$
Quality Factor (Q) Range	Not specifically limited	Restricted to m Q ($1 < Q < 10$

Phasor Diagram of Maxwell's L-C Bridge I

- At balance, the detector current is zero, which implies that node potentials V_B and V_D are equal: $\vec{V}_B = \vec{V}_D$.
- Let reference phasor be the current in Arm 1, $\vec{I}_1$. Since Arm 1 and Arm 3 are in series at balance, $\vec{I}_1 = \vec{I}_3$.
- Similarly, current in Arm 2 equals current in Arm 4: $\vec{I}_2 = \vec{I}_4$.
- Voltage drop across Arm 3 is $V_3 = I_1 R_3$. Since $V_3 = V_4$, we have $I_1 R_3 = I_4 Z_4$.
- The current $\vec{I}_4$ is divided into two parallel parts: resistive current $\vec{I}_R = \vec{V}_C / R_4$ (in phase with voltage $\vec{V}_C$) and capacitive current $\vec{I}_C = \vec{V}_C \cdot j\omega C_4$ (leading $\vec{V}_C$ by 90°).
- The total voltage drop across the bridge arm A-D-C is $\vec{V}_{AC} = \vec{I}_1(R_1 + j\omega L_1) + \vec{I}_1 R_3$.

Quality Factor and Practical Considerations I

- The Quality Factor (Q) of an inductor represents its electromagnetic purity: $Q = \frac{\omega L_1}{R_1} = \omega C_4 R_4$.
- Maxwell's L-C bridge is exceptionally suited for measuring medium-Q coils ($1 < Q < 10$).
- For high-Q coils ($Q > 10$), the resistance R_4 required for balance becomes extremely large (several megohms), which is difficult to manufacture and adjust precisely.
- For low-Q coils ($Q < 1$), the sliding balance becomes convergence-sensitive, leading to a phenomenon known as 'sliding balance' where adjustments in R_4 and C_4 interact severely.
- Applications: Primarily used for calibration of standard inductors, measurement of iron-cored coils, and laboratory education of AC impedance concepts.

Lecture Agenda I

- Introduction to AC Bridges and Capacitance Measurement
- Circuit Configuration of the Basic De Sauty's Bridge
- Derivation of the Basic Bridge Balance Equation
- Limitations of the Basic Bridge with Lossy Capacitors
- Grover's Modification: The Modified De Sauty's Bridge
- Vector / Phasor Diagram of the Balanced Modified Bridge
- Derivation of Grover's Dual Balance Conditions
- Calculation of the Capacitor Dissipation Factor (loss tangent)
- Comparative Analysis of Basic and Modified Configurations
- Sources of Error and Shielding in Bridge Measurements

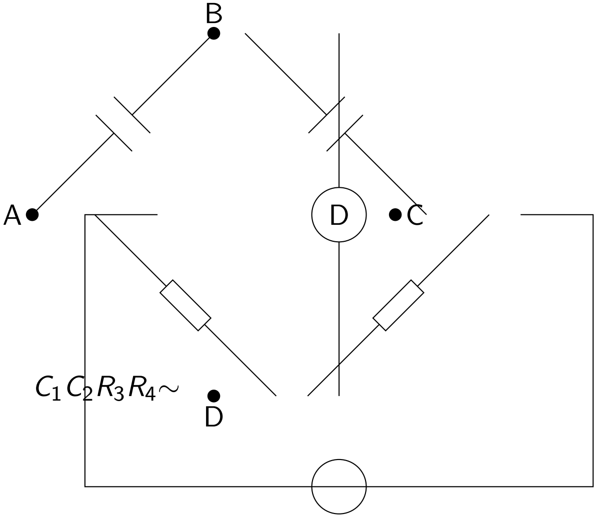
Introduction to AC Bridges & Capacitance Measurement I

- AC bridges are the standard electrical instrumentation circuits used for the precise measurement of impedance parameters: inductance, capacitance, and mutual inductance.
- A bridge operates on the null-detection principle, where two parallel branches are excited by a common AC source, and a detector measures the potential difference between them.
- Capacitance measurement is critical for evaluating dielectric properties, cable insulation quality, and manufacturing tolerances of components.
- De Sauty's bridge is the simplest method for comparing two capacitances, serving as a fundamental building block for advanced bridges like the Schering bridge.

Introduction to AC Bridges & Capacitance Measurement II

- The accuracy of De Sauty's bridge depends heavily on the purity of the standard capacitor and the non-inductive nature of the resistor arms.

Basic De Sauty's Bridge Circuit Diagram I



Derivation of Basic Balance Equations I

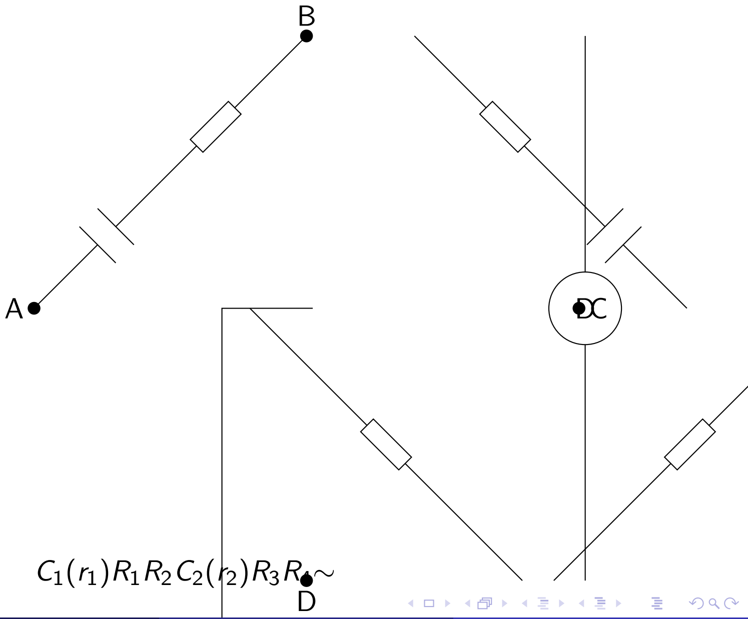
- At bridge balance, the potential at node B is equal to the potential at node D, resulting in zero current through the detector (null condition).
- The balance condition is defined by the impedance relation: $Z_1 Z_4 = Z_2 Z_3$, where Z_1 and Z_2 are the capacitive impedances, and Z_3 and Z_4 are pure resistances.
- Substituting the impedance values: $Z_1 = \frac{1}{j\omega C_1}$, $Z_2 = \frac{1}{j\omega C_2}$, $Z_3 = R_3$, and $Z_4 = R_4$.
- This yields the equation: $\left(\frac{1}{j\omega C_1}\right) R_4 = \left(\frac{1}{j\omega C_2}\right) R_3$.
- Simplifying the relation gives the final balance equation: $C_1 = C_2 \cdot \frac{R_4}{R_3}$.
- Note that this balance condition is completely independent of the source frequency (ω), allowing the use of sources with harmonics without shifting the balance point.

Limitations of the Basic Bridge & Dielectric Loss I

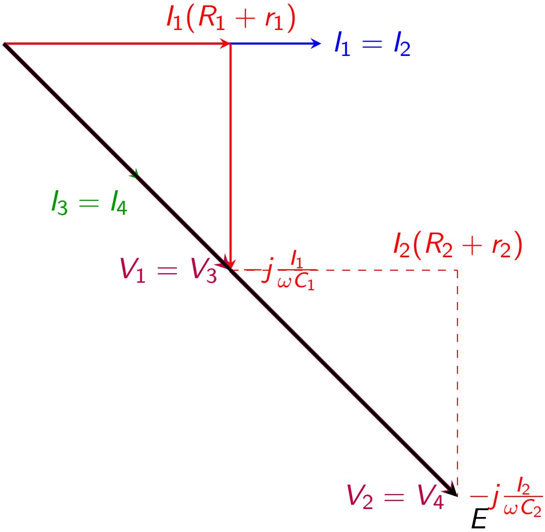
- In practice, a perfect balance (absolute zero detector current) is impossible to achieve with the basic De Sauty's bridge unless both capacitors are completely lossless.
- Real capacitors possess a dielectric loss, which can be modeled as a small resistance r_1 and r_2 in series with the ideal capacitances C_1 and C_2.
- If the capacitors have different loss angles, their voltage drops are not in phase, meaning the branch potentials V_B and V_D can never be exactly equal in both magnitude and phase.
- Attempting to balance the bridge only results in a minimum detector reading (residual voltage) rather than a sharp, zero-current null.
- This limitation makes the basic bridge unsuitable for testing commercial or degraded capacitors, necessitating a method to balance the resistive components.

Modified De Sauty's Bridge (Grover's Method) I

Modified De Sauty's Bridge (Grover's Method) II



Phasor Diagram of Balanced Modified Bridge I



Derivation of Dual Balance Equations I

- In the modified De Sauty's bridge, external non-inductive resistors R_1 and R_2 are placed in series with capacitors C_1 and C_2 respectively to compensate for internal losses r_1 and r_2.
- The balance condition is $Z_1 Z_4 = Z_2 Z_3$, where $Z_1 = (R_1 + r_1) - \frac{j}{\omega C_1}$ and $Z_2 = (R_2 + r_2) - \frac{j}{\omega C_2}$, with $Z_3 = R_3$ and $Z_4 = R_4$.
- Multiplying terms: $\left[(R_1 + r_1) - \frac{j}{\omega C_1}\right] R_4 = \left[(R_2 + r_2) - \frac{j}{\omega C_2}\right] R_3$.
- Equating real parts yields: $(R_1 + r_1)R_4 = (R_2 + r_2)R_3 \implies \frac{R_1+r_1}{R_2+r_2} = \frac{R_3}{R_4}$. This balances the in-phase resistive components.
- Equating imaginary parts yields: $\frac{R_4}{\omega C_1} = \frac{R_3}{\omega C_2} \implies C_1 = C_2 \cdot \frac{R_4}{R_3}$. This balances the quadrature reactive components.

Derivation of Dual Balance Equations II

- From the resistive balance, the internal loss of the unknown capacitor is calculated as: $r_1 = (R_2 + r_2)\frac{R_3}{R_4} - R_1$.
- The dissipation factor (loss tangent) of the unknown capacitor is defined as: $\tan\delta_1 = \omega C_1 r_1 = \omega C_2 \left[(R_2 + r_2) - R_1 \frac{R_4}{R_3}\right]$.

Basic vs. Modified De Sauty's Bridge Comparison I

Parameter	Basic Bridge	Modified Bridge
Capacitor Model	Ideal (C)	Real (C in series with r
Balance Equation 1	$C_1 = C_2 \frac{R_4}{R_3}$	$C_1 = C_2 \frac{R_4}{R_3}$
Balance Equation 2	None	$\frac{R_1+r_1}{R_2+r_2} = \frac{R_3}{R_4}$
Dissipation Factor	Not Measurable	$\tan \delta_1 = \omega C_1 r_1$
Balance Convergence	Poor for lossy caps	Sharp and independent

Agenda I

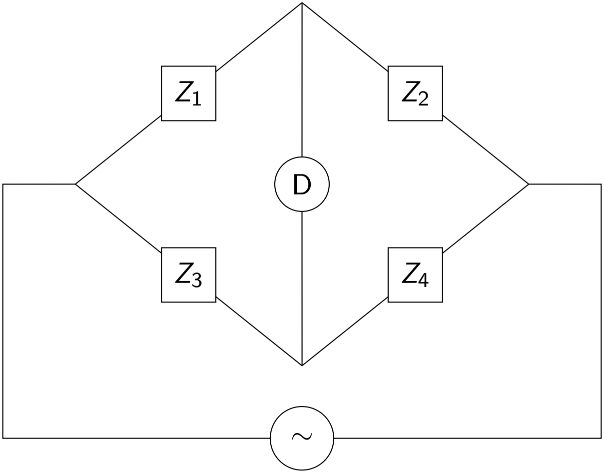
Introduction to Universal Impedance Bridges I

- A Universal Impedance Bridge is a versatile multi-functional laboratory instrument designed to measure resistance, inductance, and capacitance using a single platform.
- It integrates multiple bridge configurations (such as Wheatstone, Maxwell, Hay, and Schering) which are selected using front-panel rotary switches.
- The instrument contains internal standard components, typically highly stable precision resistors (R_s) and standard capacitors (C_s), to act as reference arms.
- By configuring these internal standards with the unknown impedance, the bridge balances the reactive and resistive components to yield accurate parameter values.

AC Bridge Balance Conditions I

- Unlike DC bridges (e.g., Wheatstone) which only require resistance balance, AC bridges must balance both magnitude and phase angle of the impedance arms.
- The general balance equation is given by: $Z_1 Z_4 = Z_2 Z_3$, where Z_i represents the complex impedance of arm i.
- In polar coordinates, this translates to: $|Z_1||Z_4| = |Z_2||Z_3|$ (magnitude condition) and $\theta_1 + \theta_4 = \theta_2 + \theta_3$ (phase condition).
- To achieve balance, two independent adjustments are required on the bridge panel (usually one resistance control and one capacitance/reactance control) to prevent interaction between adjustments.

General AC Bridge Network Topology I



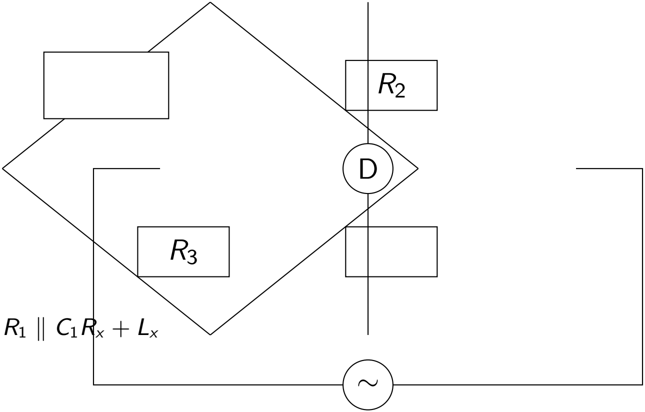
Maxwell-Wien Bridge Configuration I

- The Maxwell-Wien bridge (often called simply the Maxwell bridge) measures an unknown inductance in terms of a known standard capacitance.
- Arm 1 consists of a standard capacitor C_1 in parallel with a standard resistor R_1. Arms 2 and 3 are pure non-inductive resistors R_2 and R_3.
- Arm 4 contains the unknown inductor L_x in series with its internal resistance R_x.
- The balance equations derived from $Z_1 Z_x = Z_2 Z_3$ are: $R_x = (R_2 R_3)/R_1$ and $L_x = R_2 R_3 C_1$.
- Crucially, the balance equations are completely independent of the source frequency, making this bridge highly stable and easy to balance.
- It is suited for measuring medium-quality factor coils $(1 < Q < 10)$.

Hay's Bridge Configuration I

- Hay's bridge is a modification of the Maxwell bridge, designed specifically for measuring high-quality factor ($Q > 10$) inductors.
- In Hay's bridge, the standard capacitor C_1 is connected in series with the resistor R_1 in Arm 1, rather than in parallel.
- The balance equations depend on frequency:
  $L_x = (R_2 R_3 C_1)/(1 + \omega^2 C_1^2 R_1^2)$ and
  $R_x = (\omega^2 C_1^2 R_1 R_2 R_3)/(1 + \omega^2 C_1^2 R_1^2)$.
- Using the definition of Quality Factor $Q = 1/(\omega C_1 R_1)$, we rewrite: $L_x = (R_2 R_3 C_1)/(1 + 1/Q^2)$.
- For high-Q coils ($Q > 10$), the term $1/Q^2$ is less than 0.01, simplifying the inductance equation to $L_x \approx R_2 R_3 C_1$, which is frequency independent.

Maxwell-Wien Bridge Circuit Details I



Comparison of Bridge Configurations I

Bridge Type	**Primary Parameter**	**Target Range**
Wheatstone Bridge	DC Resistance (R)	1 Ω to 1 MΩ
Maxwell-Wien Bridge	Medium Inductance (L)	Medium Q ($1 < Q$
Hay's Bridge	High Inductance (L)	High Q ($Q > 10$)
Schering Bridge	Capacitance (C)	Low to High C

Summary and Design Considerations I

- The Universal Impedance Bridge provides high accuracy by letting users select different bridge topologies via switches.
- AC measurements require a variable standard capacitor and variable standard resistor to satisfy both magnitude and phase balances.
- At high frequencies, stray capacitances between bridge nodes and ground introduce errors. These are mitigated using shielding and Wagner Earth circuits.
- Modern digital LCR meters utilize auto-balancing bridge methods, replacing manual adjustments with digital signal processing to calculate R, L, and C instantaneously.

Lecture Agenda I

- Functional Classification: Indicating, Recording, and Integrating Instruments
- Classification based on Operating Principles & Electrical Effects
- Dynamic Force Requirements: Deflecting, Controlling, and Damping Torques
- PMMC and Moving Iron (MI) Constructional Overviews
- Controlling Systems: Comparative Analysis of Spring and Gravity Control
- Damping Mechanisms: Viscous, Pneumatic, and Electromagnetic Methods
- Behavioral Comparison under Direct (DC) and Alternating (AC) Excitation

Functional Classification of Instruments I

- Indicating Instruments: Use a pointer and scale to display the immediate value of the measured electrical quantity at the instant of measurement. Examples include standard analog ammeters, voltmeters, and wattmeters.
- Recording Instruments: Maintain a continuous chronological log of the measured variable on a moving chart or digital media. Typically used in power stations for monitoring voltage, current, or active power variations.
- Integrating Instruments: Summate and record the total product of the electrical quantity and time, effectively measuring energy consumption. The most prominent example is the household induction-type watt-hour meter.

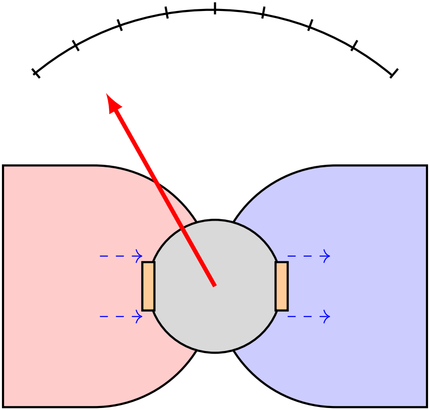
Classification by Electromagnetic & Physical Effects I

Physical Effect	Instrument Classes	Typical Engineering Applications
Magnetic Effect	PMMC, Moving Iron (MI)	DC Current/Vo (PMMC); AC/DC cu and voltage indicator
Electrodynamic	Electrodynamometer	High-precision AC Transfer Instrur Wattmeter
Induction Effect	Induction Ammeter/Energy Meter	AC Energy measurer commercial utility bill
Electrostatic	Electrostatic Voltmeter	High-voltage labor standards, lossless AC voltmeter
Thermal Effect	Hot-wire, Thermocouple	High-frequency RF rents, True RMS mea ments

The Three Essential Torques in Analog Instruments I

- Deflecting Torque (T_d): Produced by the physical effect under measurement (e.g., magnetic force, electrostatic attraction). It forces the moving system to deflect from its initial zero position.
- Controlling Torque (T_c): Opposes the deflecting torque and increases with pointer deflection. Deflection ceases when $T_d = T_c$. It also ensures the pointer returns to zero when the input quantity becomes zero.
- Damping Torque (T_d or T_v): Active only when the moving system is in motion. It absorbs kinetic energy to prevent the pointer from oscillating excessively around its final steady-state position, facilitating rapid readings.

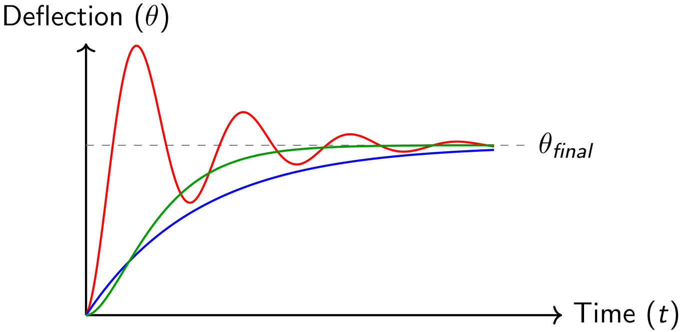
Permanent Magnet Moving Coil (PMMC) Construction I



Control Systems: Spring vs. Gravity Control I

- Spring Control: Utilizes a phosphor-bronze hairspring. The controlling torque is directly proportional to deflection angle ($T_c \propto \theta$). This linear relationship yields a highly uniform, readable scale.
- Gravity Control: Uses a small adjustable control weight. The controlling torque is proportional to the sine of the deflection angle ($T_c \propto \sin\theta$). This produces a non-uniform, cramped scale at the lower end.
- Engineering Comparison: Spring control is independent of instrument mounting position, whereas gravity control requires strict vertical mounting but is completely immune to temperature-induced aging.

Dynamic Behavior and Damping Characteristics I



Damping Mechanisms in Practice I

- Air Friction Damping: Employs a light aluminum piston moving inside a closed air chamber. Suitable for electrostatic and moving iron instruments where magnetic fields must not be disturbed.
- Fluid Friction Damping: Utilizes a vane immersed in highly viscous damping oil. Offers very smooth damping without stiction, but is restricted to stationary, vertically-mounted panel instruments.
- Eddy Current Damping: Induced currents in a rotating metallic disc or coil former react with a permanent magnet's field to produce a damping torque. Highly efficient and the standard choice for PMMC systems.

Comparison of PMMC and Moving Iron Instruments I

- Basic Operation: PMMC operates on a current-carrying coil placed in a permanent magnetic field ($T_d \propto I$); Moving Iron operates on the attraction or repulsion of iron vanes in a coil's electromagnetic field ($T_d \propto I^2$).
- Excitation Types: PMMC works exclusively on Direct Current (DC) because the average torque under AC excitation is zero; Moving Iron works on both AC and DC, reading the true RMS value.
- Scale Calibration: PMMC has a linear, uniform scale; Moving Iron has a cramped scale at the beginning due to the square-law dependence of the deflecting torque on current.
- Key Figures of Merit: PMMC features very high torque-to-weight ratio, low power consumption, and zero hysteresis loss; Moving Iron suffers from hysteresis, eddy currents, and frequency errors.

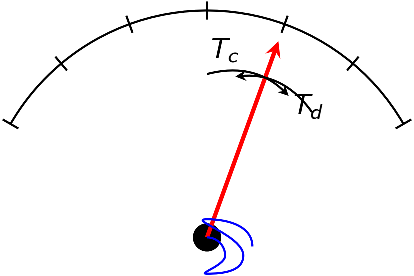
Agenda I

- The Three Fundamental Torques: Deflecting, Controlling, and Damping Torques
- Control Systems: Spring Control and Gravity Control Mechanisms
- Damping Systems: Air Friction, Fluid Friction, and Eddy Current Damping
- Classification of Instruments by Electrical Effect and Operating Principle
- Detailed Principles: Permanent Magnet Moving Coil (PMMC) and Moving Iron (MI)
- Summary of Instrument Selection Criteria for Practical Applications

The Three Essential Torques in Analog Instruments I

- Deflecting Torque (Td): Responsible for moving the pointer from its zero position. It is produced by utilizing various physical effects of the electrical current or voltage under measurement.
- Controlling Torque (Tc): Opposes the deflecting torque and increases with the deflection of the moving system. It ensures that the final deflection is unique and proportional to the measured quantity, and returns the pointer to zero when the input is removed.
- Damping Torque (Td): Essential to damp out the oscillations of the pointer about its final steady-state position quickly, facilitating rapid and accurate readings.

Mechanical Control System: Spring Control Diagram I



Damping Systems and Mechanisms I

- Air Friction Damping: Utilizes a piston moving inside a closed chamber or a light aluminum vane moving in a sector-shaped box. Simple, inexpensive, and used in Moving Iron and Electrodynamometer instruments.
- Fluid Friction Damping: Uses a vane submerged in a cup of high-viscosity oil. Provides smoother damping and reduces pivot wear, but restricted to vertically mounted panel meters to avoid oil leakage.
- Eddy Current Damping: Based on electromagnetic induction. A thin metal disc (aluminum or copper) rotates in the air gap of a permanent magnet. The movement induces eddy currents, producing a retarding torque.
- Eddy current damping is the most efficient and is standard in PMMC instruments.

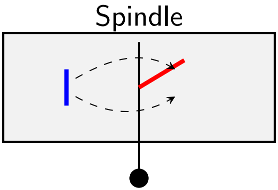
Classification by Electrical Principle of Operation I

Electrical Effect	**Instrument Type**	**Suitable for**
Magnetic	PMMC, Moving Iron	DC (PMMC), AC/DC
Electrodynamic	Electrodynamometer	AC and DC
Electromagnetic	Induction-type	AC only
Electrostatic	Electrostatic Voltmeter	AC and DC
Thermal	Hot-wire, Bolometer	AC and DC

PMMC vs. Moving Iron Instruments I

- Operating Principle: PMMC works on the Lorentz force on a current-carrying coil in a static magnetic field. Moving Iron works on the force acting on magnetic materials in an electromagnetic field.
- Deflecting Torque: PMMC deflecting torque is linear ($T_d \propto I$), yielding a uniform scale. Moving Iron deflecting torque is square-law ($T_d \propto I^2$), yielding a non-uniform, crowded scale at the lower end.
- Supply Suitability: PMMC is suitable for DC only (reverses direction with AC, resulting in zero net deflection). Moving Iron is suitable for both AC and DC.
- Damping: PMMC uses highly efficient Eddy Current damping. Moving Iron uses Air Friction damping due to the weak operating magnetic field which would be distorted by damping magnets.

Moving Iron Instrument Principle: Repulsion Type I



Electrostatic and Electrodynamometer Instruments I

- Electrostatic Instruments: Operate on the mechanical force between two charged conductors. Torque expression: $T_d = \frac{1}{2}V^2\frac{dC}{d\theta}$. Excellent for high voltages, drawing zero power in steady DC.
- Electrodynamometer Instruments: Consist of a pair of fixed coils and a moving coil. Deflecting torque: $T_d = I_1 I_2 \frac{dM}{d\theta}$. Used as transfer instruments to calibrate AC meters using DC sources.
- Precision Wattmeter: In electrodynamometers, the fixed coils carry the load current (Current Coil) and the moving coil carries current proportional to load voltage (Pressure Coil), producing $T_d \propto VI\cos\phi$.

Summary of Electromechanical Instruments I

- Classification is primarily based on: electrical effects (magnetic, heating, chemical, electrostatic, induction) and the type of moving system (PMMC, MI, Electrodynamometer).
- Each instrument requires three torques: Deflecting torque initiates movement, Controlling torque (spring or gravity) establishes equilibrium, and Damping torque eliminates oscillations.
- PMMC is unmatched in accuracy for DC, while Moving Iron provides a cost-effective solution for industrial AC measurements.
- Electrodynamometers serve as highly accurate AC/DC transfer instruments and standard wattmeters.

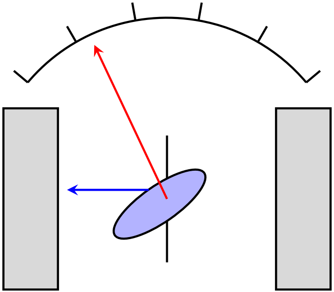
Agenda I

- Working Principle of Moving Iron (MI) Instruments
- Attraction-Type vs. Repulsion-Type MI Instruments
- Torque Equation and Mathematical Derivation
- Design considerations for MI Ammeters and Voltmeters
- Error analysis, temperature compensation, and frequency errors
- Introduction to Frequency Meters and Weston Frequency Meter
- Vibrating Reed (Mechanical Resonance) Frequency Meter

Working Principle of Moving Iron (MI) Instruments I

- Moving Iron (MI) instruments are widely used for measuring alternating currents and voltages in power frequency ranges.
- Basic Principle: When a piece of soft iron is placed near a current-carrying coil, it is attracted towards the coil, or if two soft iron pieces are placed inside a coil, they repel each other.
- The deflecting torque (T_d) is produced by the change in the magnetic energy stored in the system due to change in inductance.
- Since deflecting torque is proportional to the square of the current, these instruments can measure both AC and DC quantities.
- The scale of MI instruments is non-linear (cramped at the lower end) because the deflection is proportional to the square of the current.

Attraction-Type MI Instrument Construction I



Repulsion-Type Moving Iron Instruments I

- Repulsion-type instruments are more commonly used than attraction-type due to their higher sensitivity and more linear scale.
- Construction: Consists of two soft iron vanes inside a stationary field coil: one fixed vane and one moving vane attached to the spindle.
- Working Principle: When current flows through the coil, it magnetizes both vanes with the same magnetic polarity at adjacent ends.
- Consequently, a force of repulsion acts between them, causing the moving vane (and pointer) to deflect away from the fixed vane.
- Types of Vanes: Radial vane type (produces a force perpendicular to the vane) and Concentric vane type (offers a more uniform scale).

Torque Equation and RMS Measurement I

- Deflecting Torque: $T_d = \frac{1}{2} i^2 \frac{dL}{d\theta}$, where i is the instantaneous current and L is coil inductance.
- Control Torque: Provided by a spring, where $T_c = K\theta$ (K is spring constant).
- At steady-state deflection:
  $T_d = T_c \implies K\theta = \frac{1}{2} i^2 \frac{dL}{d\theta} \implies \theta = \frac{1}{2K} i^2 \frac{dL}{d\theta}$.
- For AC measurement, the deflecting torque is proportional to the average of the square of the current (I_{rms}^2).
- Therefore, the instrument deflection is directly proportional to the RMS value of the current or voltage, regardless of the waveform.
- The scale is non-linear (cramped at lower values) because deflection $\theta \propto I^2$ assuming $dL/d\theta$ is constant.

Design of MI Ammeters and Voltmeters I

- Moving Iron Ammeter:
- - Coil design: Few turns of thick wire to carry full-load current with minimal power loss (I^2R) and voltage drop.
- - Typical ranges: Up to 50 A directly; for higher currents, Current Transformers (CT) are used in AC circuits.
- - Shunts are not preferred due to frequency dependence and temperature coefficient mismatches between copper shunt and iron coil.
- Moving Iron Voltmeter:
- - Coil design: Many turns of thin wire to achieve high inductance and resistance, keeping current draw low.
- - Series Multiplier: A high value non-inductive resistor (made of manganin or constantan) is connected in series.

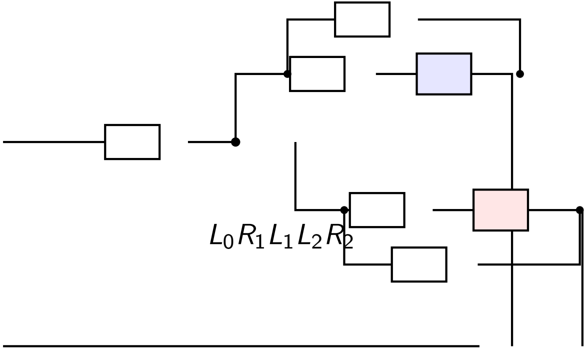
Design of MI Ammeters and Voltmeters II

- - Range extension: Voltmeters can measure up to 750 V directly; Potential Transformers (PT) are used for higher AC voltages.

Errors in MI Instruments: Causes and Remedies I

Error Source	Cause	Remedy / Compe
Hysteresis	Residual magnetism in iron parts causes different readings for ascending/descending values	Use high-per nickel-iron alloys Mumetal) with low sis.
Eddy Currents	Induced currents in metal parts of the instrument body	Minimize metal m the coil, use lamin structures.
Frequency Variation	Changes coil impedance ($X_L = 2\pi fL$)	Connect a capacito lel with the series resistance (Voltme
Stray Fields	External fields distort weak operating magnetic field	Encase the instru a high-permeabil shield.
Temperature	Variation in coil resistance due to temperature	Use manganin for s tiplier resistance to

Weston Frequency Meter Circuit and Working I



Vibrating Reed Frequency Meter & Summary I

- Vibrating Reed (Mechanical Resonance) Frequency Meter:
- - Consists of an electromagnet and a series of thin steel reeds tuned to different frequencies (e.g., 49 Hz, 50 Hz, 51 Hz).
- - When AC current passes through the electromagnet coil, the alternating magnetic pull causes all reeds to vibrate.
- - The reed whose natural frequency matches the supply frequency undergoes resonance and vibrates with maximum amplitude.
- Summary of Moving Iron & Frequency Instruments:
- - MI instruments are robust, inexpensive, and work on both AC and DC, reading RMS values.
- - Frequency meters are essential for grid monitoring, ensuring grid frequency remains within strict limits (e.g., ± 0.5 Hz).

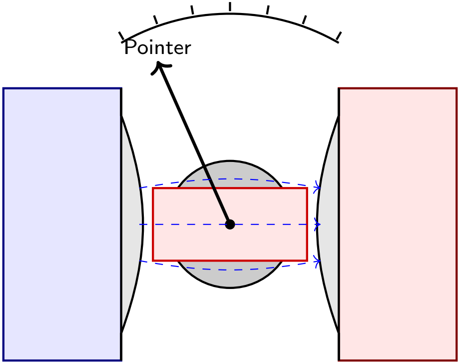
Agenda I

- Permanent Magnet Moving Coil (PMMC) Working Principle
- Constructional Features and Torque Equation
- PMMC as an Ammeter: Shunt Resistors and Range Extension
- Ammeter Shunt Configuration Circuit Diagram
- PMMC as a Voltmeter: Multipliers and Range Extension
- Voltmeter Multiplier Configuration Circuit Diagram
- Comparison: Ammeter Shunt vs. Voltmeter Multiplier
- Sensitivity and Loading Effect in Voltmeters

PMMC Working Principle I

- PMMC instruments (d'Arsonval movement) operate on the electromagnetic force principle.
- When a current-carrying coil is placed in a magnetic field, it experiences a deflecting force.
- Deflecting force on a single conductor: $F = BIL$ newtons, where B is flux density, I is current, and L is conductor length.
- Total deflecting torque: $T_d = NBIA = GI$, where N is turns, A is coil area, and $G = NBA$ is the instrument constant.
- Control torque is provided by spiral springs: $T_c = K\theta$, where K is the spring constant and θ is the angle of deflection.
- At steady-state equilibrium, $T_d = T_c \implies GI = K\theta \implies \theta = (G/K)I$, resulting in a perfectly linear scale.

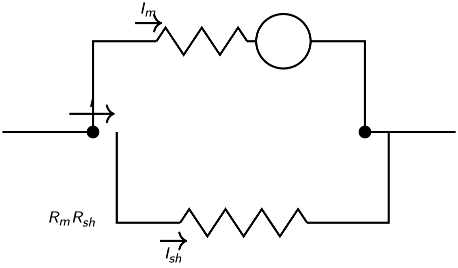
PMMC Construction Details I



PMMC as an Ammeter: Shunt Resistors I

- A basic PMMC movement is delicate and can carry only a small current (typically 10μA to 50 mA) before overheating.
- To measure larger currents, a low-value resistor called a shunt (R_{sh}) is connected in parallel with the meter resistance (R_m).
- The shunt bypasses the major portion of the total line current I, leaving only a safe current I_m to pass through the meter.
- From current division: $I_m R_m = I_{sh} R_{sh} = (I - I_m) R_{sh}$.
- Solving for shunt resistance: $R_{sh} = \frac{R_m}{m-1}$, where $m = I/I_m$ is the multiplying power of the shunt.
- Shunts must have a low temperature coefficient of resistance (typically Manganin) to prevent thermal errors during operation.

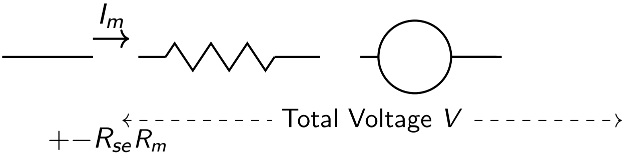
Ammeter Shunt Circuit Diagram I



PMMC as a Voltmeter: Multipliers I

- A basic PMMC movement can be converted into a voltmeter by connecting a high resistance in series with the coil.
- This series resistance is called a multiplier (R_{se}) and limits the current through the meter to the full-scale deflection current I_{fsd}.
- The voltage to be measured (V) is applied across the series combination of R_m and R_{se}.
- Using Ohm's law: $V = I_m(R_m + R_{se}) \implies R_{se} = \frac{V}{I_m} - R_m$.
- Expressed in terms of multiplying factor: $R_{se} = R_m(m-1)$, where $m = V/V_m$ is the voltage multiplying power ($V_m = I_m R_m$).
- Multipliers are made of Manganin or Constantan to reduce temperature-induced resistance changes.

Voltmeter Multiplier Circuit Diagram I



Parameter	**Ammeter Shunt**	**Voltmeter Multi**
Connection Type	Parallel with the coil	Series with the co
Resistance Value	Very low	Very high
Design Formula	$R_{sh} = R_m/(m-1)$	$R_{se} = R_m(m-1)$
Multiplying Factor	$m = I/I_m > 1$	$m = V/V_m > 1$
Material Used	Manganin	Manganin or Con
Effect on Circuit	Decreases overall resistance	Increases overall r

Voltmeter Sensitivity and Loading Effect I

- Voltmeter sensitivity (S) is defined as the reciprocal of the full-scale deflection current: $S = 1/I_{fsd}$ (expressed in Ω/V).
- The internal resistance of a voltmeter of range V_{range} is $R_v = S \times V_{range}$.
- Loading Effect: When connected across a high-resistance component, the voltmeter draws significant current, reducing the equivalent resistance and lowering the actual voltage drop.
- To minimize this error, a voltmeter must have high sensitivity (S), resulting in a very high internal resistance R_v compared to the circuit resistances.
- Percentage loading error: % Error $= \frac{V_{actual} - V_{measured}}{V_{actual}} \times 100\%$.

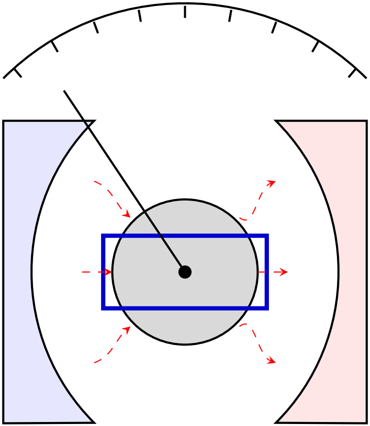
Agenda I

- Working Principle and Construction of PMMC Instruments
- PMMC Torque Equation (Deflecting, Controlling, and Damping)
- PMMC as an Ammeter: Shunt Resistance Design & Formulas
- Temperature Compensation and Swamping Resistors
- PMMC as a Voltmeter: Multiplier Resistance Design & Formulas
- Voltmeter Sensitivity and Loading Effects
- Key Differences between Ammeter and Voltmeter Configurations
- Sources of Error, Advantages, and Limitations of PMMC

Working Principle of PMMC Instruments I

- D'Arsonval Principle: Based on the electromagnetic force experienced by a current-carrying conductor when placed in a magnetic field (Lorentz Force: $F = BIL$).
- Construction: Consists of a moving coil wound on a light aluminum former, suspended in a strong, radial magnetic field generated by permanent magnet pole pieces.
- Radial Field: Cylindrical soft iron core is placed between curved pole pieces, ensuring that magnetic lines of force are perpendicular to the coil sides at all positions.
- Spring Control: Hairsprings made of phosphor bronze provide the controlling torque ($T_c = K\theta$) and also act as leads to convey current into and out of the coil.
- Eddy-Current Damping: Movement of the aluminum former through the magnetic field induces eddy currents in it, producing an opposing torque that dampens oscillations.

Schematic Diagram of PMMC Instrument I



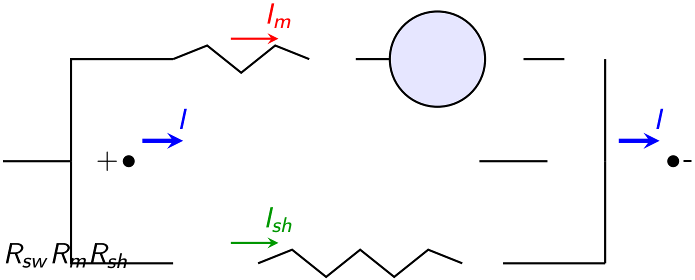
Torque Equation & Scale Linearity I

- Deflecting Torque (T_d): The force on each active conductor of length L with N turns is $F = N(BIL)$. If width is W, deflecting torque $T_d = F \times W = NBILW = NBAI$ (where $A = L \times W$).
- Controlling Torque (T_c): Opposes deflecting torque. For linear hairsprings, $T_c = K\theta$, where K is the spring constant and θ is the angular deflection.
- Steady-State Equilibrium: The pointer stops deflecting when $T_d = T_c \implies NBAI = K\theta$.
- Scale Calibration: Angular deflection is $\theta = \left(\frac{NBA}{K}\right) I = G \cdot I$, where G is the constant galvanometer instrument constant.
- Linearity: Since $\theta \propto I$, the scale of the PMMC instrument is perfectly linear and uniform, which simplifies reading compared to moving iron or electrodynamometer types.

PMMC as an Ammeter: Shunt Design I

- Current Capacity: PMMC moving coils are extremely delicate and can carry only a small current (typically 50 μA to 50 mA) without overheating.
- Shunt Extension: To measure larger currents, a low-resistance path called a shunt (R_{sh}) is connected in parallel with the meter (R_m).
- Voltage Balance: Since the meter and shunt are in parallel, $V_m = V_{sh} \implies I_m R_m = I_{sh} R_{sh} = (I - I_m) R_{sh}$.
- Shunt Formula: $R_{sh} = \frac{I_m R_m}{I - I_m} = \frac{R_m}{m-1}$, where $m = \frac{I}{I_m}$ is the current multiplying power of the shunt.
- Swamping Resistance: A resistor (R_{sw}) made of manganese or manganin is placed in series with the copper coil to minimize temperature-induced resistance drift and errors.

Circuit Diagram: Ammeter Shunt I



PMMC as a Voltmeter: Multiplier Design I

- Voltage Extension: To measure high voltages, the basic PMMC movement must be connected in series with a high-resistance multiplier (R_s).
- Multiplier Role: It drops the majority of the applied voltage and limits the current through the meter to not exceed its full-scale deflection current (I_{fsd}).
- Voltage Balance: The total voltage $V = V_m + V_s = I_m R_m + I_m R_s = I_m(R_m + R_s)$.
- Multiplier Formula: $R_s = \frac{V}{I_m} - R_m = R_m \left(\frac{V}{I_m R_m} - 1 \right) = R_m(v - 1)$, where $v = \frac{V}{V_m}$ is the voltage multiplying power.
- Voltmeter Sensitivity (S): Expressed in Ω/V (ohms per volt). $S = \frac{1}{I_{fsd}}$. Total voltmeter resistance is $R_v = S \times V$. High sensitivity reduces loading error.

Comparison: Ammeter vs. Voltmeter Configurations I

Parameter	PMMC Ammeter	PMMC Voltmeter
Connection	Connected in series with load	Connected in par with load
Extension Resistor	Shunt (R_{sh}) connected in parallel	Multiplier (R_s) c nected in series
Resistor Value	Extremely low ($R_{sh} \ll R_m$)	Extremely high (R_s R_m)
Ideal Resistance	Zero ohm	Infinite ohms
Power Consumption	Very low ($I^2 R_{eq}$)	Very low (V^2/R_{eq})
Loading Effect	Minimizes voltage drop across it	Minimizes shunt cur drawn from source

Advantages, Errors and Limitations of PMMC I

- Advantages: Highly accurate and sensitive, uniform linear scale, high torque-to-weight ratio (minimizes friction error), absence of hysteresis losses, and excellent eddy-current damping.
- Limitations: Expensive due to precise magnetic design, cannot be used directly for AC measurements (as average torque on AC is zero), and delicate hairsprings are prone to damage by overload.
- Sources of Error: Friction at pivot points, magnetic flux degradation due to aging of permanent magnets, spring constant change due to aging/temperature, and coil resistance variation with temperature.
- Summary: PMMC is the most accurate analog instrument for DC. By adding shunts, multipliers, or rectifiers, it can be configured as an ammeter, voltmeter, or AC instrument.

Agenda I

- Operating Principle of Electrodynamometer Instruments
- Mathematical Derivation of the Deflecting Torque Equation
- Physical Coil Configuration & Schematic Layout
- Ammeter and Voltmeter Connections and Limitations
- Wattmeter Operating Principle and Circuit Schematics
- Analysis of Measurement Errors and Compensation Techniques
- Comparative Evaluation of PMMC, MI, and Electrodynamometer Meters

Operating Principle of Electrodynamometer I

- Modification of PMMC: In an electrodynamometer, the permanent magnet is replaced by two fixed air-cored coils to produce the magnetic field.
- Air-Core Construction: Avoids hysteresis, eddy currents, and saturation errors when used on AC circuits, though it results in a weaker magnetic field.
- Interaction of Currents: Operating torque is produced by the interaction of the magnetic field of the fixed coils and the magnetic field of the moving coil.
- AC and DC Suitability: Since the current reverses in both the fixed and moving coils simultaneously on AC, the torque direction remains unidirectional.

Operating Principle of Electrodynamometer II

- Controlling & Damping Torque: Control torque is provided by spiral springs (which also act as current leads to the moving coil). Damping is achieved via air friction (damping vanes in a closed chamber) to avoid magnetic interference.

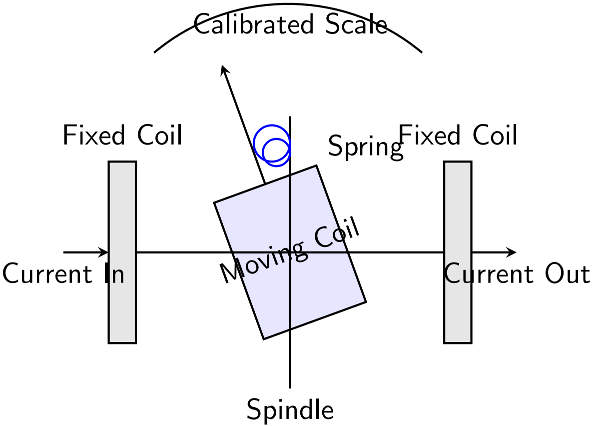
Mathematical Analysis & Torque Equation I

- Let i_1 be the instantaneous current in the fixed coils, and i_2 be the instantaneous current in the moving coil.
- Flux Linkage: The total flux linkage of the system is $\lambda_1 = L_1 i_1 + M i_2$ and $\lambda_2 = L_2 i_2 + M i_1$, where L_1, L_2 are self-inductances and M is the mutual inductance.
- Electrical Input Energy: $dE_e = e_1 i_1 dt + e_2 i_2 dt$, which simplifies to $i_1 d\lambda_1 + i_2 d\lambda_2$.
- Total Energy Change: $dE_e = i_1 d(L_1 i_1 + M i_2) + i_2 d(L_2 i_2 + M i_1)$. Assuming constant currents, the change in stored magnetic energy is $dW_m = \frac{1}{2} i_1^2 dL_1 + \frac{1}{2} i_2^2 dL_2 + i_1 i_2 dM$.
- Mechanical Work Output: $dW_g = T_d d\theta$. By the conservation of energy, $dE_e = dW_m + dW_g$.
- Deflecting Torque: Since self-inductances L_1 and L_2 are constant with respect to deflection θ, $dL_1/d\theta = 0$ and $dL_2/d\theta = 0$.

Mathematical Analysis & Torque Equation II

- Instantaneous Torque: $T_i = i_1 i_2 \frac{dM}{d\theta}$. For AC, the average torque is $T_d = I_1 I_2 \cos\phi \frac{dM}{d\theta}$, where ϕ is the phase angle between I_1 and I_2.

Schematic Diagram of Electrodynamometer Coil Arrangement I



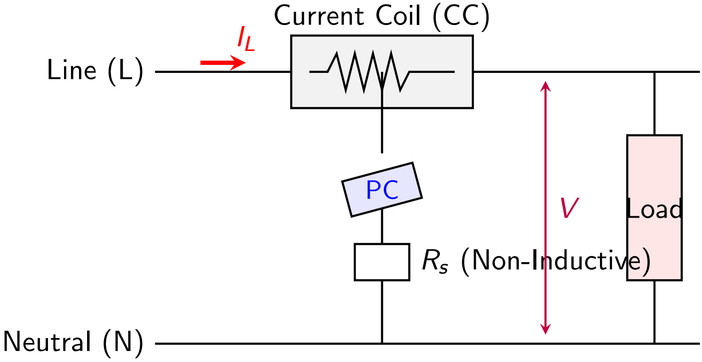
Electrodynamometer as Ammeter and Voltmeter I

- Ammeter Connection: Fixed and moving coils are connected in series. Since the moving coil must carry a small current (limited by spring leads, usually < 100 mA), shunts are used for higher currents.
- Ammeter Shunt Difficulty: To maintain accuracy on AC, the time constants (L/R) of the meter coils and the shunt must be identical, which is hard to achieve across frequencies.
- Voltmeter Connection: Fixed and moving coils are connected in series with a high non-inductive resistance (multiplier) to limit the current to $50 - 100$ mA.
- Voltmeter Frequency Error: High multipliers minimize the effect of self-inductance. However, at high frequencies, the inductive reactance increases, causing the voltmeter to read low.

Electrodynamometer as Ammeter and Voltmeter II

- Sensitivity: Electrodynamometer voltmeters have low sensitivity (typically $10 - 30\ \Omega/\mathrm{V}$) compared to PMMC ($20,000\ \Omega/\mathrm{V}$), consuming significant power.

Electrodynamometer Wattmeter Connection Schematic I



Errors in Electrodynamometer Wattmeters I

- Pressure Coil Inductance: At high frequencies or low power factors, the inductance of the pressure coil causes the current in the PC (I_p) to lag behind the voltage V. This causes the wattmeter to read high on lagging power factors and low on leading power factors.
- Pressure Coil Capacitance: Stray capacitance across the series resistance acts in opposition to the inductance, tending to compensate for inductive error, but can overcompensate at high frequencies.
- Mutual Inductance Error: Mutual inductance between the current and pressure coils introduces an error torque. This is minimized by designing the coil axes to be perpendicular at mid-scale.

Errors in Electrodynamometer Wattmeters II

- Stray Magnetic Fields: Since the operating field is weak (air-core), external magnetic fields easily distort readings. Magnetic shielding (using high-permeability alloy enclosures) is mandatory.
- Temperature Errors: Changes in temperature affect spring stiffness and coil resistance. High-resistivity alloys with low temperature coefficients (e.g., Manganin) are used for series multipliers.

Comparison of Electromechanical Instruments I

Parameter	PMMC	Moving Iron (MI)
Operating Field	Strong permanent magnet	Weak temporary electromagnet
AC/DC Capability	DC only	AC and DC
Scale	Linear (uniform)	Non-linear (squared)
Sensitivity	High (20 kΩ/V)	Low (10 – 50 Ω/V)
Hysteresis Loss	None	Significant (iron core)

Summary and Key Takeaways I

- Electrodynamometer instruments are transfer instruments, meaning they can be calibrated on DC and used to measure AC directly with high accuracy.
- The absence of magnetic materials (air-core) eliminates hysteresis and eddy current errors, making them ideal as transfer standards.
- As an Ammeter/Voltmeter, the deflection is proportional to the square of the RMS current/voltage, resulting in a crowded scale at lower ranges.
- As a Wattmeter, one coil represents load current and the other represents load voltage, yielding a linear scale because deflection is proportional to active power ($P = VI \cos \phi$).
- Shielding against stray magnetic fields and compensating for pressure coil inductance are crucial design requirements for precision measurements.

Lecture Agenda I

- Introduction to Single-Phase AC Power Components
- Electrodynamometer Wattmeter: Working Principle
- Mathematical Derivation of Deflecting Torque
- Wattmeter Connection Schemes: MC vs LC Connections
- Analyzing Measurement Errors and Correction Factors
- Low Power Factor (LPF) Wattmeter Design & Compensation
- Active and Reactive Power Measurement Methods

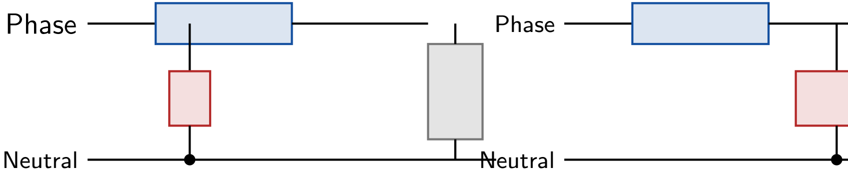
Fundamentals of Single-Phase AC Power I

- Instantaneous Power: $p(t) = v(t) \cdot i(t)$, which varies periodically with twice the supply frequency.
- Active Power (P): The average rate of energy delivery, given by $P = VI\cos(\phi)$ Watts. This represents the actual work done by the system.
- Reactive Power (Q): The power oscillating between source and inductive/capacitive elements, given by $Q = VI\sin(\phi)$ VAR.
- Apparent Power (S): The total volt-amperes of the circuit, given by $S = VI$ VA, where $S = \sqrt{P^2 + Q^2}$.
- Power Factor (PF): $\cos(\phi) = P/S$, representing the ratio of active power to apparent power.

Operating Principle of Electrodynamometer Wattmeter I

- An electrodynamometer instrument consists of two fixed coils and a moving coil.
- Fixed Coils (Current Coil - CC): Connected in series with the load, wound with thick wire to minimize resistance and heat dissipation.
- Moving Coil (Pressure Coil - PC): Connected across the load in series with a high non-inductive resistance to make the current proportional to voltage.
- The magnetic field produced by the current coil interacts with the magnetic field of the pressure coil, producing a deflecting torque.
- Electrodynamic design avoids hysteresis errors common in moving-iron instruments, providing high accuracy for AC measurement.

Wattmeter Connections: MC vs LC Schematic I



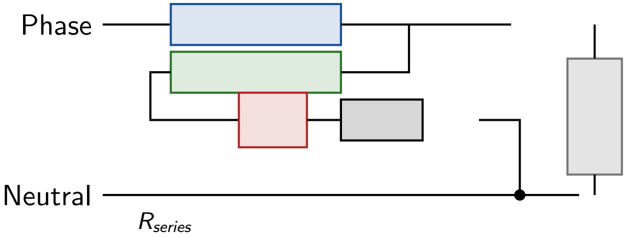
Analysis of Connection Errors I

- In MC connection (M-side PC), the Current Coil carries both the load current I_L and pressure coil current I_p. Measured Power = Actual Power + Power loss in PC (V^2/R_p).
- The error in MC connection is significant when the load current is small (high load impedance), as the PC current becomes comparable to the load current.
- In LC connection (L-side PC), the Pressure Coil is subjected to the load voltage plus the voltage drop across the current coil. Measured Power = Actual Power + Power loss in CC ($I^2 R_c$).
- The error in LC connection is significant when the load current is large (low load impedance), causing a high voltage drop across the current coil.
- To minimize error: Use MC connection for low-current (high impedance) loads, and LC connection for high-current (low impedance) loads.

Mathematical Derivation of Torque I

- Instantaneous deflecting torque: $T_{inst} = i_{cc} \cdot i_{pc} \cdot \frac{dM}{d\theta}$, where M is the mutual inductance.
- For sinusoidal currents: $i_{cc} = \sqrt{2}I \sin(\omega t - \phi)$ and $i_{pc} = \frac{v}{R_p} = \frac{\sqrt{2}V \sin(\omega t)}{R_p}$.
- Substituting: $T_{inst} = 2\frac{VI}{R_p} \sin(\omega t) \sin(\omega t - \phi) \frac{dM}{d\theta}$.
- Using trigonometry: $T_{inst} = \frac{VI}{R_p}[\cos(\phi) - \cos(2\omega t - \phi)] \frac{dM}{d\theta}$.
- Since the moving system has high inertia, it responds to the average torque: $T_d = \frac{VI}{R_p} \cos(\phi) \frac{dM}{d\theta}$.
- With spring control ($T_c = K\theta$), at equilibrium: $\theta = \left(\frac{1}{KR_p} \frac{dM}{d\theta}\right) VI \cos(\phi) = \text{Constant} \cdot P$.

Low Power Factor (LPF) Wattmeters I



Feature	M-Side (MC) Connection	L-Side (LC) C
Position of PC Connection	Connected to the line/source side of the CC	Connected load/instrument the CC
Error Power Term	V^2/R_p (due to current in PC)	I^2R_c (due to v across CC)
Type of Load	Best suited for low current (high impedance)	Best suited for (low impedance
Power Factor Impact	Negligible for typical high PF loads	Large error und ditions

Measurement of 1-Ø Reactive Power I

- Reactive Power ($Q = VI \sin\phi$) can be measured using a single wattmeter with a phase-shifting device.
- The current through the pressure coil must be made to lag the voltage across it by exactly 90°.
- A large inductance is connected in series with the pressure coil circuit to shift its current by 90° relative to the voltage.
- Under this condition, the average torque becomes proportional to $VI\cos(90^\circ - \phi) = VI\sin(\phi)$.
- The wattmeter scale then reads reactive power directly in VAR.
- Alternatively, a standard wattmeter can be connected with a phase-shifting transformer (e.g., auto-transformer) to achieve the 90° displacement.

Agenda I

- Fundamentals of AC Single-Phase Power Measurement
- Electrodynamometer Wattmeter: Construction and Operating Principle
- Internal Schematic and Connections (M-C and L-C)
- Mathematical Derivation of Deflecting Torque
- Errors in Wattmeters (Pressure Coil Inductance, Capacitance, and Connection)
- Compensation Techniques for Low Power Factor Measurements
- Three-Voltmeter Method for Power Measurement
- Three-Ammeter Method for Power Measurement
- Comparative Analysis of Measurement Techniques
- Summary, Review Questions, and Numerical Practice

Fundamentals of Single-Phase AC Power I

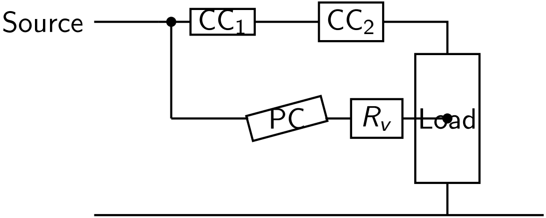
- In single-phase AC circuits, the instantaneous voltage is $v(t) = V_m \sin(\omega t)$ and current is $i(t) = I_m \sin(\omega t - \phi)$, where ϕ is the phase angle.
- Instantaneous power is $p(t) = v(t) \cdot i(t) = V_m I_m \sin(\omega t) \sin(\omega t - \phi) = VI \cos\phi - VI \cos(2\omega t - \phi)$, which consists of a constant real power term and a double-frequency fluctuating term.
- Active (Real) Power (P): The average value of instantaneous power over a complete cycle: $P = \frac{1}{T} \int_0^T p(t)dt = VI \cos\phi$ (Watts), representing actual work done.
- Reactive Power (Q): The rate of energy exchange between source and reactive elements of the load: $Q = VI \sin\phi$ (VAR), representing oscillating energy.
- Apparent Power (S): The total volt-amperes supplied to the circuit: $S = VI$ (VA), where $S = \sqrt{P^2 + Q^2}$.

Electrodynamometer Wattmeter Construction I

- Fixed Coils (Current Coil - CC): Wound with heavy copper wire to carry the full load current. Split into two halves to produce a uniform magnetic field near the center.
- Moving Coil (Potential/Pressure Coil - PC): Mounted on a spindle, wound with fine wire to have high resistance and low inductance. Placed in the magnetic field of the fixed coils.
- Series Multiplier Resistance (R_v): A high, non-inductive resistor connected in series with the PC to limit current and ensure the PC current is in phase with the applied voltage.
- Control and Damping: Controlling torque is exerted by two spiral hairsprings of phosphor bronze. Damping torque is provided by light aluminum vanes moving in a sector-shaped box (air friction damping).

- Shielding: The operating magnetic field of electrodynamometer instruments is weak (around 0.005 to 0.006 Tesla), making them highly susceptible to stray magnetic fields. Steel casing is used for magnetic shielding.

Internal Schematic of Electrodynamometer Wattmeter I



Torque Equation & Deflection Analysis I

- Instantaneous deflecting torque: $T_d = i_c i_p \frac{dM}{d\theta}$, where i_c is current in the fixed coil, i_p is current in the moving coil, and M is the mutual inductance between them.
- If the moving coil circuit is purely resistive, the current is $i_p = \frac{v}{R_p}$, where v is the instantaneous value of the supply voltage.
- Substituting i_p, the instantaneous torque becomes $T_d = i_c \left(\frac{v}{R_p}\right) \frac{dM}{d\theta} = \frac{vi_c}{R_p} \frac{dM}{d\theta}$. Since the instrument is connected to measure load, $i_c = i_{load}$, thus $T_d = \frac{vi}{R_p} \frac{dM}{d\theta}$.
- Average deflecting torque over a time period T is $T_d^{avg} = \frac{1}{T} \int_0^T T_d dt = \frac{1}{R_p} \frac{dM}{d\theta} \left(\frac{1}{T} \int_0^T vi\, dt\right) = \frac{P}{R_p} \frac{dM}{d\theta}$, where P is the active power.

Torque Equation & Deflection Analysis II

- Since spring control is used, the controlling torque is $T_c = K\theta$. Under steady-state balance ($T_d^{avg} = T_c$), the deflection angle is $\theta = \left(\frac{1}{KR_p}\frac{dM}{d\theta}\right)P$. If $\frac{dM}{d\theta}$ is constant, the scale is linear.

Errors in Electrodynamometer Wattmeters I

- Error due to Pressure Coil Inductance: The inductance L_p of the pressure coil causes its current I_p to lag the voltage V by angle $\beta = \tan^{-1}(\omega L_p/R_p)$. At lagging load power factors ($\cos\phi$), the wattmeter reads high: $P_{read} = VI\cos(\phi - \beta)\frac{\cos\beta}{\cos\phi}$.
- Error due to Pressure Coil Capacitance: Inter-turn capacitance of the PC series resistance acts in opposition to PC inductance, causing I_p to lead. Proper design balance can minimize the overall reactance error.
- Error due to Connection Methods: If PC is connected after CC (L-C connection), the reading includes I^2R_c loss. If PC is connected before CC (M-C connection), the reading includes V^2/R_p loss.

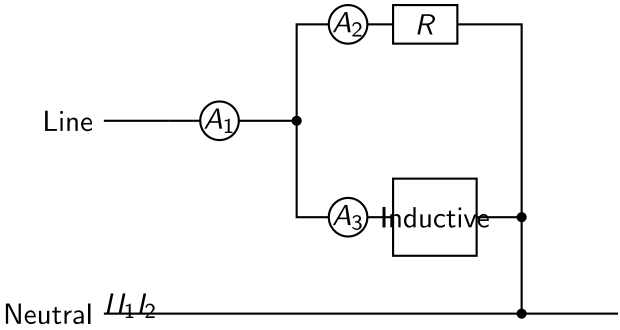
Errors in Electrodynamometer Wattmeters II

- Error due to Temperature and Aging: Heating of the coils increases resistance, reducing the PC current and decreasing the deflecting torque. This is minimized by using manganin or constantan resistors.
- Compensation: A compensating coil is wound co-axially with the fixed coils and connected in series with the pressure coil in opposition to the CC, canceling out the unwanted magnetic field contribution.

Wattmeter Connections Comparison I

Feature	L-C Connection (PC at Load)	M-C Connection (Source)
Schematic Layout	PC is connected across load terminals. CC carries load current only.	PC is connected source. CC carries current + PC curren
Measured Power (P_{meas})	$P_{load} + I^2 R_{cc}$ (Includes CC copper loss)	$P_{load} + \frac{V^2}{R_p}$ (Includ copper loss)
Relative Error	High for low-current (high impedance) loads due to $I^2 R_{cc}$.	High for high-curren impedance) loads d V^2/R_p.
Preferred Use Case	Best suited for heavy current, low impedance loads.	Best suited for lov rent, high impe loads

Three-Ammeter Method of Power Measurement I



- Three-Voltmeter Method: An alternative method to measure power and power factor of an inductive load using three voltmeters (V_1, V_2, V_3) and a non-inductive resistance R.
- Power Formula: The active power consumed by the load is given by $P = \frac{V_1^2 - V_2^2 - V_3^2}{2R}$, where V_1 is the supply voltage, V_2 is voltage across resistance R, and V_3 is voltage across the inductive load.
- Power Factor: The load power factor is calculated as $\cos\phi = \frac{V_1^2 - V_2^2 - V_3^2}{2V_2V_3}$. This method requires a high supply voltage to get accurate readings.
- Summary: The electrodynamometer wattmeter is the standard device for active power measurement, where the deflection is proportional to average power.

Three-Voltmeter Method & Lecture Summary II

- Key Takeaways: High pressure coil inductance leads to measurement errors at low power factors, requiring special compensation (LPF wattmeters). The 3-voltmeter/3-ammeter methods are useful when wattmeters are unavailable.

Agenda I

- Theoretical Foundation: Blondel's Theorem
- Three-Wattmeter Method for 3-Phase 4-Wire Systems
- Two-Wattmeter Method for 3-Phase 3-Wire Systems
- Mathematical Derivation of Active Power
- Phasor Diagram Analysis under Balanced Load
- Effect of Load Power Factor on Wattmeter Readings
- Measurement of Reactive Power in 3-Phase Systems
- Summary and Practical Guidelines

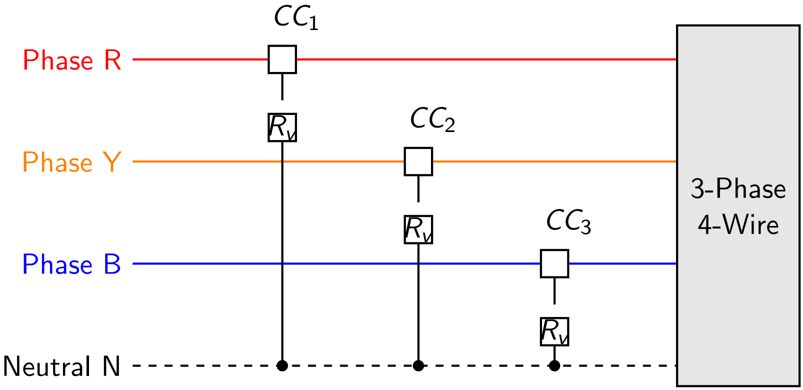
Blondel's Theorem: The Foundation of Power Measurement I

- Blondel's Theorem states that the total active power in an N-conductor system can be measured using N-1 wattmeters if their potential coils are returned to a common reference conductor.
- If the common reference point is chosen arbitrarily outside the system, N wattmeters are required to measure the total power.
- For a 3-phase, 4-wire system (R-Y-B-N), $N = 4$. Hence, N-1 $= 3$ wattmeters are required to measure power under both balanced and unbalanced load conditions.
- For a 3-phase, 3-wire system (R-Y-B), $N = 3$. Therefore, N-1 $= 2$ wattmeters are sufficient to measure total power, regardless of load balance or connection type (Star or Delta).

Three-Wattmeter Method: Theory and Analysis I

- The Three-Wattmeter Method is primarily used in 3-phase, 4-wire systems where the neutral connection is accessible.
- Each wattmeter current coil is connected in series with a phase line, and the pressure coil is connected between that line and the neutral point.
- The total instantaneous power is: $p = v\_RN * i\_R + v\_YN * i\_Y + v\_BN * i\_B$.
- Under unbalanced load conditions, each phase might have different currents and power factors; the three wattmeters measure phase powers independently.
- The total active power is the simple algebraic sum of the three readings: $P\_total = W\_1 + W\_2 + W\_3$.

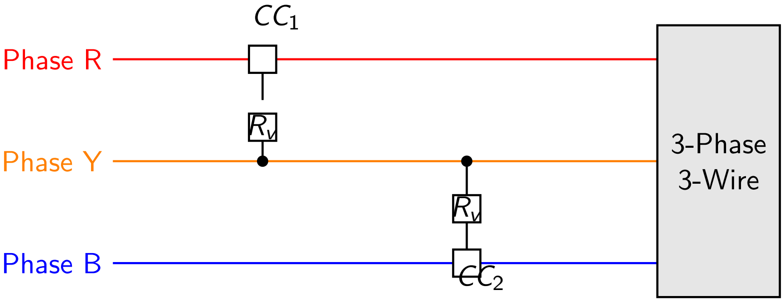
Circuit Configuration: Three-Wattmeter Method I



Two-Wattmeter Method: Working Principle I

- The Two-Wattmeter Method is the standard industrial method for measuring power in 3-phase, 3-wire systems.
- It is applicable to both balanced and unbalanced loads, connected in either Star or Delta configuration.
- Current coils of the wattmeters are placed in any two of the line conductors (e.g., Phase R and Phase B).
- The potential coils of both wattmeters are connected to the remaining line conductor (e.g., Phase Y) which acts as the common reference point.
- The total active power is the sum of the two wattmeter readings under all load conditions: $P\_total = W\_1 + W\_2$.

Circuit Configuration: Two-Wattmeter Method I



Two-Wattmeter Method: Derivation & Equations I

- Let the load be balanced, star-connected with a lagging power factor angle ϕ. Phase sequence is RYB.
- Wattmeter 1 is in Phase R (referred to Y): Current is I_R, Voltage is V_{RY}. The angle between V_{RY} and I_R is $(30^\circ + \phi)$. Reading: $W_1 = V_{RY} I_R \cos(30^\circ + \phi) = V_L I_L \cos(30^\circ + \phi)$.
- Wattmeter 2 is in Phase B (referred to Y): Current is I_B, Voltage is V_{BY}. The angle between V_{BY} and I_B is $(30^\circ - \phi)$. Reading: $W_2 = V_{BY} I_B \cos(30^\circ - \phi) = V_L I_L \cos(30^\circ - \phi)$.
- Total active power:
  $W_1 + W_2 = V_L I_L[\cos(30^\circ + \phi) + \cos(30^\circ - \phi)] = \sqrt{3} V_L I_L \cos\phi$.
  This proves the validity of the method.
- Difference between readings:
  $W_2 - W_1 = V_L I_L[\cos(30^\circ - \phi) - \cos(30^\circ + \phi)] = V_L I_L \sin\phi$.

Effect of Power Factor on Wattmeter Readings I

Power Factor ($\cos\phi$)	**Load Angle (ϕ)**	**Wattmeter 1 (W_1)**	**W**
1.0	0°	$0.866 V_L I_L$	0
0.866	30°	$0.5 V_L I_L$	V
0.5	60°	0	0
0.0	90°	$-0.5 V_L I_L$	0
< 0.5	$> 60^\circ$	Negative	P

Reactive Power Calculation and Measurement Summary I

- Under balanced load conditions, reactive power can be computed using the difference: $Q = \sqrt{3}(W_2 - W_1) = \sqrt{3} V_L I_L \sin\phi$.
- The load power factor angle can be derived from the ratio of the readings: $\tan\phi = \sqrt{3}\frac{W_2 - W_1}{W_1 + W_2}$.
- If the power factor is less than 0.5 (i.e. $\phi > 60^\circ$), the angle $(30^\circ + \phi)$ exceeds 90°, causing W_1 to record a negative value (pointer deflects backward).
- To read the negative deflection, one must reverse the polarity of the current coil or potential coil, record the value as negative, and subtract it: $P = W_2 - W_1$.
- Conclusion: Use the Two-Wattmeter method for three-wire systems, and the Three-Wattmeter method for four-wire unbalanced systems to ensure precision.

Lecture Agenda I

- Introduction to Energy Meters: Integrating instruments vs. indicating/deflecting instruments.
- Fundamental Operating Principle: Ferraris induction principle and rotating magnetic fields.
- Detailed Construction: Shunt magnet (voltage coil), series magnet (current coil), aluminum disc, and brake magnet.
- Mathematical Torque Derivation: Driving torque (T_d) and braking torque (T_b) relation to power and energy.
- Phasor Diagram Analysis: Representation of voltage, current, fluxes, and eddy currents.
- Errors in Induction Energy Meters: Phase angle error, friction, creeping, and temperature variations.

Lecture Agenda II

- Compensation and Adjustments: Lag adjustment, friction compensation, anti-creep holes, and temperature compensation.
- Polyphase (Three-Phase) Energy Meters: Blondel's theorem, 2-element and 3-element configuration, and mutual interference.
- Testing and Calibration: Phantom loading testing, starting tests, and determination of meter constant (K).

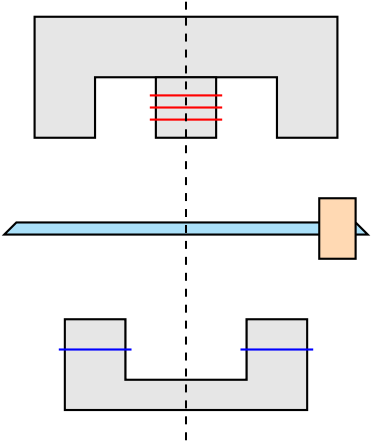
Operating Principle of Induction Energy Meters I

- Classification: Energy meters are integrating instruments that continuously record and sum the total electrical energy consumed over time ($\int P\,dt$).
- Fundamental Principle: Operates on the electromagnetic induction principle (similar to induction motors), where alternating magnetic fluxes induce eddy currents in a moving conductor.
- Dual Magnet System: Employs two electromagnets - a shunt magnet connected across the supply voltage (voltage coil) and a series magnet in series with the load (current coil).
- Flux Interactions: The shunt magnet flux (Φ_{sh}) lags the applied voltage by nearly 90°, while the series magnet flux (Φ_{se}) is in phase with the load current (I).

Operating Principle of Induction Energy Meters II

- Eddy Current Induction: These phase-displaced alternating fluxes pass through a rotatable aluminum disc, inducing eddy currents (i_{sh} and i_{se}) within it.
- Driving Torque Generation: The interaction of the shunt flux with the series eddy currents, and the series flux with the shunt eddy currents, produces forces that create a unidirectional driving torque (T_d).

Schematic Diagram of Induction Energy Meter I



Mathematical Derivation of Torque Equations I

- Shunt Flux Relation: The shunt magnet flux is proportional to the applied voltage: $\Phi_{sh} \propto V$. It lags V by phase angle Δ.
- Series Flux Relation: The series magnet flux is proportional to the load current: $\Phi_{se} \propto I$. It is in phase with I.
- Induced EMFs: The eddy currents induced in the aluminum disc lag their respective inducing fluxes by 90°.
- Driving Torque Expression: The net driving torque is given by: $T_d \propto \Phi_{sh}\Phi_{se}\sin(\beta)\cos(\theta)$, where β is the phase angle between the two fluxes.
- Substituting Flux Parameters: Since $\Phi_{sh} \propto V$, $\Phi_{se} \propto I$, and $\beta = \Delta - \phi$, we get $T_d \propto VI\sin(\Delta - \phi)$.
- Lag Adjustment to 90°: In a properly calibrated meter, the lag adjustment is set so that $\Delta = 90^\circ$. Therefore, $T_d \propto VI\sin(90^\circ - \phi) = VI\cos\phi$, which is the Active Power (P).

Mathematical Derivation of Torque Equations II

- Braking Torque: The permanent magnet produces a braking torque (T_b) by inducing eddy currents in the rotating disc: $T_b \propto N$, where N is the rotational speed.
- Steady State Condition: At steady speed, driving torque equals braking torque ($T_d = T_b \implies N \propto P$). Thus, total revolutions ($\int N\, dt$) is directly proportional to total consumed Energy ($\int P\, dt$).

Phasor Diagram of Single Phase Energy Meter I

ϕ: Load phase angle (lagging)

Δ: Lag angle of shunt flux Φ_{sh} relative to voltage V

Goal: $\Delta \to 90^\circ$ for correct active power measurement.;

Type of Error	Root Cause	Compensation / Ad- justment
Phase Error	Shunt flux does not lag the supply voltage by exactly 90° due to coil resistance and core losses.	Lag adjustment: ...tioning a copper sh... band (lag coil) ov... central limb.
Friction Error	Mechanical friction in spindle bearings, jewels, and register gears causes slow registration at low loads.	Friction compens... shading loop ... unsymmetrically t... troduce a small co... driving torque.
Creeping Error	Overcompensation of friction causes the disc to rotate continuously under no-load when voltage coil is energized.	Creep preve... drilling two diamet... opposite holes i... aluminum disc to... rotation under no-l...

Polyphase (Three-Phase) Induction Energy Meters I

- Applicability: Standard single-phase energy meters cannot measure total energy in polyphase systems directly. Multi-element energy meters are required.
- Blondel's Theorem: In an N-wire system, the total active power/energy can be measured using $N - 1$ wattmeter or energy-meter elements.
- Three-Phase Three-Wire (3P3W) Systems: Consists of two elements (two voltage coils and two current coils) acting either on two separate discs or a single disc.
- Three-Phase Four-Wire (3P4W) Systems: Consists of three elements (three voltage and three current coils) to accurately record energy under unbalanced load conditions.
- Common Spindle Integration: All elements are mechanically coupled to a single spindle, summing the driving torques ($T_{d,total} = T_{d1} + T_{d2} + T_{d3}$).

Polyphase (Three-Phase) Induction Energy Meters II

- Mutual Coupling / Cross-Torque: Interaction between the magnetic fields of different elements. Prevented by using laminated magnetic shields and proper spacing.

Testing and Calibration of Energy Meters I

- Phantom Loading: Standard testing at high load currents consumes enormous power if direct loading is used. In phantom loading, the pressure coil is connected to rated voltage, while the current coil is supplied from a separate low-voltage source to match rated current. Power consumed during testing is minimal.
- Creep Testing: Performed at 110% of rated voltage with the current coil open-circuited. The disc must not complete more than one full revolution under this condition.
- Meter Constant (K): Expressed in revolutions per kilowatt-hour (rev/kWh). It represents the factory-calibrated relationship between disc rotation and registered energy.
- Calculation of Percentage Error: $\% \text{ Error} = \frac{\text{Recorded Energy} - \text{Actual Energy}}{\text{Actual Energy}} \times 100$. Positive error indicates fast running; negative indicates slow running.

- Calibration Adjustments: The brake magnet is moved radially inward or outward to adjust the speed ($T_b \propto d^2$, where d is distance from spindle center).

Review Questions & Numerical Practice I

- Q1. Prove that the driving torque in an induction energy meter is proportional to the active power under the condition that the shunt flux lags voltage by 90°.
- Q2. Explain the difference between indicating, integrating, and recording instruments, and categorize the energy meter.
- Q3. How does the position of the brake magnet affect the speed of rotation of the aluminum disc? Explain using the braking torque equation.
- Q4. A 230V, 5A, single-phase energy meter has a meter constant of 480 revolutions/kWh. On testing at full load (unity power factor), the disc makes 40 revolutions in 60 seconds. Calculate the percentage error of the meter.
- Q5. Why is phantom loading preferred for high capacity energy meter testing? Illustrate the connection diagram for phantom loading.

Agenda I

- Introduction & Operating Principle
- Constructional Features of Single-Phase Induction Energy Meter
- Theory of Operation & Mathematical Expression
- Phasor Diagram Representation
- Driving, Braking & Registering Torques
- Common Errors & Compensation Adjustments
- Three-Phase Induction Energy Meters (2-Element and 3-Element)
- Blondel's Theorem and Phase/Torque Balancing

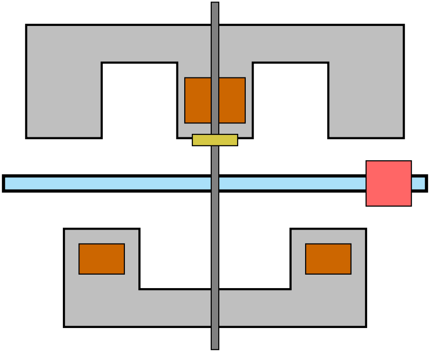
Basic Operating Principle I

- Integrating Instrument: An energy meter is an integrating type instrument that measures the total electrical energy consumed ($E = \int Pdt$) over a period.
- Electromagnetic Induction: It operates on the principle of induction, where alternating magnetic fluxes induce eddy currents in a moving conductor (aluminum disc).
- Dual Electromagnet System: It features a shunt magnet (connected across supply, producing flux proportional to voltage) and a series magnet (connected in series with load, producing flux proportional to current).
- Eddy Currents: The alternating fluxes from these electromagnets induce eddy currents in the rotating aluminum disc placed in the air gap.

Basic Operating Principle II

- Driving Torque (T_d): Produced by the interaction between the magnetic fluxes and the induced eddy currents, causing the disc to rotate.
- Braking Torque (T_b): A permanent magnet (brake magnet) induces eddy currents in the rotating disc, producing a controlling/braking torque proportional to the disc speed.

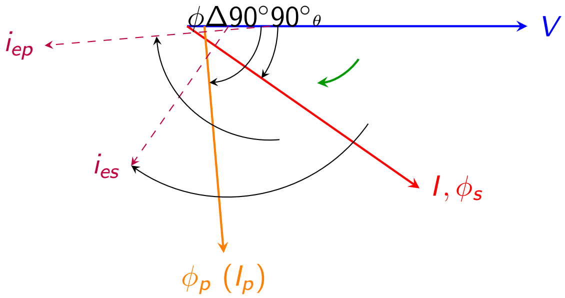
Construction of Single-Phase Energy Meter I



Theory of Operation and Torque Equations I

- Flux Production: The pressure coil (highly inductive) is connected across supply voltage V, producing shunt flux $\phi_p \propto V$ lagging V by angle $\Delta \approx 90^\circ$.
- Series Flux: The current coil (low resistance) is connected in series with load, carrying load current I and producing series flux $\phi_s \propto I$ in phase with I.
- Eddy Currents Induction: Shunt flux ϕ_p induces eddy current i_{ep} in the disc lagging ϕ_p by 90°. Series flux ϕ_s induces eddy current i_{es} in the disc lagging ϕ_s by 90°.
- Driving Torque Development: Interaction of ϕ_p with i_{es} and ϕ_s with i_{ep} produces deflecting/driving torque: $T_d \propto \phi_p \phi_s f \sin\theta$, where θ is the phase angle between ϕ_p and ϕ_s.
- Lag Angle Adjustment: Since $\theta = \Delta - \phi$, we have $T_d \propto VI \sin(\Delta - \phi)$. For a perfect 90° lag ($\Delta = 90^\circ$), $T_d \propto VI \sin(90^\circ - \phi) = VI \cos\phi$ (Active Power).

Phasor Diagram of Single-Phase Energy Meter I



Braking Torque and Energy Registration I

- Braking Torque Mechanism: A permanent magnet (C-shaped) is positioned near the disc's edge. As the disc rotates, it cuts the brake magnet's flux ϕ_m, inducing eddy currents in the disc.
- Braking Torque Equation: The braking torque T_b is proportional to the speed of the disc (n) and the square of the brake magnet flux: $T_b = K_2 \phi_m^2 n$.
- Steady-State Speed: At steady-state speed, the driving torque equals the braking torque:
  $T_d = T_b \implies K_1 VI \cos\phi = K_2 \phi_m^2 n$.
- Speed Proportionality: Assuming ϕ_m is constant, the disc speed n is directly proportional to active power:
  $n = KVI \cos\phi = KP$.

Braking Torque and Energy Registration II

- Energy Integration: The total number of revolutions N of the spindle in time t is
$N = \int n dt = K \int VI \cos\phi dt = K \cdot \text{Electrical Energy}$.

- Registering Mechanism: A gear train mechanism coupled to the spindle translates the total revolutions N into kilowatt-hours (kWh) shown on a register.

Type of Error	Cause	Adjustment /
Phase / Lag Error	Shunt coil resistance prevents flux ϕ_p from lagging voltage by exactly 90°.	Copper shadin ment) placed of the shunt m
Friction / Light Load	Friction in bearings and gear train retards disc rotation at light loads.	Friction co loop/shading shunt magnet small constant
Creeping	Disc rotates slowly under no-load condition when only voltage is applied to the pressure coil.	Two diametri drilled in the a tion stops whe der the shunt

Three-Phase Induction Energy Meter I

- Multi-Element System: To measure energy in a 3-phase system, multiple single-phase elements are combined into a single instrument.
- Blondel's Theorem: In an N-wire system, the number of measuring elements required is $(N - 1)$ to accurately register total energy.
- 3-Phase, 3-Wire (2-Element): Uses two elements (two shunt and two series systems). The total torque is the sum of both: $T_{d,\text{total}} = T_{d1} + T_{d2} \propto P_1 + P_2$.
- 3-Phase, 4-Wire (3-Element): Uses three elements to account for current in the neutral wire under unbalanced conditions.
- Spindle Configuration: The elements act either on a single common aluminum disc or on separate discs mounted on a single spindle driving a common register.

Three-Phase Induction Energy Meter II

- Mutual Interference (Cross-Talk): Flux from one element can link with the disc of another element, causing errors. Laminated steel magnetic shields are used to isolate elements.
- Torque Balancing: An adjustable magnetic shunt is provided on the series magnet of one element to ensure both elements produce equal torque under equal load.

Lecture Summary and Review I

- Core Concept: Induction energy meters integrate active electrical power over time using eddy current principles in an aluminum disc.
- Key Subsystems: Driving system (electromagnets), Moving system (spindle/disc), Braking system (permanent magnet), and Registering system (gear/pointer).
- Compensating Adjustments: Copper shading bands for lag correction, shading loops for friction compensation, and disc holes for creep prevention.
- Polyphase Measurement: Designed based on Blondel's Theorem. Two elements are required for 3-wire systems, and three elements for 4-wire systems.
- Review Question 1: Explain the construction and working of a single-phase induction energy meter with a neat schematic diagram.

Lecture Summary and Review II

- Review Question 2: Derive the driving torque expression. Show that it is proportional to the active power under ideal lag conditions.
- Review Question 3: What is creeping? Explain its causes and remedies in detail.
- Review Question 4: How does a three-phase energy meter handle unbalanced loads, and how is cross-talk prevented between elements?

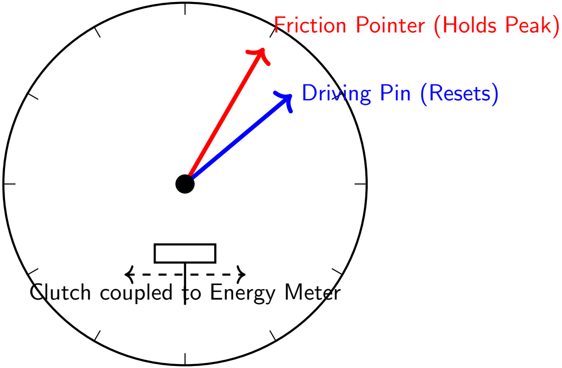
Lecture Agenda I

- Introduction to Maximum Demand Indicators (MDI) & Merz-Price MDI
- Principles and Functionality of Tri-Vector Meters
- Phase Sequence Indicators: Rotating & Static Types
- Solid State (Electronic) Energy Meters: Architecture & Working
- Clip-on (Clamp) Meters: Working Principle and Applications

Maximum Demand Indicator: Core Concepts I

- Maximum Demand is the highest average power consumed by a load during any pre-defined interval (typically 15, 30, or 60 minutes) during a billing cycle.
- Merz-Price Maximum Demand Indicator integrates energy consumed over a predetermined time interval (t) and records the average rate of energy consumption.
- The pointer is driven forward by the register mechanism of the energy meter, which is coupled via a clutch.
- At the end of the time interval (e.g., 30 minutes), a cam-reset mechanism resets the driving pin to zero, while a friction pointer remains at the maximum position reached.
- Mathematical representation of Maximum Demand (MD) in kW: $MD = \frac{\text{Energy consumed in interval (kWh)}}{\text{Interval duration in hours (h)}}$.

Merz-Price Maximum Demand Indicator Mechanism I



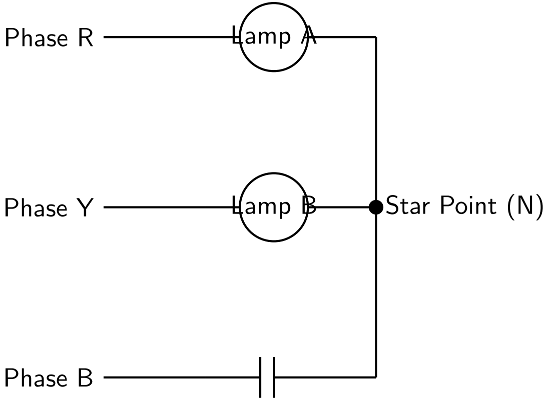
Tri-Vector Meter: Measurement of Apparent Energy I

- A Tri-Vector Meter is used to measure active power (kW), reactive power (kVAR), and apparent power (kVA) simultaneously in a three-phase system.
- Apparent power calculation is non-linear: $S = \sqrt{P^2 + Q^2}$ or $kVA = \sqrt{kW^2 + kVAR^2}$. Mechanical tri-vector meters used complex gearing to approximate this sum.
- Modern digital tri-vector meters calculate kVA electronically by sampling phase voltage and current waveforms and computing $S = V_{RMS} \times I_{RMS}$ per phase.
- A vector sum approximation was historically done using a sphere-gear or Bailey system, where two driving shafts (one for kW and one for kVAR) driven by separate meter discs engaged with a sphere to turn a third kVA register.
- Utility billing often charges industrial consumers based on kVA maximum demand to penalize low power factor operation.

Phase Sequence Indicator: Rotating & Static Types I

- Phase sequence determines the order in which phase voltages reach their peak values. The standard positive sequence is Red-Yellow-Blue (R-Y-B).
- Rotating Type Phase Sequence Indicator works on the principle of an induction motor. Three star-connected coils produce a rotating magnetic field.
- A light aluminum disc placed above the coils rotates in the direction of the phase sequence. Clockwise indicates positive sequence (R-Y-B), counter-clockwise indicates negative.
- Static Type Phase Sequence Indicator uses a combination of resistors, inductors/capacitors, and two lamps (or neon bulbs).
- In a static RC-lamp circuit, one lamp glows bright and the other glows dim. The bright lamp indicates the sequence: if Lamp 1 is bright, the sequence is R-Y-B; if Lamp 2 is bright, the sequence is R-B-Y.

Static Phase Sequence Indicator (Capacitor-Lamp Method) I



Solid State (Electronic) Energy Meter: Architecture I

- Solid State Energy Meters replace mechanical discs with analog-to-digital converters (ADCs), digital signal processors (DSPs), and microcontrollers.
- Current sensing is typically performed using a Current Transformer (CT), a low-resistance shunt, or a Rogowski coil.
- Voltage sensing is performed using a simple resistive voltage divider network to scale high grid voltage to millivolt levels.
- The DSP multiplies the sampled voltage and current samples to compute instantaneous power: $p(t) = v(t) \times i(t)$.
- These computed power samples are integrated over time to calculate total Active Energy (kWh), Reactive Energy (kVARh), and Apparent Energy (kVAh). The data is stored in non-volatile memory (EEPROM) to prevent loss during power outages.

Comparison: Electromechanical vs. Solid State Energy Meters I

Parameter	Electromechanical Meter	Solid State (Meter
Working Principle	Electromagnetic induction (aluminum disc rotation)	ADC sampling Signal Processi
Accuracy Class	Typically Class 2.0 (lower accuracy)	Class 0.5S or tremely high ac
Power Consumption	High (typically 1.5W to 2.5W in voltage coil)	Very low (typica 0.5W)
Anti-tampering	Prone to mechanical tampering and magnetic fields	Advanced tamp (phase/neutral cover open)
Data Logging	Only cumulative energy register	Logs load profile demand, billing events

Clip-on Meter (Clamp Meter): Working Principle I

- A Clip-on meter or Clamp meter allows measurement of AC current in a conductor without breaking the circuit or making electrical contact.
- The split jaw of the meter is made of high-permeability silicon steel. When clamped around a conductor carrying AC current, it acts as a magnetic core.
- The conductor itself acts as a single-turn primary winding of a current transformer (CT), inducing an alternating magnetic flux in the core.
- A secondary winding wrapped around the internal core has many turns (N_2). The induced current is stepped down: $I_2 = I_1/N_2$. This secondary current is then measured and calibrated.

Clip-on Meter (Clamp Meter): Working Principle II

- For DC current measurement, since there is no changing magnetic flux, Hall Effect sensors are embedded in the jaws of the clamp to measure static magnetic field strength.

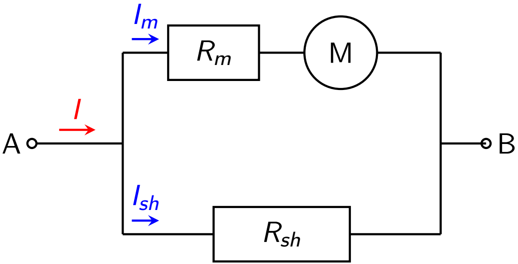
Agenda I

- Introduction to range extension in PMMC instruments
- Ammeter shunts: Working principle, circuit configuration, and derivation of the shunt equation
- Design considerations for shunts: Materials, temperature error, and swamping resistors
- Voltmeter multipliers: Working principle, circuit configuration, and derivation of the multiplier equation
- Comparative analysis: Shunts vs. Multipliers
- Solved design problems for range extension

Need for Range Extension in PMMC Instruments I

- PMMC instruments are low-power devices. The moving coil is wound with fine copper wire, limiting the current capacity (I_m) to 50 μA - 50 mA.
- The coil resistance (R_m) is small (typically 5 to 100 Ω), causing a full-scale voltage drop (V_m) of only 50 mV to 150 mV.
- To measure larger currents (amperes) or voltages (hundreds of volts), direct connection would burn the coil or cause insulation breakdown.
- Hence, range extension is required to bypass excess current or drop excess voltage.
- This is achieved by connecting a low resistance in parallel (shunt) for ammeters, and a high resistance in series (multiplier) for voltmeters.

Ammeter Range Extension: Circuit Configuration I



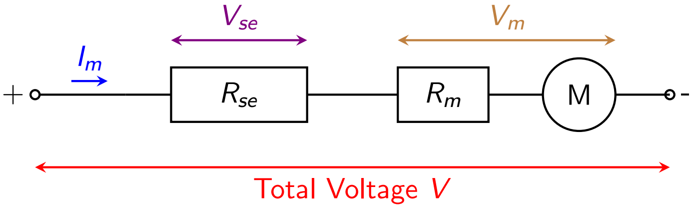
Mathematical Derivation for Ammeter Shunt I

- Let I = total current to be measured, I_m = full-scale deflection current of the meter coil, I_{sh} = current through the shunt resistor.
- Let R_m = internal resistance of the meter coil, R_{sh} = resistance of the parallel shunt.
- Since the meter and shunt are in parallel, voltage across them is equal: $V_m = V_{sh} \implies I_m R_m = I_{sh} R_{sh}$.
- Applying Kirchhoff's Current Law (KCL) at the junction: $I = I_m + I_{sh} \implies I_{sh} = I - I_m$.
- Substituting I_{sh} into the voltage equation: $I_m R_m = (I - I_m) R_{sh}$.
- Solving for R_{sh}: $R_{sh} = \frac{I_m R_m}{I - I_m} = \frac{R_m}{\frac{I}{I_m} - 1}$.
- Defining the multiplying factor of the shunt, $m = \frac{I}{I_m}$, we get the final equation: $R_{sh} = \frac{R_m}{m-1}$.

Properties and Selection of Shunt Materials I

- Shunt resistors must carry large currents and maintain stable resistance values under varying thermal conditions.
- Manganin (84% Cu, 12% Mn, 4% Ni) is standard for DC shunts because of its extremely low temperature coefficient ($4 \times 10^{-5}/^{\circ}C$).
- Manganin also exhibits low thermoelectric EMF against copper, preventing error-inducing thermal parasitic voltages.
- For AC shunts, low inductance is critical; shunts are constructed as thin concentric tubes or bifilar strips to minimize inductive reactance.
- To offset the high temperature coefficient of the copper coil ($0.004/^{\circ}C$), a Manganin swamping resistor (20-30 times R_m) is connected in series with the coil.

Voltmeter Range Extension: Circuit Configuration I



Mathematical Derivation for Voltmeter Multiplier I

- Let V = extended voltage range to be measured, v = full-scale deflection voltage drop across the meter ($v = I_m R_m$).
- Let R_m = internal resistance of the meter coil, R_{se} = resistance of the series multiplier.
- The current through the series circuit is limited to the full-scale deflection current I_m: $I_m = \frac{V}{R_{se}+R_m}$.
- Since the meter alone requires $I_m = \frac{v}{R_m}$, we equate the two current relations: $\frac{V}{R_{se}+R_m} = \frac{v}{R_m}$.
- Cross-multiplying and dividing gives: $\frac{V}{v} = \frac{R_{se}+R_m}{R_m} = 1 + \frac{R_{se}}{R_m}$.
- Defining the multiplying factor of the multiplier, $m = \frac{V}{v}$, the expression simplifies to: $m = 1 + \frac{R_{se}}{R_m}$.
- Rearranging the terms yields the final multiplier design equation: $R_{se} = R_m(m - 1)$.

Comparison of Shunt and Multiplier Techniques I

Parameter	Ammeter Shunt	Voltmeter
Connection Type	Connected in parallel with the meter coil	Connected coil
Resistance Value	Very low (typically fraction of an ohm)	Very high (mega-ohms
Design Formula	$R_{sh} = \frac{R_m}{m-1}$	$R_{se} = R_m($
Multiplying Factor	$m = \frac{I}{I_m}$ (Current multiplier ratio)	$m = \frac{V}{v}$ (Vo
Primary Material	Manganin strips with heavy copper terminals	Manganin (non-induc
Power Handling	Must dissipate high heat due to	Lower curre

Numerical Problems: Design Examples I

- Example 1 (Ammeter): A PMMC instrument gives full-scale deflection at 10 mA and has a coil resistance of 50 Ω. Find the shunt resistance required to measure up to 5 A.
- Solution 1: $I_m = 0.01$ A, $R_m = 50\ \Omega$, $I = 5$ A. Multiplying factor $m = I/I_m = 5/0.01 = 500$. Shunt resistance $R_{sh} = R_m/(m-1) = 50/(500-1) = 50/499 \approx 0.1002\ \Omega$.
- Example 2 (Voltmeter): Design a multiplier for the same 10 mA, 50 Ω meter to measure voltages up to 250 V.
- Solution 2: Voltage drop at full deflection $v = I_m R_m = 0.01 \times 50 = 0.5$ V. Target voltage $V = 250$ V. Multiplying factor $m = V/v = 250/0.5 = 500$. Series resistance $R_{se} = R_m(m-1) = 50 \times (500-1) = 50 \times 499 = 24,950$ $\Omega = 24.95$ kΩ.

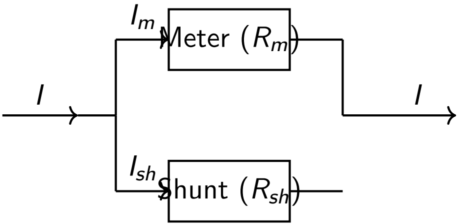
Agenda I

- Limitations of basic PMMC moving coil instruments
- Ammeter Shunts: Connection topology and working principle
- Mathematical derivation of the shunt resistor equation
- Temperature errors and their compensation using swamping resistors
- Voltmeter Multipliers: Series resistor design and principle
- Mathematical derivation of the multiplier resistor equation
- Comparative analysis of shunts and multipliers in instrument design

Need for Range Extension in PMMC Instruments I

- PMMC instruments are highly sensitive and accurate, but they can only carry very small currents through their moving coil.
- Typical full-scale deflection (FSD) current of a PMMC coil ranges from 10 microamperes to 50 milliamperes.
- The coil winding is made of very thin copper wire, which has a low current-carrying capacity. Exceeding this limit will cause thermal damage.
- The voltage drop across the moving coil at FSD is typically very small, on the order of 50 to 200 millivolts.
- Therefore, to measure large currents (ammeters) or high voltages (voltmeters), external circuitry must bypass the excess current or drop the excess voltage.
- This range extension is achieved by shunt resistors (for current) and series multipliers (for voltage).

Ammeter Shunt Connection Diagram I



Derivation of Ammeter Shunt Equation I

- Let R_m be the internal resistance of the meter coil, and R_{sh} be the shunt resistance.
- Let I_m be the full-scale deflection current of the meter, and I_{sh} be the current through the shunt.
- Let I be the total line current to be measured, where $I > I_m$.
- Since the meter coil and the shunt resistor are connected in parallel, the voltage drop across them is identical: $V_m = V_{sh} \implies I_m R_m = I_{sh} R_{sh}$.
- By Kirchhoff's Current Law (KCL) at the junction: $I = I_m + I_{sh} \implies I_{sh} = I - I_m$.
- Substituting I_{sh} into the voltage equality yields: $I_m R_m = (I - I_m) R_{sh}$.
- Solving for the shunt resistance: $R_{sh} = \frac{I_m R_m}{I - I_m} = \frac{R_m}{\frac{I}{I_m} - 1}$.

Derivation of Ammeter Shunt Equation II

- Defining the multiplying power of the shunt as $m = \frac{I}{I_m}$, we get: $R_{sh} = \frac{R_m}{m-1}$.
- Thus, to extend the current range by a factor of m, a shunt of value $R_m/(m-1)$ must be connected in parallel.

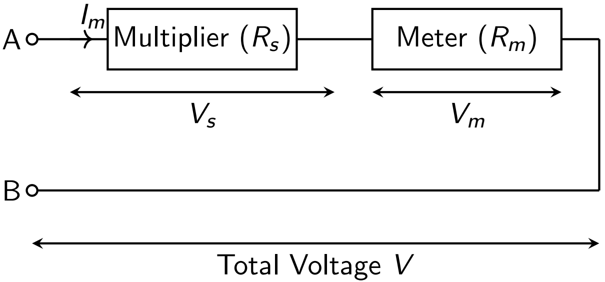
Temperature Compensation in Shunted Ammeters I

- The copper moving coil has a high temperature coefficient of resistance (approximately 0.004 per degree Celsius).
- As temperature increases, R_m increases, which alters the current division ratio: more current flows through the shunt R_{sh}, and less through the meter, causing a negative measurement error.
- To counter this, a swamping resistor (R_{sw}) made of a material with a near-zero temperature coefficient (like manganin) is connected in series with the coil.
- The swamping resistance is typically 9 times the resistance of the meter coil ($R_{sw} \approx 9R_m$), rendering the temperature-sensitive copper resistance a small fraction of the branch's total resistance.

Temperature Compensation in Shunted Ammeters II

- The shunt resistor is also constructed from manganin to ensure that the parallel division ratio remains highly stable over wide temperature ranges.

Voltmeter Multiplier Connection Diagram I



Derivation of Voltmeter Multiplier Equation I

- Let R_m be the internal resistance of the meter coil, and R_s be the series multiplier resistance.
- Let V_m be the voltage drop across the meter for full-scale deflection current $I_m \implies V_m = I_m R_m$.
- Let V be the total voltage to be measured, representing the extended scale limit.
- Since the multiplier and the meter are connected in series, the same FSD current I_m passes through both: $I_m = \frac{V}{R_s + R_m}$.
- This can be rewritten as: $V = I_m R_s + I_m R_m = I_m R_s + V_m$.
- Solving for the series multiplier resistance: $R_s = \frac{V - V_m}{I_m} = \frac{V}{I_m} - R_m$.
- Substituting $I_m = \frac{V_m}{R_m}$ into the equation gives: $R_s = \frac{V}{\frac{V_m}{R_m}} - R_m = R_m \left(\frac{V}{V_m} - 1 \right)$.

Derivation of Voltmeter Multiplier Equation II

- Defining the voltage multiplying factor as $m = \frac{V}{V_m}$, we obtain the multiplier equation: $R_s = R_m(m-1)$.
- Therefore, to extend the voltage range by a factor of m, we connect a series resistor R_s equal to $R_m(m-1)$.

Design Requirements and Materials I

- Low Temperature Coefficient: The resistance of shunts and multipliers must remain highly stable across working temperature ranges.
- Thermal EMF Minimization: The contact potential (thermal EMF) between the resistor material and copper terminals must be negligible to prevent DC measurement bias.
- Manganin is the preferred alloy for both shunts and multipliers due to its low temperature coefficient ($0.00001/^\circ C$) and low thermal EMF against copper.
- Constantan is sometimes used for AC instruments but is avoided in DC because of its high thermal EMF against copper.
- High Power Dissipation: Ammeter shunts carry large currents and must be physically large with fins or grids to facilitate convective cooling.

Design Requirements and Materials II

- Non-Inductive Winding: Voltmeter multipliers should be wound non-inductively (e.g., using bifilar windings) to prevent inductive reactance errors in AC applications.

Parameter	Ammeter Shunt	Voltmeter M
Connection	Parallel with the meter coil	Series with th
Resistance Value	Very Low ($R_{sh} < R_m$)	Very High (R_s
Design Formula	$R_{sh} = \frac{R_m}{m-1}$	$R_s = R_m(m -$
Multiplying Factor	$m = \frac{I}{I_m}$	$m = \frac{V}{V_m}$
Primary Function	Bypasses major part of current	Limits the vo meter
Material Used	Manganin (low temperature drift)	Manganin or

Agenda I

- Limitations of direct-connected meters and shunts/multipliers in high-power AC systems
- Introduction to Instrument Transformers: Basic principles and necessity
- Current Transformer (CT): Construction, operating principles, and standard terminal markings
- Potential Transformer (PT): Structural details, parallel connections, and functions
- Equivalent circuit models, nominal ratios, turns ratios, and actual transformation ratios
- Key comparisons between CT and PT applications and design differences
- Analysis of Instrument Transformer errors: Ratio error and phase angle error

Agenda II

- Crucial safety procedures: Why a CT secondary must never be left open-circuited

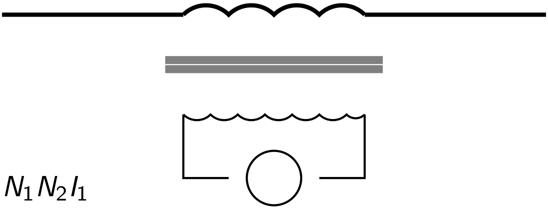
Need for Instrument Transformers I

- Extending the range of AC meters using traditional shunts (for ammeters) or multipliers (for voltmeters) is highly impractical at high currents and voltages.
- Shunts carry the full line current, leading to excessive heating, bulkiness, and power loss (I^2R). They also introduce parasitic inductance that distorts AC measurements.
- Multipliers for high-voltage systems require extremely large resistances, causing severe insulation breakdown issues and thermal stability concerns.
- Safety Hazard: Direct connection of measuring instruments to high-voltage lines puts operators and panel equipment at severe risk of electric shock.
- Solution: Instrument transformers provide complete galvanic isolation between the high-voltage/high-current power line and the low-voltage/low-current measuring circuit.

Need for Instrument Transformers II

- Standardization: They step down voltages and currents to standardized, safe values—typically 5 A (or 1 A) for current and 110 V for voltage.

Current Transformer (CT) Connection & Schematic I

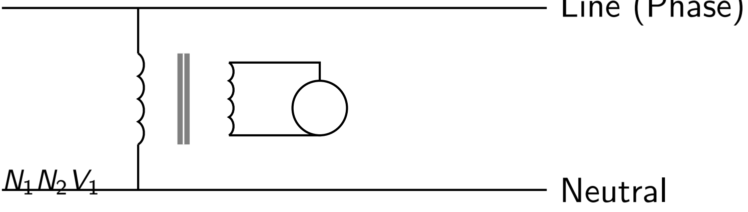


$N_1 N_2 I_1$

Working Principle of Current Transformers I

- The CT is a step-up transformer in terms of voltage, which results in a step-down effect in terms of current ($I_1/I_2 \approx N_2/N_1$).
- Primary Winding: Connected in series with the power line carrying the current to be measured. Constructed with a few turns of heavy-cross-section conductor.
- Secondary Winding: Wound with a large number of turns of thin copper wire, designed to connect directly across a low-impedance ammeter or relay coil.
- Nominal Ratio (K_n): The ratio of rated primary current to rated secondary current (e.g., 500/5 A or 100/5 A).
- Actual Ratio (R): The ratio of the actual primary RMS current to the actual secondary RMS current ($R = I_p/I_s$).
- Turns Ratio (n): The physical ratio of secondary turns to primary turns ($n = N_2/N_1$).

Potential Transformer (PT) Connection & Schematic I



Feature	Current Transformer (CT)	Potential Trans (PT)
Connection	Connected in series with the line.	Connected in with the line.
Primary Winding	Carries full line current; has very few turns of thick wire.	Connected acros voltage; has man of thin wire.
Secondary Winding	Connected to low range ammeter; has many turns.	Connected to lov voltmeter; has fev
Standard Rating	Secondary current is rated at 5 A (or 1 A).	Secondary volta rated at 110 V.
Operation	Must never be open-circuited while energized.	Can be operated c circuit safely.
Core Design	Designed for low leakage reactance and low excita-	Designed for low ratio error and ph

Errors in Instrument Transformers I

- In practical transformers, winding resistances, magnetic leakage fluxes, and core excitation requirements cause the actual ratio to differ from the turns ratio.
- Ratio Error: Occurs because the primary current or voltage is partially consumed by the core's magnetizing and core-loss current components.
- Ratio Error Formula: Ratio Error $= \frac{K_n - R}{R} \times 100\%$, where K_n is the nominal ratio and R is the actual transformation ratio.
- Phase Angle Error: The phase difference between the primary phasor (current/voltage) and the reversed secondary phasor differs slightly from 180°.
- Phase Angle (θ): The angle by which the reversed secondary phasor leads/lags the primary phasor. Expressed in minutes or radians.

Errors in Instrument Transformers II

- Impact: Phase angle error introduces significant measurement errors in wattmeters and energy meters, where the phase relationship between voltage and current directly impacts calculated power ($\cos\phi$).

Critical Safety: Open Circuiting CT Secondary I

- Primary line current is completely independent of the load (burden) connected to the CT secondary; it is determined solely by the power system load.
- Under normal operation, secondary current produces an MMF ($N_2 I_2$) that opposes and cancels out most of the primary MMF ($N_1 I_1$).
- If the secondary winding is open-circuited while the primary is carrying current (I_1), the secondary current (I_2) drops to zero.
- The opposing secondary MMF disappears. The entire primary MMF ($N_1 I_1$) now acts as the magnetizing MMF ($I_0 = I_1$).
- This drives the magnetic core deep into saturation, inducing a extremely high, non-sinusoidal voltage spike across the open secondary terminals.

Critical Safety: Open Circuiting CT Secondary II

- Dangers: Poses a fatal shock hazard to operating personnel, risks breakdown of winding insulation, and causes severe core overheating due to high iron losses.

Summary & Engineering Highlights I

- Instrument transformers (CT & PT) are indispensable for safe, standardized, and cost-effective measurement of high currents and voltages in AC networks.
- A CT is always connected in series and steps down current (secondary rated 5A), whereas a PT is connected in parallel and steps down voltage (secondary rated 110V).
- To prevent hazardous voltage spikes and thermal runaway, a CT secondary must always be short-circuited before removing or replacing an ammeter.
- Ratio and phase angle errors occur due to magnetizing and iron-loss currents, and are minimized by utilizing high-permeability magnetic cores (e.g., Mumetal or Cold-Rolled Grain-Oriented steel).

Summary & Engineering Highlights II

- Review Question: Derive the expression for the actual transformation ratio (R) and phase angle (θ) of a Current Transformer using its phasor diagram.

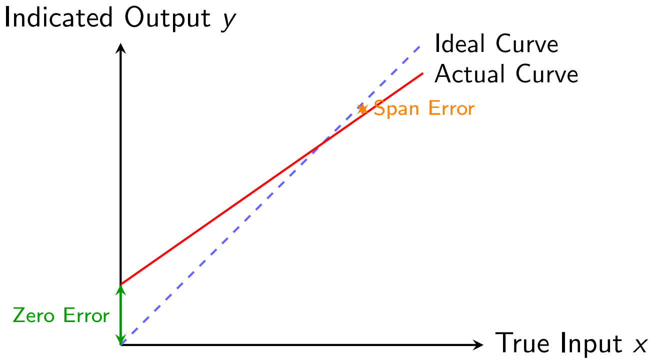
Agenda I

Fundamental Concept of Calibration I

- Calibration is the quantitative comparison between a measuring instrument (Unit Under Test - UUT) and a reference standard of known, higher accuracy.
- It establishes the relationship between the indicated value (by the UUT) and the true value (asserted by the standard) under specified environmental conditions.
- Unlike adjustment, calibration only documents the deviation (errors) and determines the uncertainty of the measurement system.
- Calibration is essential to maintain quality control, ensure regulatory compliance (ISO 9001/ISO 17025), and guarantee safety in electrical systems.

Metrological Traceability Chain I

Static Calibration Curve and Sensitivity I



Classification of Calibration Errors I

- Zero Error (Offset): A constant error across the entire measurement range, caused by shifting of the calibration curve parallel to the ideal line.
- Span Error (Gain): The slope of the actual calibration curve differs from the ideal line, resulting in an error that increases proportionally with the measured input.
- Linearity Error: The maximum deviation of the actual calibration curve from a straight line reference, reflecting non-linear behavior of the sensor or transducer.
- Hysteresis Error: The difference in output indications when the same input value is approached from opposite directions (increasing and decreasing).

Hierarchy of Calibration Standards I

Standard Level	Primary Location	Characteristics tion
Primary Standards	National Metrology Labs	Highest accuracy units directly (e. Junction)
Secondary Standards	Accredited Cal Labs	Calibrated agai standards, used working standards
Working Standards	Industrial Standards Labs	High precision re dards for calibrati ments
Field Instruments	Process Floor / Plant	Devices (multime gauges) used in da

Standard Calibration Process Cycle I

- Pre-calibration inspection: Cleaning, visual check for physical damage, and checking power supply and connection integrity.
- Environmental stabilization: Allowing the UUT and standards to reach thermal and humidity equilibrium in the calibration lab (typically 23°C +/- 2°C, RH 45% +/- 15%).
- Zero Adjustment: Checking and adjusting the zero-point indication of the UUT before taking measurement points.
- Multipoint Verification: Taking measurements at 5 or more points across the span (usually 0%, 25%, 50%, 75%, 100%) in both ascending and descending directions.
- Documentation & Labeling: Recording raw data, calculating errors and uncertainties, issuing calibration certificate, and applying a calibration label showing the date and next calibration due.

Calibration Interval and Instrument Drift I

- Drift is the slow variation of metrological characteristics of a measuring instrument over time, caused by component aging, mechanical stress, or environmental exposure.
- Calibration Interval is the maximum period between successive calibrations, selected to balance calibration costs against the risk of an instrument going out-of-tolerance (OOT).
- Methods for determining interval: Fixed-time intervals (e.g., 1 year), control chart tracking (drift modeling), or usage-hours basis.
- If an instrument is found OOT during calibration, a retrospective impact analysis must be performed on all measurements made since the last successful calibration.

Importance of Calibration Certificates I

- Legal and Quality Compliance: Serves as audit evidence for international standards like ISO 9001, ISO 14001, and IATF 16949.
- Traceability Record: Documents the exact standard used and the traceability link up to the SI units (via NMI).
- Measurement Uncertainty: Specifies the expanded uncertainty (typically at 95% confidence level, k=2) associated with each calibration point.
- Process Safety and Product Quality: Minimizes measurement errors, reducing the risk of bad products passing inspection or dangerous over-voltage/current conditions going undetected.

Agenda I

- Concept of Metrological Calibration
- The Metrological Traceability Chain
- Calibration Standards Hierarchy
- Standard Calibration Test Setup
- Static Calibration Characteristics
- Systematic and Dynamic Calibration Errors
- Comparison of Calibration Standards
- Calibration Frequency and Intervals
- Industrial Significance & Quality Standards
- Lecture Summary and Assessment

Introduction to Calibration I

- Calibration defines the metrological relationship between an instrument's readings and a known standard reference.
- It is not adjustment: Calibration is the act of measuring deviation, whereas adjustment (or 'calibration correction') is the act of aligning the device to minimize the error.
- Without calibration, even the most advanced instrumentation systems provide readings of unknown accuracy, rendering data scientifically and industrially invalid.
- It addresses aging, environmental drift (temperature, humidity), mechanical wear, and electrical component degradation over time.

Traceability Hierarchy in Metrology I

(International Standard); ode (ns) at (0,1.8) National Metrology Institutes (NIST, NPL)

(Primary Standards); ode (ss) at (0,0.6) Accredited Calibration Labs

(Secondary Standards); ode (ws) at (0,-0.6) Working / Transfer Standards

(Reference Standards); ode (iut) at (0,-1.8) Instruments Under Test (IUT)

(Field / Industrial Devices); [-¿, ¿=stealth, thick] (si) – (ns); [-¿, ¿=stealth, thick] (ns) – (ss); [-¿, ¿=stealth, thick] (ss) – (ws); [-¿, ¿=stealth, thick] (ws) – (iut);

Primary vs. Secondary Standards I

Characteristic	Primary Standards	Secondary Standards
Traceability Origin	Derived directly from physical constants and SI definitions.	Calibrated against primary standards in certified national labs.
Typical Uncertainty	Extremely low ($< 10^{-6}$ or ppm levels).	Moderately low (10^{-4} to 10^{-5} range).
Primary Application	National standard maintenance and international comparisons.	Calibration of working standards and precision laboratory instruments.
Physical Examples	Cesium fountain clocks (Time), Josephson voltage arrays.	Standard resistors, precision decade boxes, temperature baths.

Calibration Block Diagram I

Static Characteristics in Calibration I

- Calibration Curve: The graphical plot of the input (measurand) vs. the output (instrument indication). Ideal curves are perfectly linear ($y = mx + c$).
- Sensitivity: Defined as the slope of the calibration curve (dy/dx). A constant slope signifies uniform sensitivity across the full scale.
- Zero Error (Offset): A constant error across the entire range of measurement, shifting the calibration curve vertically up or down.
- Gain/Span Error: A multiplicative error that alters the slope of the calibration curve, leading to progressive error increases toward full-scale value.

Errors Addressed by Calibration I

- Hysteresis: The difference in output readings for the same input value when approached from opposite directions (ascending vs. descending input).
- Non-Linearity: The maximum deviation of the calibration curve from a straight reference line, usually expressed as a percentage of Full-Scale Output (FSO).
- Dead Band: The range of input values for which there is no change in the instrument's output reading.
- Calibration Correction: Systematic errors identified during calibration are mathematically corrected using lookup tables, polynomial fit formulas, or manual adjustments.

Importance of Calibration in Industry I

- Ensures Safety: Critical in high-risk environments such as nuclear reactors, avionics, and medical equipment where out-of-tolerance readings cause catastrophic failures.
- Compliance with Standards: Required for adherence to global quality management systems (e.g., ISO 9001, ISO/IEC 17025).
- Process Optimization: Accurate measurements minimize raw material waste, maintain consistent product quality, and maximize throughput in chemical/refining processes.
- Economic Impact: Avoids legal disputes in trade measurements (e.g., electricity billing, custody transfer of oil and gas).

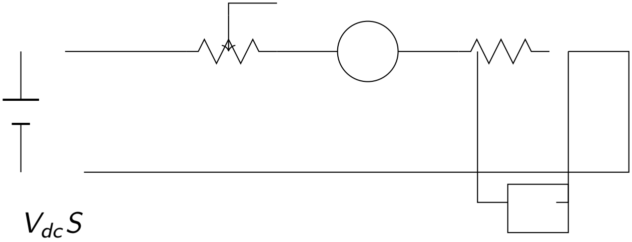
Summary and Review Questions I

- Summary: Calibration is a fundamental metrological process establishing a traceable connection between real measurements and defined SI standards.
- Review Question 1: Explain the distinction between primary, secondary, and working standards in an electrical calibration laboratory.
- Review Question 2: Differentiate between instrument calibration and instrument adjustment. Why is calibration performed first?
- Review Question 3: Sketch a typical calibration curve showing the combined effects of zero offset and span error.

Agenda I

- Calibration of DC Ammeter using Potentiometer
- Calibration of DC Voltmeter using Volt Ratio Box
- Calibration of Wattmeter using Phantom Loading
- Testing of Single-Phase Energy Meter
- Indian Standards (IS) for Meter Calibration & Limits

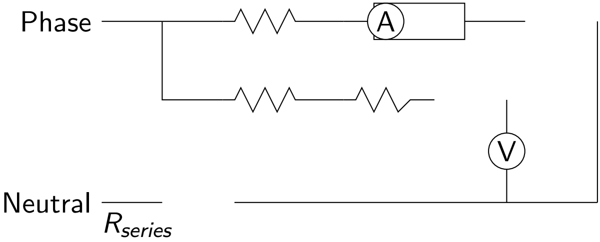
Calibration of Ammeter (Potentiometer Method) I



Calibration of Voltmeter I

- Voltmeter calibration involves comparing readings against a standard voltmeter or a DC potentiometer setup.
- Since a potentiometer can measure voltages only up to 1.5 V, a Volt Ratio Box is used as a voltage divider to scale down higher voltages.
- The Volt Ratio Box has a precisely known step-down ratio (e.g., 100:1) to keep the output voltage within the potentiometer range.
- A stable DC voltage source is adjusted via a potential divider rheostat to vary the voltage across the voltmeter under test.
- The actual voltage is calculated as: $V_{act} = V_{pot} \times K_{vr}$, where V_{pot} is the potentiometer reading and K_{vr} is the ratio multiplier.
- Percentage Error is computed as: $\% \text{ Error} = \frac{V_{meas} - V_{act}}{V_{act}} \times 100$.

Calibration of Wattmeter using Phantom Loading I



Calibration of Single-Phase Energy Meter I

- Energy meter calibration determines the percentage error in registration under different load conditions and power factors.
- Testing is usually performed against a Rotated Sub-Standard (RSS) meter or a calibrated electronic reference standard.
- Phantom loading is preferred to avoid wasting large amounts of power during high current testing.
- The current coil is connected to a low-voltage circuit, while the pressure coil is excited by the rated voltage supply.
- Calibration is carried out at standard test points: Rated Current (UPF), 50% Rated Current (UPF), 10% Rated Current (UPF), and Rated Current (0.5 lagging PF).
- Environmental parameters such as temperature and frequency are controlled as per Indian Standard limits.

Testing and Calculation of Energy Meter Error I

- The meter constant (N) defines the number of revolutions or pulses per kilowatt-hour (kWh).
- The true energy consumed during a test period of t seconds is: $E_{act} = \frac{V \cdot I \cdot \cos\theta \cdot t}{3600 \times 1000}$ kWh.
- The energy registered by the meter under test is: $E_{obs} = \frac{n}{N}$ kWh, where n is the registered revolutions or pulses.
- Percentage error is calculated as: $\%\ \text{Error} = \frac{E_{obs} - E_{act}}{E_{act}} \times 100$.
- A positive error indicates the meter runs fast; a negative error indicates it runs slow.
- Mechanical and electrical adjustments (such as lag adjustment and light load adjustment) are done to bring the error within IS limits.

Indian Standards (IS) for Meter Calibration & Limits I

Equipment	IS Standard	Accuracy Class
Analog Ammeter/Voltmeter	IS 1248 (Part 2)	Class 0.5, 1.0, 1.5
Analog Wattmeter	IS 1248 (Part 3)	Class 0.5, 1.0
Single-Phase Energy Meter	IS 13779	Class 1.0, 2.0

Calibration Curves and Error Analysis I

- A calibration curve plots Instrument Reading vs. True Value, or Correction vs. Instrument Reading.
- Correction is the mathematical negative of the error: Correction = True Value − Measured Value.
- The calibration curve is reference data used to correct intermediate readings during actual field measurements.
- Primary causes of error in meters include temperature variation, frequency fluctuation, aging of permanent magnets, and friction.
- Strict adherence to IS standards requires testing at controlled laboratory environments to eliminate ambient noise.
- Meters exceeding maximum permissible limits are adjusted or downgraded to a lower accuracy class.

Summary and Review Questions I

- Calibration is the comparison of an instrument's readings against a known reference standard under defined conditions.
- DC Ammeters and Voltmeters are calibrated using precise DC Potentiometers combined with standard resistors and Volt Ratio Boxes.
- Wattmeter calibration utilizes Phantom Loading to reduce energy waste by separating current and voltage excitation circuits.
- Energy meter calibration checks revolutions/pulses against actual energy E_{act} to verify the meter constant accuracy.
- Indian Standards (IS 1248 and IS 13779) define the technical requirements, testing procedures, and tolerance limits.
- Review Question 1: Describe the phantom loading technique. Explain why it is energetically efficient for calibration.

- Review Question 2: A 230 V, 5 A energy meter makes 194 revolutions during a 30-minute test at full load UPF. If the meter constant is 400 rev/kWh, calculate the percentage error.

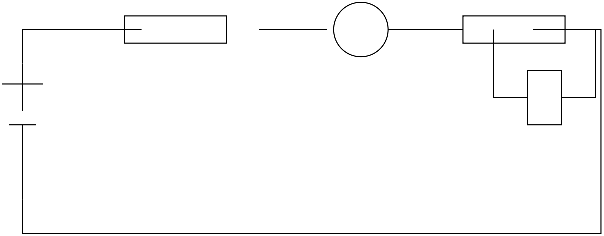
Lecture Agenda I

- Concept of Calibration and Standard Traceability
- Indian Standards (IS) for Calibration of Electrical Instruments
- Calibration of DC/AC Ammeters using Potentiometers
- Calibration of DC/AC Voltmeters using Potentiometers
- Calibration of Single-Phase Wattmeters (Direct and Phantom Loading)
- Calibration of Single-Phase Induction-Type Energy Meters
- Determination of Percentage Error in Energy Meters
- Sources of Errors and Tolerances as per IS 1248 and IS 13779

Fundamentals of Calibration & Traceability I

- Calibration is the process of comparing a measuring instrument against a standard of higher accuracy to detect, report, or eliminate errors.
- The standard used must have traceability to national standards (e.g., National Physical Laboratory, India) or international standards (SI units).
- A primary standard is compared with secondary standards, which calibrate laboratory or working standards used in industries.
- Indian Standard IS 1248 (Parts 1 to 9) governs the specifications for direct-acting indicating electrical measuring instruments.
- Calibration establishes the relationship between indicated values and known reference values, yielding a correction factor or calibration curve.

Circuit Diagram: Calibration of Ammeter I

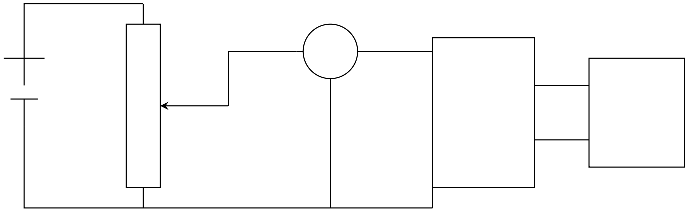


$R_h R_s$

Detailed Method: Calibration of Ammeter I

- In this circuit, a standard resistor R_s of suitable current-carrying capacity is connected in series with the ammeter under test.
- A regulating rheostat R_h controls the current flowing through the circuit from a stable DC voltage source.
- The voltage drop across the standard resistor R_s is measured precisely using a DC potentiometer (V_s).
- The true current is calculated using Ohm's Law: $I_{true} = V_s/R_s$.
- The ammeter reading ($I_{indicated}$) is compared with I_{true}, and the percentage error is computed as: % Error $= \frac{I_{indicated} - I_{true}}{I_{true}} \times 100$.
- Calibration is performed at multiple points across the full scale of the ammeter (usually at 10% increments).

Circuit Diagram: Calibration of Voltmeter I



Detailed Method: Calibration of Voltmeter I

- A potential divider (rheostat) is connected across the stable DC supply to vary the voltage from zero to the maximum value.
- The voltmeter under test is connected in parallel with the output of the potential divider.
- Since the voltmeter voltage usually exceeds the standard potentiometer range (1.5V-1.8V), a Volt Ratio Box is used.
- The Volt Ratio Box acts as a precision voltage divider with an accurate stepping-down ratio (e.g., 100:1 or 10:1).
- The stepped-down voltage fraction is measured by the DC potentiometer: $V_{pot} = V_{true}/K_{ratio}$, where K_{ratio} is the box ratio.
- The percentage error is calculated as:
  $\% \text{ Error} = \frac{V_{indicated} - V_{true}}{V_{true}} \times 100$.

Calibration of Single-Phase Wattmeter I

- Wattmeters can be calibrated using direct loading or phantom loading methods.
- Under direct loading, the instrument is subjected to full current and voltage, resulting in massive power waste in the test load.
- For high-capacity wattmeters, phantom (indirect) loading is used where pressure coil (PC) is excited by normal voltage and current coil (CC) by a low voltage source.
- In phantom loading, power required is only that needed to supply the CC copper losses and PC core/excitation losses, saving over 90% energy.
- A standard wattmeter or standard ammeter-voltmeter potentiometer setup is used to measure the true power: $P_{true} = V_{pot} \times I_{pot} \times \cos\theta$.
- Percentage error is computed as: $\% \text{ Error} = \frac{P_{indicated} - P_{true}}{P_{true}} \times 100$.

Calibration of Single-Phase Energy Meter as per IS 13779 I

Test Parameter	**Test Condition (as per IS 13779)**
Limits of Error (Full Load)	1.0 I_n (Basic Current) at Unity Powe
Limits of Error (Low Load)	0.1 I_n (Basic Current) at Unity Powe
Limits of Error (Lagging PF)	0.5 I_n to I_{max} at 0.5 Lagging Power F
Starting Current Test	Meter must start and run at 0.004 I_b
No-Load (Creep) Test	Voltage at 115% rated value, current

Mathematical Calculations and IS Compliance Summary I

- Energy meter constant K is expressed in revolutions/kWh (induction type) or pulses/kWh (static/electronic type).
- True energy consumed in t seconds is $E_{true} = \frac{P \times t}{3600 \times 1000}$ kWh, where P is true power in Watts measured by standard instruments.
- Indicated energy by induction meter: $E_{indicated} = \frac{N}{K}$ kWh, where N is the number of disc revolutions.
- Percentage Error is:
  $\%\ \text{Error} = \frac{E_{indicated} - E_{true}}{E_{true}} \times 100 = \frac{N/K - E_{true}}{E_{true}} \times 100.$
- As per IS 13779, the meter must not record any energy under no-load conditions when 110% of rated voltage is applied (Creep Test).

Mathematical Calculations and IS Compliance Summary II

- Regular calibration ensures consumer billing accuracy, minimizes distribution losses, and satisfies the legal metrology standards of India.

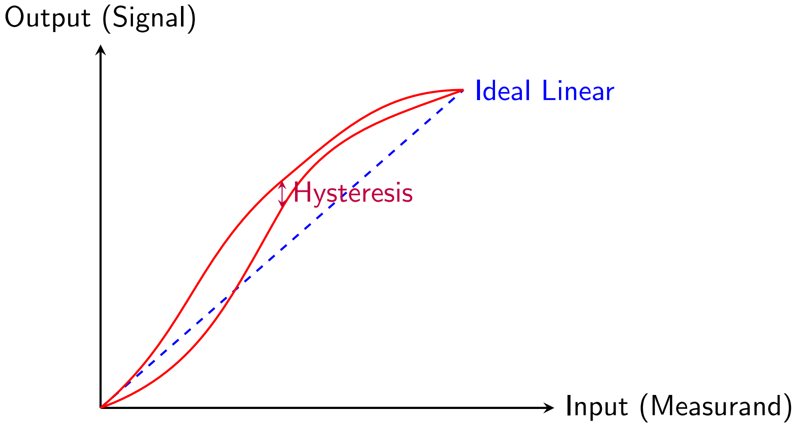
Agenda I

- Introduction to Transducers and Sensor Definitions
- Essential Static Characteristics: Linearity, Ruggedness, and Repeatability
- Dynamic Performance Criteria: Speed of Response and Fidelity
- Electrical Interface Requirements: Input/Output Impedance and Loading Effects
- Environmental and Operating Constraints
- Summary of Design & Selection Criteria

Introduction to Transducers I

- Definition: A transducer is a device that converts a physical quantity (measurand) from one energy domain to another, typically into an electrical signal (voltage, current, or impedance change).
- Distinction: While a sensor detects changes in physical quantities, a transducer performs the actual energy conversion.
- Role in Instrumentation: Transducers serve as the primary sensing elements in electrical measurement systems, forming the interface between the physical world and electronic instrumentation.
- Fundamental Selection Rule: The transducer must detect the desired physical quantity with high fidelity while remaining completely insensitive to all other environmental inputs.

Linearity and Hysteresis I



Static Characteristics: Ruggedness & Sensitivity I

- Ruggedness: The transducer must withstand overload and harsh operating conditions (vibration, shock, over-range inputs) without permanent damage or change in calibration.
- High Sensitivity: It should produce a large, detectable electrical output change for a small change in the physical input, yielding a high Signal-to-Noise Ratio (SNR).
- Resolution: The smallest increment of physical input that the transducer can detect and display as a distinct change in output.
- Hysteresis: The difference in output readings for the same input value depending on whether the input was approached from a lower or higher value; must be minimized.

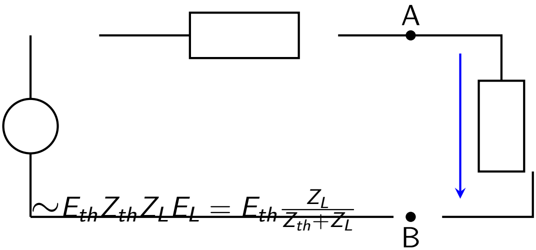
Repeatability and Stability I

- Repeatability: The capability of a transducer to reproduce output readings when the same input value is applied repeatedly under identical environmental conditions.
- Stability (Drift): The ability of the transducer to maintain its calibration and characteristics over long periods without deviation.
- Zero Drift: A shift in the output of the transducer over time when the input is zero, often caused by thermal changes or aging.
- Sensitivity Drift: Changes in the slope of the calibration curve (sensitivity) due to aging of components or temperature variations.

Key Requirements Comparison I

Requirement	Description	Desired Engine
High Sensitivity	Large output change per unit change in input	High signal-to-r (SNR)
High Linearity	Proportional relationship between input and output	Simplified calibr processing
Low Output Impedance	Small internal impedance compared to load	Minimizes loadin next stage
High Input Impedance	High load impedance presented to source	Minimizes loadi measured system
Excellent Stability	Consistent calibration over extended periods	Low drift, high r

Loading Effects and Impedance Matching I



Dynamic Performance Requirements I

- Speed of Response: The capability of a transducer to rapidly track rapid changes in the measured physical quantity.
- Dynamic Error: The difference between the true value of the quantity changing with time and the value indicated by the transducer, assuming zero static error.
- Fidelity: The degree to which a transducer can reproduce changes in the input signal without any distortion (phase or frequency distortion).
- Bandwidth: The range of frequencies over which the transducer's sensitivity remains relatively constant (typically within -3 dB).

Environmental Compatibility & Noise Rejection I

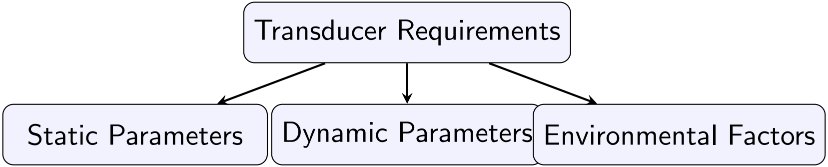
- Temperature Immunity: Minimizing the thermal coefficient of resistance/sensitivity to prevent drift across the operating temperature range.
- Electromagnetic Shielding: Guarding against electro-static and electromagnetic interference (EMI) using Faraday cages and twisted pairs.
- Corrosion Resistance: Using chemically inert materials (like stainless steel or Teflon) for parts in direct contact with corrosive media.
- Summary: Selecting a transducer requires balancing sensitivity, linearity, response speed, electrical loading, and cost against the application's environment.

Agenda I

Fundamental Concepts: What is a Transducer? I

- A transducer is a device that converts a physical quantity (non-electrical) into an electrical signal (e.g., voltage, current, frequency).
- Primary requirements ensure that the electrical representation is an accurate, noise-free, and stable reflection of the physical quantity.
- Selection of a transducer depends on both the physical quantity to be measured and the environment in which it operates.
- Key requirements are broadly divided into electrical, mechanical, and environmental constraints.

Transducer Selection Criteria Map I



Core Requirements: Ruggedness & Linearity I

- Ruggedness: The transducer must withstand mechanical strain, vibration, temperature fluctuations, and environmental hazards without failing or losing calibration.
- Linearity: The input-output relationship should be linear ($y = mx + c$) across the entire operating range to simplify signal conditioning and calibration.
- Non-linearity errors complicate subsequent processing steps and increase system computational load in digital instrumentation systems.
- High linearity ensures a constant sensitivity throughout the measurement range.

Core Requirements: Sensitivity & Resolution I

- Sensitivity: Defined as the change in output per unit change in input (dS/dx). A high sensitivity is desired to ensure detectable output changes for small input variations.
- Resolution: The smallest increment in input that produces a detectable change in the output signal.
- High sensitivity reduces the requirement for high-gain amplification stages, thereby reducing noise susceptibility.
- However, excessively high sensitivity might lead to saturation or narrow the dynamic measurement range.

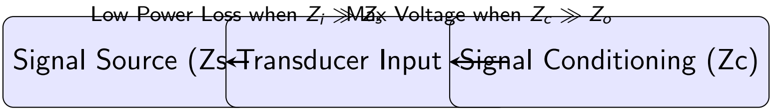
Static vs. Dynamic Performance Requirements I

Requirement Type	Key Metric	Instrumenta
Static	Linearity	Minimizes ca ity and signa
Static	Sensitivity	Determines plitude per put.
Static	Repeatability	Assures iden peated ident
Dynamic	Speed of Response	Evaluates ho tracks transi
Dynamic	Fidelity	Quantifies h

Impedance Matching and Loading Effects I

- Input Impedance (Zi): Should be very high to minimize loading effects on the physical system under measurement.
- Output Impedance (Zo): Should be very low to facilitate maximum power transfer or voltage transfer to the subsequent signal conditioning unit.
- Loading Effect: A transducer with low input impedance draws significant power from the source, altering the measured quantity itself.
- For voltage-measuring transducers, Zi must satisfy: Zi ¿¿ Zs, where Zs is the source impedance.

Transducer Loading Effect Diagram I



Summary of Basic Transducer Requirements I

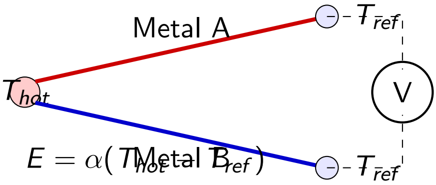
- Accuracy: The transducer output must represent the true value of the measured variable with minimal systematic or random error.
- Environmental Stability: Output must remain invariant to changes in temperature, pressure, humidity, or electromagnetic interference.
- Cost and Availability: The selection must align with economic constraints without compromising critical safety or precision parameters.
- Calibration and Maintenance: Simple calibration procedures and low maintenance are desirable for long-term industrial deployments.

Agenda I

- Classification based on Transduction Phenomenon (Thermoelectric, Photoelectric, Piezoelectric, etc.)
- Classification by Electrical Principle Involved (Resistive, Inductive, Capacitive)
- Classification by Application: Active vs. Passive, and Primary vs. Secondary Transducers
- Classification by Signal Nature: Analog vs. Digital Transducers

Classification by Transduction Phenomenon I

- Transduction phenomenon refers to the physical or chemical process used to convert a non-electrical quantity to an electrical signal.
- Thermoelectric: Uses temperature difference to generate voltage (e.g., Thermocouples via Seebeck Effect).
- Photoelectric: Converts light intensity to electrical variations (e.g., Photovoltaic, Photoemissive, Photoconductive cells).
- Piezoelectric: Mechanical strain generates electric charge in asymmetrical crystalline materials (e.g., Quartz, Rochelle salt, BaTiO3).
- Magnetostrictive: Changes in magnetic properties under mechanical stress, or dimensional changes under magnetic fields.



$$E = \alpha(T_{hot} - T_{ref})$$

Comparison of Electrical Transduction Principles I

Electrical Principle	**Variable Parameter**	**Typical Applications**
Resistive	Resistance ($R = \rho L/A$)	Strain gauges, RTDs, tentiometers
Inductive	Self/Mutual Inductance	LVDT, Synchros
Capacitive	Capacitance ($C = \epsilon A/d$)	Condenser mic, Pre sensor

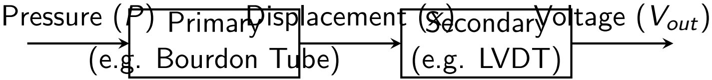
Active vs. Passive Transducers I

- Active (Self-Generating) Transducers: Develop their own electrical output without requiring an external power source.
- Energy for the output signal is drawn directly from the physical quantity being measured.
- Examples of Active: Piezoelectric crystals (charge), Thermocouples (emf), Photovoltaic cells (voltage).
- Passive (Externally Power-Driven) Transducers: Require an external electrical power source to operate.
- They produce a change in an electrical parameter (R, L, or C) which is then measured using an external source.
- Examples of Passive: LVDT, Strain Gauges, Resistance Thermometers (RTD), Capacitive thickness sensors.

Analog vs. Digital Transducers I

- Analog Transducers: Convert the physical input quantity into a continuous-time analog output signal (e.g., voltage, current, or phase).
- The output signal is a continuous function of the input quantity.
- Examples: LVDT, Thermocouple, strain gauge.
- Digital Transducers: Convert the input quantity into a discrete-time electrical output, usually in the form of pulses or coded digital signals.
- They have high accuracy, noise immunity, and are directly compatible with microprocessors.
- Examples: Shaft encoders (optical or magnetic), turbine flow meters (producing frequency output), digital tachometers.

Primary vs. Secondary Transducers I



Transduction Principles & Transducers Classification I

- Classification by Output Formats: Analog, Digital, and Pulse-frequency modulated.
- Classification by Physical Quantity to be Measured: Temperature, Pressure, Displacement, Velocity, Acceleration, Force, Torque, Flow.
- Classification by Mode of Operation: Deflection type (e.g., Spring balance) vs. Null-balance type (e.g., Potentiometer circuit).
- Self-generating vs. Power-required: Active transducers (piezo, pyro, thermo) vs. Passive transducers (resistance, inductance, capacitance).

Summary and Key Takeaways I

- Transducer classification is multi-faceted, aligning with application demands, signal types, and physical laws.
- Transduction phenomenon (e.g., Seebeck, Piezoelectric, Photoelectric) dictates the energy conversion mechanism.
- Electrical principle (resistive, capacitive, inductive) determines the signal conditioning circuitry required.
- Choosing between Active and Passive, or Analog and Digital, depends on power constraints, distance to signal processing, and system noise levels.
- Primary and secondary transducer combinations (like Bourdon tube + LVDT) are common for complex mechanical-to-electrical conversions.

Lecture Agenda I

- 1. Transduction Principles of Resistive Sensors
- 2. Potentiometric Displacement Transducers & Loading Effects
- 3. Resistive Strain Gauges: Working Theory & Equations
- 4. Construction of Metal Foil Strain Gauges
- 5. Resistance Temperature Detectors (RTDs) & Pt100 Characteristics
- 6. Semiconductor Thermistors (NTC & PTC Operating Principles)
- 7. Signal Conditioning: Wheatstone Bridge Circuit Analysis
- 8. Performance Comparison Table
- 9. Practical Application Notes & Summary

Fundamental Operating Principles I

- Resistive transducers convert a physical variable (measurand) into a corresponding change in electrical resistance.
- The resistance of a homogeneous conductor of length L, cross-sectional area A, and resistivity ρ is given by: $R = \rho \frac{L}{A}$.
- Transduction is achieved by varying one or more of these parameters using the physical input:
- 1. Dimensional Variation: Displacement changes the active length L (e.g., sliding contact in potentiometers).
- 2. Piezoresistive Variation: Mechanical strain changes dimensions (L, A) and alters the material's bulk resistivity ρ.
- 3. Temperature Variation: Heat changes resistivity ρ due to altered electron-phonon scattering inside the lattice.

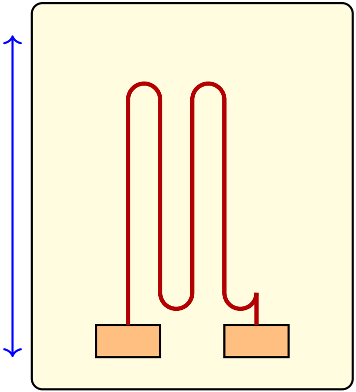
Potentiometric Transducers & Loading Error I

- A potentiometer consists of a resistive track and a sliding wiper moved by the displacement to be measured.
- For a linear stroke length L_t and input voltage E_i, the ideal open-circuit output is: $V_o = E_i \frac{x_i}{L_t}$ where x_i is wiper position.
- Under load conditions (meter resistance R_m connected across output R_x), the response becomes non-linear.
- The actual output voltage is: $V_o = E_i \frac{k}{1+k(1-k)(R_p/R_m)}$, where $k = x_i/L_t$ and R_p is total potentiometer resistance.
- To keep the loading error below 1%, the load resistance ratio R_m/R_p must be at least 15 or higher.
- Loading error is maximum when the wiper is at approximately 67% of its full-scale displacement ($k = 0.67$).

Theory of Strain Gauges I

- Resistive strain gauges measure local mechanical strain. Tension causes elongation ($L \to L + dL$) and narrowing ($A \to A - dA$).
- Taking the natural logarithm and differentiating $R = \rho L/A$, we get the fractional change: $dR/R = dL/L - dA/A + d\rho/\rho$.
- Using Poisson's ratio $u = -(dA/A)/(2dL/L)$, this simplifies to: $dR/R = (1 + 2u)dL/L + d\rho/\rho$.
- The Gauge Factor (G) represents the sensor's sensitivity: $G = \frac{dR/R}{dL/L} = 1 + 2u + \frac{d\rho/\rho}{\epsilon}$, where $\epsilon = dL/L$.
- For metallic foil gauges, piezoresistive term $\frac{d\rho/\rho}{\epsilon} \approx 0$, yielding $G \approx 2.0$ (primarily dimensional changes).
- For semiconductor gauges, piezoresistive effect is dominant, yielding high Gauge Factors ($G \approx 100$ to 150).

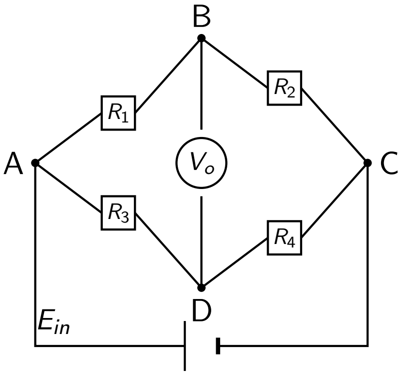
Bonded Metal Foil Strain Gauge Construction I



Temperature Sensors: RTDs & Thermistors I

- RTDs utilize pure metals (e.g., Platinum, Copper) with a highly stable Positive Temperature Coefficient (PTC).
- The standard Pt100 RTD has $100\,\Omega$ resistance at $0°C$ and follows the linear approximation: $R_T = R_0(1 + \alpha T)$.
- Pt100 temperature range is very wide ($-200°C$ to $+850°C$) with excellent stability and precision.
- Thermistors are semiconductor-based devices, commonly showing a Negative Temperature Coefficient (NTC).
- The NTC resistance-temperature relation is highly non-linear: $R_T = R_0 \exp[\beta(1/T - 1/T_0)]$, where β is 3000K-5000K.
- NTCs provide very high sensitivity ($-4\%/°C$) and rapid response, but over a narrow range ($-100°C$ to $+300°C$).

Wheatstone Bridge Signal Conditioning I



Transducer	Variable	Sensitivity	Typical Ra
Potentiometer	Length (L)	High	$100\,\Omega$ to 10
Strain Gauge	Area/Length (A, L)	$G \approx 2$ to 150	$120\,\Omega$ to 10
RTD	Resistivity (ρ)	$0.385\,\Omega/^\circ$C	$100\,\Omega$ at 0°
Thermistor	Resistivity (ρ)	Up to $-4\%/^\circ$C	$1\,k\Omega$ to 100

Practical Considerations & Summary I

- Select resistive transducers based on required linearity, range, temperature stability, and response speed.
- Wheatstone bridges are essential for detecting the minute fractional resistance modifications typical of strain gauges.
- Bridge temperature compensation is achieved by mounting an inactive 'dummy gauge' in the adjacent arm of the bridge.
- Self-heating error (I^2R power dissipation) must be minimized in RTDs and Thermistors by maintaining low excitation currents.
- Lead-wire resistance in RTDs is compensated for using 3-wire or 4-wire configuration measurements.

Lecture Agenda I

- Introduction to Inductive Transducers and Principle of Self & Mutual Inductance
- Linear Variable Differential Transformer (LVDT): Construction & Working Principle
- LVDT Mathematical Model & Output Characteristics (Residual Voltage)
- LVDT Schematic Diagram (TikZ Circuit Diagram)
- LVDT Phase Relations, Advantages, and Disadvantages
- Rotary Variable Differential Transformer (RVDT): Construction and Operation
- RVDT Diagram (TikZ Diagram)
- Key Comparison: LVDT vs. RVDT (LaTeX Table)
- Signal Conditioning Circuits for Differential Transformers (Phase Sensitive Detection)
- Applications, Practical Selection Criteria, and Summary

Basic Principle of Inductive Transducers I

- Inductive transducers operate on the principle of variation of inductance caused by a change in the physical quantity being measured (e.g., displacement).
- The self-inductance L of a coil is given by L = (N$\hat{2}$ * \{}mu * A) / l, where N is the number of turns, \{}mu is the permeability of the core, A is the cross-sectional area of the magnetic path, and l is the length of the magnetic path.
- Inductance can be varied by three main methods: variation of self-inductance of a single coil, variation of mutual inductance between coils, or variation of eddy current loss.
- Differential arrangement (mutual inductance variation) is widely preferred to improve sensitivity, linearity, and reduce common-mode errors like temperature drift.

Basic Principle of Inductive Transducers II

- LVDT and RVDT are passive, mutual-induction transducers that translate linear and angular displacement, respectively, into electrical signals.

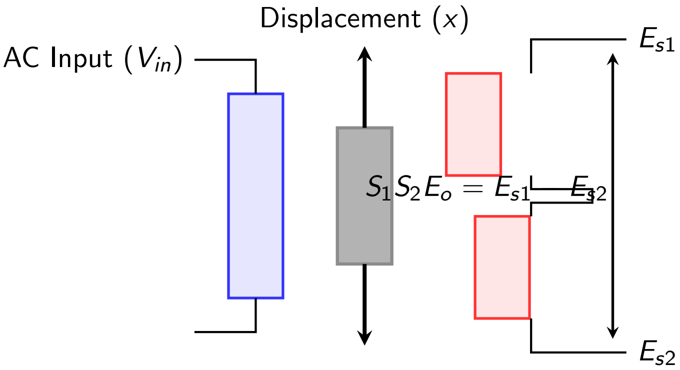
Linear Variable Differential Transformer (LVDT) I

- Construction: Consists of a single primary winding (P) energized by an AC source, and two identical secondary windings (S1 and S2) wound symmetrically on either side of the primary.
- The two secondary windings are connected in series-opposition (phase opposition) so that the net output voltage is the difference of their individual induced voltages: Eo = Es1 - Es2.
- A movable high-permeability nickel-iron ferromagnetic core is positioned inside the hollow coil assembly and is mechanically coupled to the target body whose displacement is to be measured.
- At the Null Position: The core is exactly centered, linking equal magnetic flux to S1 and S2, resulting in Es1 = Es2 and an ideal net output voltage Eo = 0 V.

Linear Variable Differential Transformer (LVDT) II

- Displacement from Null: Moving the core toward S1 increases the mutual inductance of S1 and decreases that of S2 (Es1 ¿ Es2, Eo is in phase with primary). Moving toward S2 does the opposite (Es2 ¿ Es1, Eo is 180 degrees out of phase).

LVDT Schematic & Circuit Diagram I



LVDT Characteristics & Residual Voltage I

- Differential Output Voltage: The magnitude of the output voltage is given by —Eo— = K * x, where K is the sensitivity (mV/V/mm) and x is the displacement from the null position.
- Phase Shift: When the core moves in one direction, Eo is in phase with the excitation voltage. When moved in the opposite direction, the phase of Eo shifts by 180 degrees.
- Residual Voltage: At the null position, the net output voltage is not exactly zero. A small voltage called 'residual voltage' (typically ¡ 1% of full scale) remains due to line frequency harmonics, stray capacitances, magnetic asymmetries, and core impurities.
- Linear Range: The output is linear over a specified displacement range, beyond which the magnetic flux leakage increases and sensitivity decreases, causing non-linearity.

LVDT Characteristics & Residual Voltage II

- Sensitivity: Defined as output voltage per unit displacement per unit primary excitation voltage (units typically in mV/V/mm or mV/V/mil).

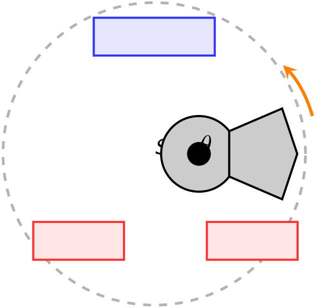
Rotary Variable Differential Transformer (RVDT) I

- Overview: RVDT is the angular counterpart of LVDT, designed to measure angular displacement (rotation) rather than linear displacement.
- Construction: Consists of one primary winding, two secondary windings connected in phase-opposition, and a specially shaped cam-like or cardioid-shaped ferromagnetic core.
- Core Rotation: The core is mounted on a shaft and rotates within the coil assembly. The profile of the core is designed such that the change in mutual inductance is linearly proportional to the rotation angle \{}theta.
- Angular Range: Typically exhibits a narrower linear range compared to LVDT, generally within \{}pm 40 degrees (often highly linear up to \{}pm 40\{}degree, and up to \{}pm 60\{}degree with specialized designs).

Rotary Variable Differential Transformer (RVDT) II

- Operating Principle: When the shaft is at its null position, the coupling to both secondaries is equal (Es1 = Es2, Eo = 0). Clockwise or counterclockwise rotation increases coupling to one secondary while decreasing it to the other.

RVDT Schematic & Core Assembly I



Comparison: LVDT vs. RVDT I

Parameter	**LVDT**	**RVDT**
Measurement Type	Linear displacement	Angular displa
Range	$\pm 100\ \mu mto \pm 25$ cm	Typically ± 40
Core Shape	Cylindrical rod (plunger)	Cam/cardioid
Sensitivity	High (typically 1–10 mV/V/mm)	Lower re LVDT (typ mV/V/degree
Linearity	Highly linear (up to $\pm 0.1\%$)	Linear over sm to $\pm 0.5\%$)
Applications	Actuator feedback, thickness, valves	Flight contr throttle pedals

Signal Conditioning & Phase Sensitive Demodulation I

- AC Excitation: Since LVDT and RVDT are passive inductive sensors, they require an AC carrier voltage (typically 1 to 10 V RMS, 50 Hz to 20 kHz) to energize the primary.
- Phase-Sensitive Demodulator (PSD): An amplitude demodulator that uses the primary excitation as a phase reference. It extracts both the magnitude (displacement distance) and polarity/direction (phase shift) from the AC output.
- Operation: The PSD multiplies the output AC signal by a reference square wave in phase with the primary excitation, followed by a low-pass filter to remove carrier frequency ripple.

Signal Conditioning & Phase Sensitive Demodulation II

- DC Output: The resulting signal is a smooth DC voltage whose magnitude is proportional to displacement, and polarity (positive or negative) indicates the direction of movement relative to null.
- Practical Considerations: Shielding is crucial to prevent electromagnetic interference (EMI); temperature compensation is required to mitigate changes in winding resistance and core permeability.

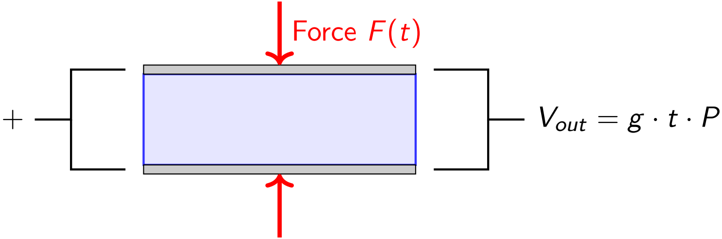
Lecture Agenda I

- Capacitive Transducers: Operating principles, change of distance, area, and dielectric.
- Piezoelectric Transducers: Basic theory, charge generation, materials, and equivalent circuit models.
- Strain Gauge Transducers: Gauge factor derivation, bonded vs. unbonded configurations, and temperature compensation.
- Temperature Transducers: In-depth analysis of Thermocouples, RTDs, and Thermistors.

Capacitive Transducers: Principles and Sensitivity I

- Operating Principle: Capacitive transducers operate on the formula C = (\{}epsilon_0 \{}epsilon_r A) / d. Sensing is achieved by varying plate separation (d), active plate area (A), or the dielectric constant (\{}epsilon_r).
- Displacement Sensitivity (Variable Separation): The change in capacitance is non-linear relative to d: C = k/d, leading to dC/dd = -k/d$\hat{2}$. This configuration is highly sensitive for micro-displacements.
- Displacement Sensitivity (Variable Area): The change is linear: C = k_1 \{}cdot x (where x is displacement), making it ideal for larger linear or angular displacement measurements.
- Dielectric Variation: Used for liquid level measurement and thickness sensing, where the effective dielectric constant changes as the target material enters the inter-plate gap.

Piezoelectric Transducers: Working Model I



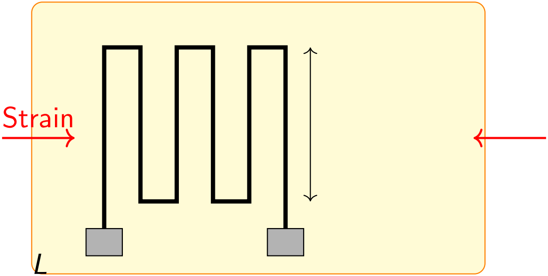
Strain Gauge Transducers: Principles I

- Piezoresistive Effect: When a conductor is subjected to mechanical strain, its electrical resistance changes due to physical dimensional changes and changes in material resistivity.
- Gauge Factor Derivation: Starting with R = \{}rho L / A, taking log derivatives yields dR/R = dL/L - dA/A + d\{}rho/\{}rho. Since dA/A = -2 u \{}cdot dL/L (where u is Poisson's ratio), Gauge Factor G = (dR/R) / (dL/L) = 1 + 2 u + (d\{}rho/\{}rho) / (dL/L).
- Bonded Strain Gauges: Consist of a thin metallic foil grid (typically Constantan) cemented onto a flexible backing material. The gauge is directly bonded to the test specimen using adhesive, transferring the surface strain.

Strain Gauge Transducers: Principles II

- Unbonded Strain Gauges: Comprise a grid of fine wires tensioned between fixed and movable anchor pins. Applied displacement changes the tension (and thus resistance) without adhesive bonding, providing high linearity and low hysteresis.

Bonded Foil Strain Gauge Structure I



Temperature Sensors Comparison Matrix I

Parameter	RTD	Thermistor	T
Principle	Positive Temp Coefficient of Resistance	Non-linear NTC or PTC resistance change	Se m
Material	Pure metals (Platinum, Nickel)	Metal oxides (Manganese, Cobalt)	D ti
Range	$-200°C$ to $+850°C$	$-100°C$ to $+300°C$	−
Sensitivity	Moderate (0.4%/°C)	Very High (4%/°C to 6%/°C)	Lo
Linearity	Highly Linear	Highly Non-linear (Exponential)	M li

Thermocouples: Seebeck Effect and Compensation I

- Thermoelectric Principles: The Seebeck effect occurs when two dissimilar metal wires are joined at both ends, and a temperature difference exists between the junctions, generating a thermoelectric voltage.
- Seebeck Voltage Equation: The EMF produced is given by E = \{}alpha(T_1 - T_2) + \{}beta(T_12̂ - T_22̂) + \{}dots, where T_1 is the sensing (hot) junction and T_2 is the reference (cold) junction temperature.
- Reference Junction Compensation: Because thermocouples measure the differential temperature (T_1 - T_2), the reference junction must either be kept at 0 degrees Celsius or compensated using a software or hardware compensation circuit.

- Common Thermocouple Types: Type K (Chromel/Alumel) is most common for general use, Type J (Iron/Constantan) offers high sensitivity but oxidizes easily, and Type S (Platinum/Rhodium) is used for high-temperature calibration.

Resistance Temperature Detectors (RTD) I

- Principle of Resistance Change: Pure metals show a predictable positive temperature coefficient (PTC) of resistance. The resistance increases as thermal agitation of the lattice increases electron scattering.
- Callendar-Van Dusen Equation: The resistance-temperature characteristic is represented as R_T = R_0[1 + A\{}cdot T + B\{}cdot T2̂ + C\{}cdot(T-100)\{}cdot T3̂] (where C is used only for sub-zero temperatures). For positive temperatures, the relationship is highly linear.
- Pt100 Standard: Platinum is the material of choice because of its high chemical stability, resistance to oxidation, and wide temperature range (-200 to +850 degrees Celsius). The standard Pt100 has a resistance of 100 Ohms at 0 degrees Celsius.

Resistance Temperature Detectors (RTD) II

- Lead Wire Compensation: Since RTD resistance changes are relatively small, lead-wire resistance introduces significant errors. This is mitigated using 3-wire and 4-wire Wheatstone bridge connections to isolate the sensor element.

Thermistors: Characteristics and Self-Heating I

- Material Characteristics: Thermistors are ceramic semiconductors (sintered oxides of Mn, Ni, Co, Cu) with high negative temperature coefficients (NTC), where resistance decreases exponentially as thermal energy promotes electrons to the conduction band.
- Exponential Model: The resistance-temperature relation is given by R(T) = R(T_0) \{}cdot \{}exp(\{}beta \{}cdot (1/T - 1/T_0)), where T and T_0 are in Kelvin, and \{}beta is the material constant (typically 3000 to 5000 K).
- PTC Thermistors: Positive Temperature Coefficient thermistors exhibit a sudden increase in resistance at their switching temperature (Curie point), making them useful as self-resetting overcurrent fuses or heaters.

Thermistors: Characteristics and Self-Heating II

- Self-Heating Effect: Because thermistors are resistive, the measurement current (I) generates internal heat ($I\hat{2}$ R). If this power is high, the thermistor's temperature rises above the ambient fluid temperature, introducing a measurement error.

Lecture Agenda I

- Capacitive Transducers: Operating Principles & Equations
- Piezoelectric Transducers: Piezoelectric Effect & Equivalent Circuit
- Strain Gauge Transducers: Gauge Factor Derivation & Types (Bonded/Unbonded)
- Strain Gauge Instrumentation: Wheatstone Bridge Configurations
- Temperature Transducers: Principles of Thermocouples
- Temperature Transducers: RTD & Thermistor Working and Comparison

Capacitive Transducers: Operating Principles I

$C = \frac{\epsilon_0 \epsilon_r A}{d}$;

Piezoelectric Transducers: Principles and Equivalent Circuit I

- Piezoelectric Effect: Dynamic generation of an electric charge (q) across specific crystalline materials when subjected to mechanical stress. The generated charge is directly proportional to the applied force: $q = d \cdot F$, where d is the charge sensitivity coefficient (C/N).
- Key Materials: Quartz (natural, highly stable, low leakage), Barium Titanate ($BaTiO_3$, ferroelectric ceramic, high sensitivity), Lead Zirconate Titanate (PZT, high coupling coefficient), and PVDF (flexible polymer).
- Equivalent Circuit: Modeled as a charge source in parallel with internal leakage resistance ($R_p \approx 10^{12}\ \Omega$) and internal electrode capacitance ($C_p \approx 100\ pF$ to $1\ nF$).

Piezoelectric Transducers: Principles and Equivalent Circuit II

- High-Impedance Amplification: Requires high input impedance signal conditioners (charge amplifiers or electrometers) to prevent rapid decay of the charge. The system behaves as a high-pass filter with time constant $\tau = R_p C_p$.
- Frequency Response: Excellent high-frequency response up to hundreds of kHz, making them ideal for dynamic measurements (vibrations, shocks, pressure waves) but unusable for static or DC measurements.

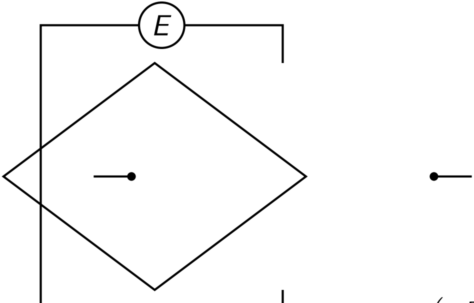
Strain Gauge Transducers: Theory and Gauge Factor I

- Piezoresistive Effect: The fundamental operating principle where mechanical strain causes a proportional change in the electrical resistance of a conductor: $R = \rho L/A$.
- Gauge Factor (G_f) Derivation: Defined as $G_f = \frac{\Delta R/R}{\Delta L/L}$. Differentiating the resistance formula yields: $G_f = 1 + 2u + \frac{\Delta\rho/\rho}{\epsilon}$, where u is Poisson's ratio ($-\epsilon_{transverse}/\epsilon_{longitudinal}$) and ϵ is strain.
- Dimensional Contribution ($1 + 2u$): Accounts for physical deformation of the wire (change in length and reduction in cross-sectional area). For most metals, $u \approx 0.3$, making the dimensional factor around 1.6.

Strain Gauge Transducers: Theory and Gauge Factor II

- Piezoresistive Contribution ($\frac{\Delta\rho/\rho}{\epsilon}$): Represents the change in resistivity due to mechanical strain. Highly dominant in semiconductor gauges (giving G_f values from 100 to 200), but negligible in metal gauges ($G_f \approx 2.0$).
- Temperature Compensation: Necessary to counter thermal expansion and temperature-induced resistivity drift. Often accomplished using a matching dummy gauge in an adjacent arm of the measuring bridge circuit.

Strain Gauge Instrumentation: Wheatstone Bridge Circuit I



$R_2 R_g R_1 R_4 V_1 V_2 V_{out} = V_2 - V_1 = E \left(\frac{R_g}{R_2+R_g} - \frac{R}{R_1+} \right.$

Bonded vs. Unbonded Strain Gauge Transducers I

- Bonded Strain Gauges: Formed by a thin metallic grid (foil or wire, thickness 3 to 5 μm) mounted on a carrier base (epoxy/polyimide) and cemented directly onto the test specimen. Strain is transmitted through the adhesive layer.
- Bonded Characteristics: Offers high mechanical ruggedness, excellent heat dissipation, and low sensitivity to transverse strain. Hysteresis and creep in the adhesive under cyclical stress are the main limitations.
- Unbonded Strain Gauges: Consists of fine resistance wires (platinum-tungsten alloy, diameter ≈ 25 μm) stretched between insulated posts mounted on a fixed outer frame and a movable inner armature.

Bonded vs. Unbonded Strain Gauge Transducers II

- Unbonded Characteristics: Motion of the armature alters wire tension, increasing resistance in one pair while decreasing it in the other. It features zero adhesive hysteresis, high sensitivity, but is highly fragile and vulnerable to vibration.
- Primary Applications: Bonded gauges are the industry standard for load cells, pressure sensors, and structural stress analysis. Unbonded gauges are historically used in specialized low-displacement accelerometers and medical pressure sensors.

Thermocouples: Theory and Junction Compensation I

- Seebeck Effect: The physical phenomenon where a temperature gradient across two dissimilar conductors generates an electromotive force (EMF): $E_{out} = \alpha(T_1 - T_2) + \beta(T_1^2 - T_2^2)$, where T_1 is the hot junction and T_2 is the cold junction.
- Hot and Cold Junctions: The measuring (hot) junction is placed at the measurement target. The reference (cold) junction is kept at a known reference temperature. The measured voltage is proportional to the temperature difference.
- Cold Junction Compensation (CJC): To determine the absolute temperature of the hot junction, the cold junction temperature must be monitored. Modern systems measure this reference temperature using an RTD or thermistor and add the corresponding EMF electronically.

Thermocouples: Theory and Junction Compensation II

- Standard Thermocouple Types: Type K (Chromel-Alumel, -200°C to $+1250^\circ$C, most common and linear), Type J (Iron-Constantan, up to $+750^\circ$C, cheaper but vulnerable to oxidation), Type S (Platinum-Rhodium, up to $+1600^\circ$C, highly stable, used for calibration).
- Key Engineering Trade-offs: Self-powered (active), highly rugged, fast thermal response, and wide temperature range. However, they exhibit very low sensitivity (10 to 60 μV/$^\circ$C), susceptibility to electromagnetic noise, and non-linear outputs.

Resistance Temperature Detector (RTD) and Thermistor I

- RTD Working Principle: Utilizes the positive temperature coefficient (PTC) of pure metals (usually Platinum, Pt100) where resistance increases linearly with temperature: $R_T = R_0(1 + AT + BT^2)$. A Pt100 RTD has 100 Ω resistance at 0°C.
- RTD Characteristics: Highly linear over a wide temperature range (-200°C to $+850$°C), extremely stable over time, and highly accurate. The primary disadvantage is self-heating error caused by excitation current (I^2R dissipation).
- RTD Wiring Configurations: 3-wire and 4-wire Wheatstone bridge configurations are mandatory to cancel the resistance of the lead wires (R_{lead}), preventing measurement bias in long industrial runs.

Resistance Temperature Detector (RTD) and Thermistor II

- Thermistor Working Principle: Composed of semiconductor metal oxides (manganese, nickel, cobalt). Usually exhibits a highly non-linear, Negative Temperature Coefficient (NTC), where resistance drops exponentially as temperature increases.
- Steinhart-Hart Equation: Accurately models NTC thermistors: $\frac{1}{T} = A + B\ln(R) + C[\ln(R)]^3$. Thermistors have extremely high sensitivity (up to $5\%/^\circ$C) but a narrow temperature range (-100°C to $+300^\circ$C) and severe non-linearity.

Comparison of Electrical Transducers I

Transducer	Type	Parameter	Working Principle	K
Capacitive	Passive	Displacement	Change in capacitance ($C = \epsilon A/d$)	H i f
Piezoelectric	Active	Force / Shock	Charge generation ($q = d \cdot F$)	D r s
Strain Gauge	Passive	Mechanical Strain	Change in resistance ($R = \rho L/A$)	C 2
Thermocouple	Active	Temperature	Seebeck Effect ($V = \alpha \Delta T$)	S t
RTD	Passive	Temperature	Change in metal resistance ($R \propto T$)	H l
Thermistor	Passive	Temperature	Change in semiconductor resistance	E s

Agenda I

Overview of Selection Criteria I

- Selecting the right transducer is the most critical decision in designing an instrumentation system, directly impacting accuracy and cost.
- The selection process evaluates three primary domains: electrical performance, physical interface, and environmental durability.
- A mismatch between transducer characteristics and the measured environment leads to signal degradation, noise, or early component failure.
- Engineering constraints require trade-offs between precision, speed, robustness, and cost-effectiveness.

Input Characteristics and Loading Effects I

- Type of Measurand: Must align with the primary physical parameter (e.g., pressure, temperature, acceleration, flow rate).
- Span and Operating Range: The sensor must operate within its linear range, but survive extreme transient overloads.
- Sensitivity: High sensitivity produces large electrical outputs, improving the Signal-to-Noise Ratio (SNR) for weak inputs.
- Loading Effect: The physical insertion of the transducer must not draw significant energy from, or modify, the measured system.

Transducer Loading Model I

(Source V_s,
Impedance Z_s); [thick, fill=green!5] (6,0) rectangle (9,2);
ode at (7.5,1) [align=center] Signal Conditioner
(Impedance Z_{in}); [thick, -¿] (3,1.5) – node[above] V_{in} (6,1.5);
[thick, ¡-] (3,0.5) – node[below] Ground (6,0.5);
ode at (4.5,-0.8) [align=center] $V_{in} = V_s \frac{Z_{in}}{Z_s+Z_{in}}$

Rule: $Z_{in} \gg Z_s$;

Transfer & Static Characteristics I

- Linearity: Represents the maximum deviation of the calibration curve from a straight line; simplifies scaling.
- Hysteresis: The variance in output values when the input is swept upwards versus swept downwards; indicates friction or magnetic lag.
- Repeatability & Precision: The sensor's ability to consistently reproduce identical outputs for a static input over time.
- Resolution & Threshold: The smallest change in input that causes a measurable change in output; limits the system's absolute precision.

Comparison of Selection Criteria I

Category	Key Selection Parameters	Design Cons
Input	Range, Sensitivity, Loading effect, Bandwidth	Match phys without signa
Transfer	Linearity, Hysteresis, Repeatability, Resolution	Controls meas racy and calib
Environmental	Temperature limit, Vibration, EMI resistance	Ensures long-t in harsh envir
Electrical	Output impedance, Signal level, Power requirement	Simplifies in standard AD systems.

Environmental & Operating Constraints I

- Operating Temperature: Ambient temperature changes cause zero-drift and sensitivity-drift, requiring compensation.
- Ingress Protection (IP Rating): Enclosure must protect internal circuitry against dust, moisture, and corrosive chemicals.
- Vibration & Shock: Industrial environments subject transducers to mechanical stress; requires robust mounting and ruggedized housings.
- Electromagnetic Interference (EMI): Shielding and differential signal routing protect low-level sensor signals from electrical noise.
- Power Constraints: Remote or hazardous locations demand low-power consumption or intrinsically safe designs.

(Pressure, Temp, Flow);
ode (specs) [draw, rectangle, below of=start, fill=green!10, text width=5cm, align=center] Analyze System Constraints (Accuracy, Span, Loading);
ode (env) [draw, rectangle, below of=specs, fill=yellow!10, text width=5cm, align=center] Evaluate Operating Environment (Temp, Ingress, Vibration);
ode (match) [draw, rectangle, below of=env, fill=orange!10, text width=5cm, align=center] Match Electrical Output (4-20mA, RS-485, 0-10V);
ode (final) [draw, rectangle, rounded corners, below of=match, fill=red!10, text width=5cm, align=center] Final Transducer Selection;
[-¿, thick] (start) – (specs); [-¿, thick] (specs) – (env); [-¿, thick] (env) – (match); [-¿, thick] (match) – (final);

Conclusion & Summary I

- Transducer selection requires a comprehensive analysis of the physical, electrical, and environmental interfaces.
- The transducer must be treated as part of a complete measurement chain, matching it to the downstream signal conditioning.
- Avoid over-specifying accuracy or response speed, as this unnecessarily inflates project budgets and system complexity.
- Standardized industrial outputs (like 4-20mA current loop or digital Modbus) should be preferred for long-distance transmission.

Lecture Agenda I

- Overview of Non-Electrical Quantity Measurement Systems
- Displacement Measurement using Linear Variable Differential Transformers (LVDT)
- Pressure Transduction with Strain Gauges and Wheatstone Bridge Circuits
- Temperature Sensing via RTDs, Thermistors, and Thermocouples
- Electromagnetic Flow Measurement and Faraday's Law of Induction
- System Integration and Signal Conditioning Challenges

Transducer Comparison Matrix I

Physical Quantity	Transducer Type	Signal Range
Displacement	LVDT	0.1 mm to 500 m
Pressure	Piezoresistive Strain Gauge	10 kPa to 100 M
Temperature	Platinum RTD (PT100)	-200°C to 850°C
Temperature	K-Type Thermocouple	-200°C to 1250°
Flow Velocity	Electromagnetic Flowmeter	0.1 m/s to 10 m

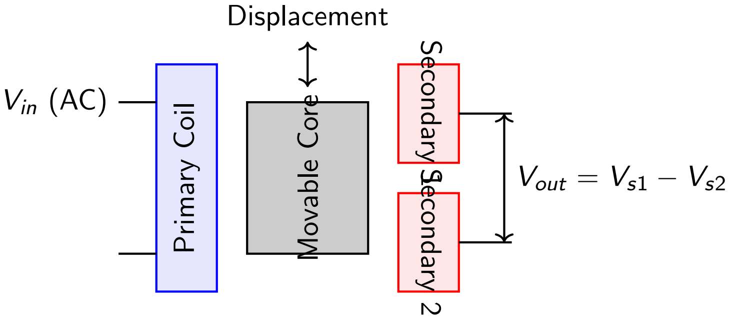
Linear Variable Differential Transformer (LVDT) I

- Operating Principle: Employs variable mutual inductance to convert linear displacement of a ferromagnetic core into a proportional AC voltage.
- Physical Structure: Comprises one central primary coil excited by an AC voltage (typically 1-10 kHz) and two identical secondary coils wound symmetrically.
- Differential Output: Secondaries are connected in a series-opposing configuration, meaning the net output voltage is the vector difference: V_out = V_s1 - V_s2.
- Null Position: At the mechanical center, the magnetic flux linking both secondary windings is equal, resulting in V_s1 = V_s2 and a net output voltage of zero.
- Phase Sensitivity: As the core moves from the null position, the phase of V_out changes by 180 degrees depending on the direction of displacement.

Linear Variable Differential Transformer (LVDT) II

- Engineering Advantages: Offers high sensitivity, virtually infinite resolution, minimal mechanical wear (contactless operation), and high ruggedness.

LVDT Schematic & Operating States I



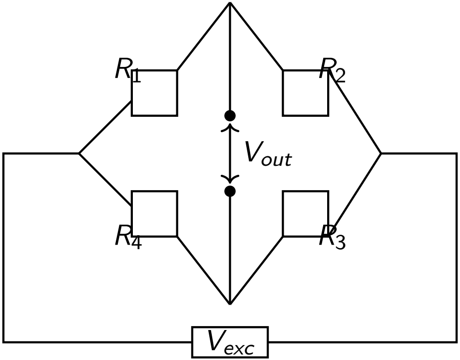
Pressure Measurement using Strain Gauges I

- Piezoresistive Effect: Strain gauges experience a change in electrical resistance when subjected to mechanical strain, governed by Gauge Factor (G_f = (delta R/R)/epsilon).
- Diaphragm Transducer: To measure fluid pressure, a diaphragm acts as the primary elastic element. The applied pressure deflects the diaphragm, causing local tensile and compressive strains.
- Gauge Placement: Strain gauges are bonded to the surface of the diaphragm, positioned specifically where strain is maximum to optimize measurement sensitivity.
- Wheatstone Bridge Configuration: Gauges are connected in a Wheatstone bridge circuit. Using four active gauges (full bridge) provides maximum sensitivity and automatic temperature compensation.

Pressure Measurement using Strain Gauges II

- Poisson's Ratio Effect: Typically, two gauges are placed in tension (radially) and two in compression (circumferentially) to maximize output voltage.
- Output Equation: For a balanced full-bridge, the output voltage V_out = V_in * G_f * epsilon, which is directly proportional to the applied pressure.

Wheatstone Bridge Signal Conditioning I



Temperature Measurement: RTD, Thermistor, and Thermocouple I

- Resistance Temperature Detectors (RTDs): Rely on the positive temperature coefficient of metals (typically platinum, PT100). The resistance-temperature relation is linear: R_t = R_0(1 + alpha*t).
- Thermistors: Made from semiconductor metal oxides, showing highly non-linear negative temperature coefficient (NTC). They are extremely sensitive over a narrow temperature range.
- Thermocouples: Passive sensors working on the Seebeck Effect. When two dissimilar metals are joined at two junctions kept at different temperatures, an EMF is generated: E = a*delta_T + b*delta_T2̂.

Temperature Measurement: RTD, Thermistor, and Thermocouple II

- Cold Junction Compensation: Thermocouples measure differential temperature; thus, the reference junction temperature must be known or electronically compensated (usually to 0 degrees C).
- RTD Lead-Wire Resistance: To eliminate the effect of long lead wires in RTD installations, 3-wire or 4-wire configuration is used within the Wheatstone bridge.

Flow Measurement using Electromagnetic Flowmeters I

- Operating Principle: Based on Faraday's Law of Electromagnetic Induction: $E = B * L * v$, where a conductive fluid behaves as a moving conductor.
- Magnetic Field: An electromagnetic coil placed around the pipe generates a uniform magnetic field (B) perpendicular to the direction of fluid flow.
- Electrode Placement: Two electrodes flush-mounted on opposite sides of the non-conductive pipe wall detect the induced EMF (E) across the fluid width (L).
- Induced EMF: The generated voltage is directly proportional to the average velocity (v) of the fluid, independent of viscosity, density, or pressure.

Flow Measurement using Electromagnetic Flowmeters II

- Fluid Requirements: The process fluid must possess a minimum electrical conductivity (typically ¿ 5 microSiemens/cm) to generate a detectable voltage.
- Advantages & Limitations: High accuracy, zero pressure drop (no obstruction), but cannot measure non-conductive fluids (e.g., pure water, hydrocarbons).

Practical Signal Conditioning and Engineering Challenges I

- Low-Level Signals: Transducer outputs are often small (e.g., millivolts for strain gauges/thermocouples) and require high input impedance amplification.
- Instrumentation Amplifiers: Configured with three op-amps to provide high Common Mode Rejection Ratio (CMRR) to reject common mode noise.
- Filtering: Low-pass active filters (e.g., Butterworth or Chebyshev) are implemented to attenuate high-frequency noise and prevent aliasing during analog-to-digital conversion.
- Calibration & Linearity: Software linearization algorithms or hardware analog compensators are applied to rectify non-linear transducer characteristics.

Practical Signal Conditioning and Engineering Challenges II

- Cable Shielding: Twisted shielded pair cables are mandatory for transmitting analog transducer signals in noisy industrial environments to mitigate EMI.

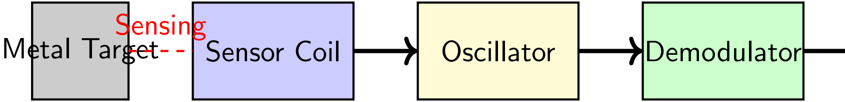
Agenda I

- Introduction to Non-contact Proximity Sensing
- Inductive Proximity Sensors: Principles and Block Diagram
- Eddy Current Killed Oscillator (ECKO) Working Mechanism
- Capacitive Proximity Sensors: Principles and Block Diagram
- Electrostatic Field and Dielectric Constant Effects
- Ultrasonic Proximity Sensors: Time of Flight Method
- Photoelectric Proximity Sensors: Thru-beam, Retro-reflective, Diffuse-reflective
- Performance Comparison of Different Sensing Technologies
- Selection Criteria and Industrial Application Cases

Introduction to Proximity Sensing I

- Proximity sensors detect the presence or absence of objects without any physical contact, preventing wear and mechanical degradation.
- They operate by emitting an electromagnetic field, electrostatic field, light beam, or acoustic wave, and detecting changes in the return signal.
- Key performance indicators include sensing range (Sn), switching frequency, hysteresis, repeat accuracy, and temperature drift.
- They are widely used in factory automation, process control, automotive safety, and robotics for position, speed, and level detection.
- Output switching options include solid-state transistors (NPN or PNP) configured in normally open (NO) or normally closed (NC) modes.

Inductive Proximity Sensor Block Diagram I



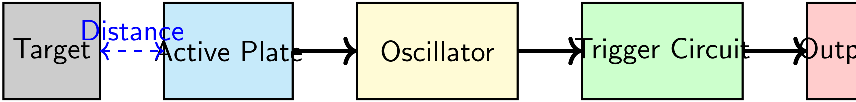
Inductive Sensors: ECKO Principle I

- Specifically engineered to detect only metallic targets (ferromagnetic metals like iron and non-ferromagnetic like aluminum).
- Operates on the Eddy Current Killed Oscillator (ECKO) principle, using an internal LC resonance circuit.
- The LC tank circuit generates a high-frequency alternating magnetic field radiating outward from the active face of the sensor.
- When a metallic target enters this field, eddy currents are induced on the surface of the metal target.
- These eddy currents create an opposing magnetic field, causing energy loss (reflected resistance increases) and damping the oscillation amplitude.

Inductive Sensors: ECKO Principle II

- An internal trigger circuit (Schmitt trigger) monitors the amplitude decay and switches the output stage when threshold is reached.

Capacitive Proximity Sensor Block Diagram I



Capacitive Sensors: Theory and Operation I

- Designed to detect both metallic and non-metallic targets, including liquids, wood, plastic, glass, and powders.
- The active face of the sensor contains two concentric metal electrodes that form an open-loop capacitor.
- An RC oscillator is used; when the target is absent, the capacitive coupling is low and the oscillator remains inactive.
- As a target approaches, it acts as a dielectric material or virtual plate, changing the dielectric constant (ϵ_r) and capacitance.
- The capacitance equation $C = \epsilon A/d$ describes how the change in target proximity increases the overall capacitance.
- Once capacitance exceeds a critical value, oscillations start, which are rectified and used to trigger the output stage switch.

Ultrasonic and Photoelectric Technologies I

- Ultrasonic sensors emit high-frequency acoustic pulse packets (40 to 400 kHz) and listen for the reflected echo.
- Target distance is calculated using the Time-of-Flight (ToF) equation: $d = (v \cdot t)/2$, where v is sound velocity.
- Ultrasonic sensors are highly effective for detecting targets of any color, shape, transparency, or state (liquid, solid, dust).
- Photoelectric sensors utilize light beams (visible red or infrared LEDs/Lasers) to detect targets.
- Three main modes: Thru-beam (longest range, separate emitter/receiver), Retro-reflective (single housing with reflector), and Diffuse-reflective.

Proximity Sensor Technology Comparison I

Sensor Type	Operating Principle	Target Material
Inductive	Eddy Current Loss	Ferrous/Non-Ferrou
Capacitive	Dielectric/Capacitance Change	Conductive and No
Ultrasonic	Acoustic Wave reflection	Any (Solid, Liquid,
Photoelectric	Light beam interruption	Opaque, Translucer

- Selecting the correct sensor depends on: Target material, sensing distance, space availability, and response speed.
- Environmental factors: Inductive/Capacitive are highly immune to dust, while Photoelectric is heavily affected by contamination.
- Typical Application 1: Inductive sensors used for gear tooth speed sensing and end-of-travel limits on CNC machinery.
- Typical Application 2: Capacitive sensors used for liquid level sensing through non-metallic tank walls (e.g., plastic or glass).
- Typical Application 3: Photoelectric thru-beam sensors used for packaging line bottle detection and sorting.
- Typical Application 4: Ultrasonic sensors used for bin level monitoring of bulk solids and distance measurement of vehicle parking.