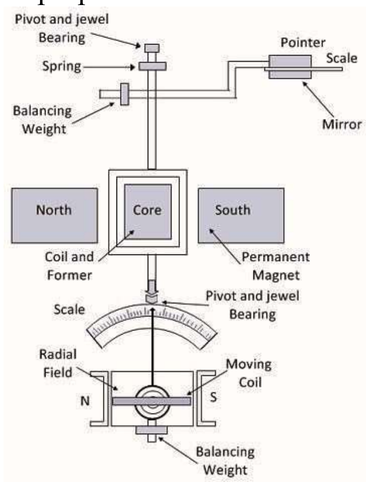
Unit 2
PRINCIPLE OF ANALOG INSTRUMENTS

Permanent Magnet Moving Coil (PMMC)

A Permanent Magnet Moving Coil (PMMC) meter is a type of electromechanical instrument used for measuring direct current (DC) voltage or current in electrical circuits. It operates based on the interaction between a permanent magnet and a moving coil, resulting in deflection proportional to the electrical quantity being measured.

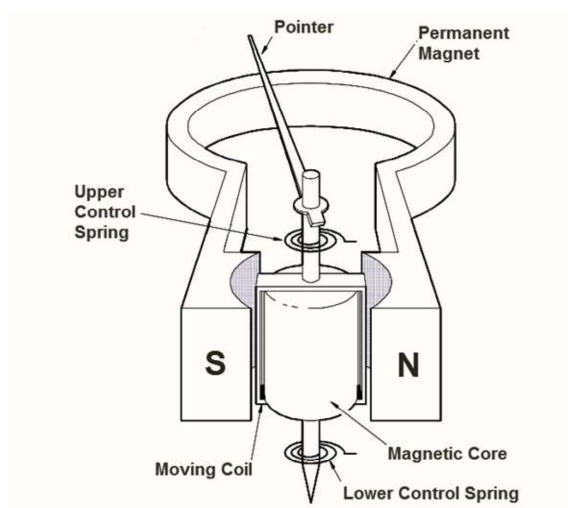


Permanent Magnet Moving Coil Instrument

2.1 Overview of DC/AC Voltmeter and Ammeter: The D'Arsoval Principle

D'Arsonval Principle:

The most commonly used sensing mechanism in DC ammeters, voltmeters and Ohm meters is a current-sensing device called a D'Arsonval meter movement. The D'Arsonval movement is a DC moving coil-type movement in which an electromagnetic core is suspended between the poles of a permanent magnet.



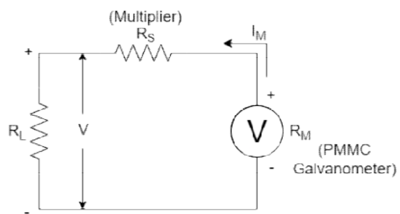
The current measured is directed through the coils of the electromagnet so that the magnetic field produced by the current opposes the field of the permanent magnet and causes rotation of the core. The core is restrained by springs so that the needle will deflect or move in proportion to the current intensity. The more current applied to the core, the stronger the opposing field and the larger the deflection, up to the limit of the current capacity of the coil. When the current is interrupted, the needle is returned to zero by the restraining springs. The limit of the movement is usually less than one mili-ampere.

DC and AC voltmeters and ammeters are essential instruments used for measuring voltage and current in electrical circuits.

DC Voltmeter:

- Measures the voltage across a DC circuit.
- Consists of a sensitive galvanometer (usually a moving coil or moving iron instrument) connected in parallel with a high resistance (known as a multiplier resistor).
- When connected to a circuit, it deflects proportionally to the voltage being measured, and the degree of deflection indicates the voltage.

A simple DC voltmeter can be constructed by placing a resistor (R_s), called a multiplier, in series with the ammeter meter movement, and marking the meter face to read voltage, voltmeters are connected in parallel with the load (R_L) being measured.



When constructing a voltmeter, the resistance of the multiplier must be determined to measure the desired voltage.

$$V = I_M R_S + I_M R_M$$

$$I_M R_S = V - I_M R_M$$

$$R_S = \frac{V}{I_M} - R_M \ldots\ldots\ldots\ldots (1)$$

Where,

$V = Voltage\ range\ desired$

$I_M = Meter\ current$

$R_M = Meter\ resistance$

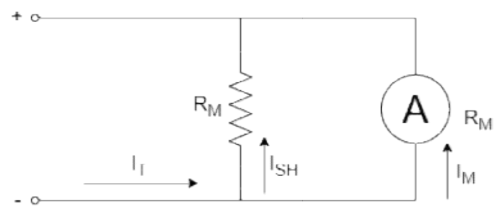
$R_S = Multiplier\ resistance\ or\ series\ resistance$

Equation (1) is the mathematical representation of the voltmeter's multiplier resistance.

DC Ammeter:

- Measures the current flowing through a DC circuit.
- Consists of a sensitive galvanometer connected in series with the circuit under test, with a very low resistance (known as a shunt resistor).
- The current passing through the circuit also passes through the ammeter, causing a deflection proportional to the current, which is then scaled accordingly.

When an ammeter is placed in series with a circuit, it will increase the resistance of that circuit by an amount equal to the internal resistance of the meter R_M.



By Kirchhoff's Current Law

$$I_{SH} = I_T - I_M$$

Since, the voltage across the shunt must be equal to the voltage across the ammeter; shunt resistance is calculated as follows;

$$I_{SH}R_{SH} = I_M R_M$$

$$R_{SH} = \frac{I_M R_M}{I_{SH}}$$

$$R_{SH} = \frac{I_M R_M}{I_T - I_M}$$

Where,

$R_{SH} = Shunt\ Resistor$
$I_{SH} = Shunt\ Current$
$I_M = Meter\ Current$
$R_M = Meter\ Resistance$
$I_T = Total\ current\ across\ circuit$

AC Voltmeter:

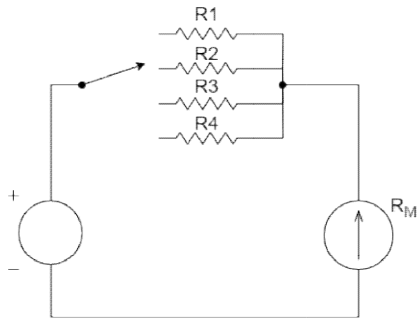
- Measures the voltage across an AC circuit.
- Uses techniques such as electromagnetic induction or electronic circuits to measure the time-varying voltage waveform.
- Modern AC voltmeters are typically electronic and can measure both AC and DC voltages. They may use rectification and filtering to measure the RMS (root mean square) value of the AC voltage.

AC Ammeter:

- Measures the current flowing through an AC circuit.
- Similar to AC voltmeters, AC ammeters use electromagnetic induction or electronic circuits to measure the time-varying current waveform.
- Modern AC ammeters are typically electronic and can measure both AC and DC currents. They may use techniques such as current transformers to scale down the current for measurement.

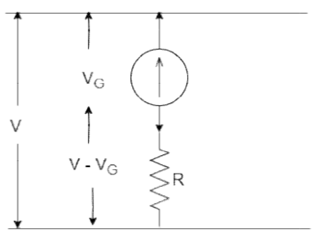
2.2 DC Multi range Ammeters and Extending Ammeter Ranges

The adding of a number of multipliers together with range switch is known as multi range voltmeter. The voltmeter provides the facility to work with number of voltage range. Figure shows schematic diagram of multi range voltmeter having four multipliers R_1, R_2, R_3 and R_4.



The range of instrument when used as a voltmeter can be increased by using a high resistance in series with it.

Let, I_G be the full scale deflection current, R_G is the resistance of instrument, $V_G=I_GR_G$ is the full scale potential difference, V be the voltage to be measured and R is the series resistance to be added.



We know,

$$I_G = \frac{V}{R + R_G}$$

Also,

$$V_G = I_G R_G$$

$$V_G = \frac{V}{R + R_G} R_G \quad \left[\therefore I_G = \frac{V}{R + R_G}\right]$$

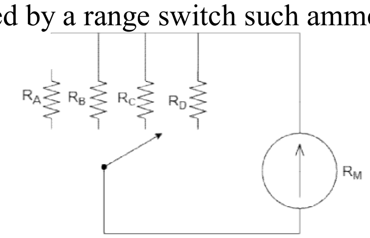
$$\frac{R + R_G}{R_G} = \frac{V}{V_G}$$

$$\therefore \frac{V}{V_G} = 1 + \frac{R}{R_G} \ldots\ldots\ldots\ldots\ldots..(1)$$

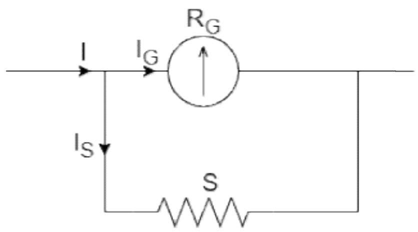
Above equation (1) shows that multiplication factor increases by increase in value of 'R'.

2.3 DC Multi range Voltmeters and Extending Voltmeter Ranges

The current range of DC ammeter may be further extended by a number of shunts, selected by a range switch such ammeter is called multi range ammeter.



When PMMC is used as ammeter, it can be extended with the help of low shunt resistance, where shunt provides a path for extra-current.



This shunted instrument can be made to measure current many times greater than normal full scale deflection. The ration of maximum current (with shunt) to full scale deflection current (without shunt) is known as multiplying factor of the shunt.

Let,

$R_G = Shunt\ resistance$

$S = Shunt\ Resistance$

$I_G = full\ scale\ deflection\ current$

$I = Line\ current\ to\ be\ measured.$

We know that, voltage across shunt and instrument are equal as they are connected in parallel.

$V_G = V_S$

$or, I_G R_G = I_S S$

$or, I_G R_G = (I - I_G)S$

$$\therefore \frac{I}{I_G} = 1 + \frac{R_G}{S}$$

It can be seen that lower the value of shunt greater is multiplying factor.

2.4 AC Voltmeter and multi range voltmeter

An AC voltmeter is an instrument used to measure the voltage across an alternating current (AC) circuit. An AC voltmeter measures the root mean square (RMS) value of the AC voltage waveform. It uses techniques such as electromagnetic induction or electronic circuits to measure the time-varying voltage accurately.

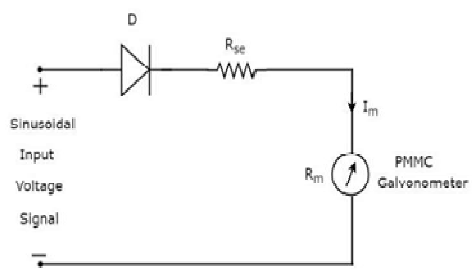


Fig: AC Voltmeter using Half Wave Rectifier

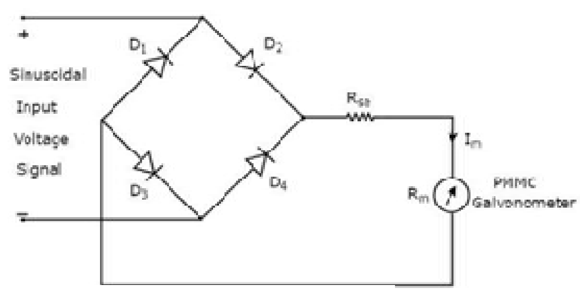


Fig: AC Voltmeter using full Wave Rectifier

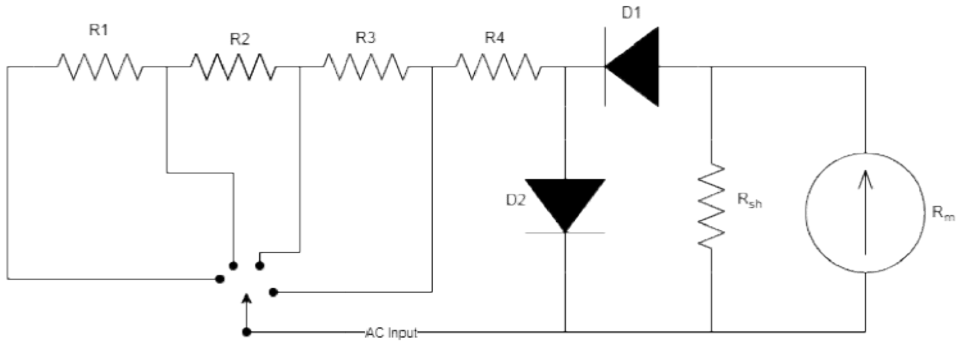
The rms value of sinusoidal (AC) input voltage signal is;

$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

Where,

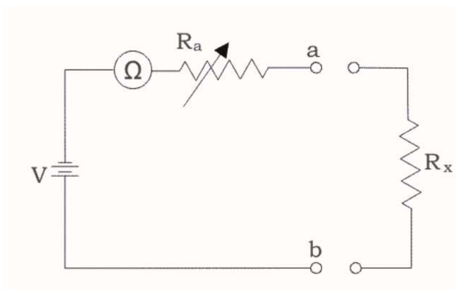
V_m Is the maximum value of sinusoidal (AC) input voltage signal.

A multi-range voltmeter is a type of voltmeter that offers multiple voltage measurement ranges, allowing it to measure a wide range of voltages accurately. It typically includes a selector switch or button that allows the user to choose the appropriate voltage range for the measurement. Multi-range voltmeters may have different input impedance values for each range to ensure accurate measurements across the entire range. Some multi-range voltmeters include automatic range selection features that automatically select the best range based on the measured voltage.



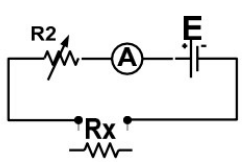
2.5 Ohm Meter and Multi range

An ohmmeter can be defined as, it is one kind of electronic device mainly used for calculating electrical resistance of a circuit, and the unit of resistance is ohm. Electrical resistance is a calculation of how much an object resists allowing the flow of current through it. There are different types of meters available with different sensitivity levels such as micro, mega and milli-ohmmeters.



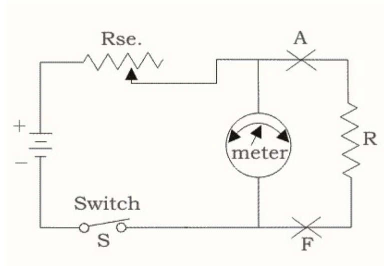
i) Series Type Ohm meter

R_x is the unknown resistor to be measured, R_2 is variable adjusted resistance so that the pointer read zero at short circuit test. The scale of series ohmmeter is nonlinear with zero at the right and infinity at extreme left. Series ohmmeter is the most generally used meter for resistance measurement.



ii) Shunt Type Ohm meter

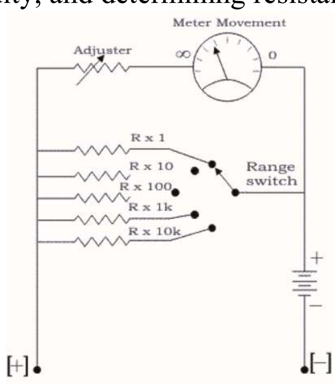
Shunt ohmmeter are used to measure very low resistance values. The unknown resistance R_{se} is now shunted across the meter, so portion of current will pass across this resistor and drop the meter deflection proportionately. The switch is necessary in shunt ohmmeter to disconnect the battery when the instrument is not used. The scale of shunt ohmmeter is nonlinear with zero at the left and infinity at extreme right.



iii) Multi Range Ohm Meter

A multi-range ohmmeter, like its voltmeter counterpart, offers the capability to measure resistance across various ranges, allowing it to accommodate a wide range of resistance values accurately. A multi-range ohmmeter typically employs the same fundamental measurement principles as a standard ohmmeter. It applies a known voltage across the resistance to be measured and measures the resulting current flow through the resistor.

Multi-range ohmmeters find applications in various fields, including electronics, electrical engineering, and maintenance. They are used for troubleshooting circuits, testing continuity, and determining resistance values of components across different ranges.



Example

1. **How will you use a PMMC instrument which gives full scale deflection at 50mV and 10mA current has;**
   a) **Ammeter 0 to 10A range**
   b) **Voltmeter 0 to 250V range**

Solution:

$$I_G = 10mA$$
$$V_G = 50mV$$
$$R_G = \frac{50}{10} = 5\ \Omega$$
$$\frac{I}{I_g} = 1 + \frac{R_g}{S}$$
$$0r, \frac{10}{10 \times 10^{-3}} - 1 = \frac{5}{S}$$
$$or, 10 - \frac{10 \times 10^{-3}}{10 \times 10^{-3}} = \frac{5}{S}$$
$$or, S = \frac{5 \times 10 \times 10^{-3}}{9.99}$$
$$\therefore S = 5 \times 10^{-3}\ \Omega$$

Again,

$$\frac{V}{V_G} = 1 + \frac{R}{R_G}$$

$$\left(\frac{250}{50 \times 10^{-3}}\right) \times R_G = R$$

$$R = 25k\Omega$$

'R' is connected in series to increase range.

So, I'll use a shunt resistance of $5 \times 10^{-3}\Omega$ in order to increase the range from 10mA to 0-10A.

2.6 Electronic Multimeter

It is one of the most versatile general purpose instruments capable of measuring dc and ac voltages as well as current and resistances. The solid-state electronic multimeter (or VOM) generally consists of the following elements.

(i) A balanced bridged amplifier and a PMMC meter.

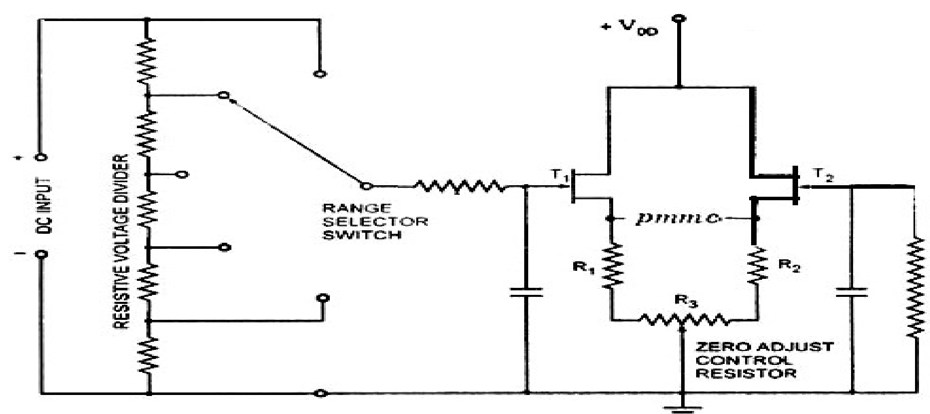
(ii) An attenuator in input stage to select the proper voltage range.

(iii) A rectifier for converting of an AC input voltage to proportionate DC value.

(iv) An internal battery and additional circuitry for providing the capability of resistance measurement.

(v) A function switch for selecting various measurement functions of the meter such as voltage, current or resistance.

In addition, the instrument is usually provided with a built-in power supply for operation on AC mains and, in most cases, one or more batteries for operation as a portable



test instrument. The schematic diagram of a balanced-bridge DC amplifier using two field effect transistors (FETs) is given in figure. The two FETs and the source resistors R_x and R_2, together with zero adjust control resistor R_3, constitute a bridge circuit. The PMMC meter is connected between the source terminals of the FETs, representing two opposite corners of the bridge.

In the absence of input signal, the gate terminals of the FETs are at ground potential and the transistors operate under identical quiescent conditions. Ideally no current should flow through the PMMC movement but in practice, on account of some mismatch between the two FETs and slight tolerance differences in the values of various resistors a current does flow and causes the meter movement to deflect from zero position. This current is reduced zero by the adjust control resistor R_3. Now the bridge is balanced. With a positive input signal applied to the gate of input transistor T_1 its drain current creases causing the voltage at the source terminal to rise. The resulting unbalance between the two transistors T_1 and T_2 source voltages is shown by the meter movement, whose scale is calibrated in terms of the magnitude of the applied input voltage. The maximum voltage that can be applied to the gate of input transistor T_1 is determined by its operating range, which is usually of the order of a few volts.

2.7 Multimeter as a micro ammeter and DC ammeter Types pf voltmeter: Differential type and True RMS

2.8 Wattmeter: Types and Working principles

A wattmeter is essentially an independent combination of ammeter and voltmeter and therefore consists of two coils known as current coil and pressure coil (voltage coil). The general connection of wattmeter for single phase wattage (power measurement) is shown in figure.

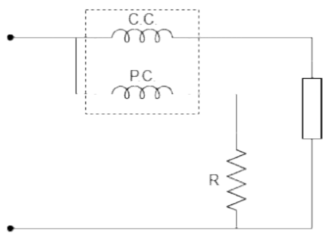


Fig: 1-Phase Wattmeter Conncetion

Types of Wattmeter

i) Electrodynamometer Type Wattmeter

The instrument whose working depends on the reaction between the magnetic field of moving and fixed coils is known as the Electrodynamo-meter Wattmeter. It uses for measuring the power of both the AC and DC circuits.

Construction: It consists of two coils; fixed coil and moving coil. The fixed coil is divided into two halves; F1 and F2 which are connected in series with load whose power is to be measured. The moving coil is connected to the supply voltage in parallel. A high resistance 'R' is connected in series with moving coil as moving is connected across the supply voltage.

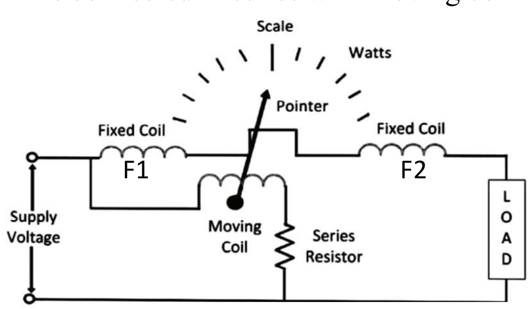


Fig: Electrodynamometer Wattmeter

Mathematical Derivation: In case of dynamometer type wattmeter, there is no iron core so field strength and hence the flux density is directly proportional to current 'I_1' and is given by;

$B = kI_1 \dots\dots\dots\dots..(1)$

So, the fixed coils 'F1' and 'F2' are responsible for producing required magnetic field. Now, when the current flows through the moving coil, it experiences deflecting torque and moves to show deflection. The deflecting torque produced is given by

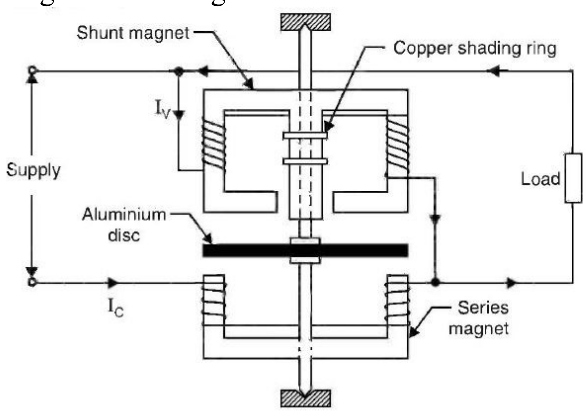
$T_d \propto BI_2 \dots\dots\dots\dots.(2)$

Since, $I_2 \propto kV$ and $B \propto kI$,
$T_d \propto kVI$,
$T_d = k.Power \qquad (For\ dc)$
$T_d = vi \qquad (For\ ac)$
$P = vicos\emptyset$

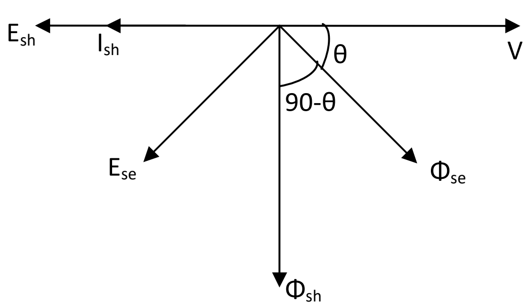
ii) Induction Type Wattmeter

The induction type wattmeter can be used to measure a.c. power only in contrast to dynamometer wattmeter which can be used to measure d.c. as well as a.c. power. The principle of operation of an induction wattmeter is the same as that of induction ammeter and voltmeter i.e., induction

Construction: It consists of two laminated electromagnets. One electromagnet, called shunt magnet is connected across the supply and carries current proportional to the supply voltage. The other electromagnet, called series magnet is connected in series with the supply and carries the load current. A thin aluminium disc mounted on the spindle is placed between the two magnets so that it cuts the flux of both the magnets. The controlling torque is provided by spiral springs. The damping is electro-magnetic and is usually provided by a permanent magnet embracing the aluminium disc.



Working Principle:



Let,

$V = circuit\ voltage$
$I = crcuit\ current$
$\theta = angle\ between\ V\ and\ I$
$\emptyset_{se} = Flux\ created\ by\ the\ series\ electromegnet\ this\ will\ be\ in\ phase\ with\ I$
$\emptyset_{sh} = Flux\ created\ by\ shunt\ electromagnet, his\ will\ be\ inphase\ with\ V$

The flux $\emptyset_{se}$ of series electromagnet induces emf of E_{se} in the disc. This emf causes the eddy current I_{se} in the disc. Let us assume that, the disc is fully resistive. Hence, eddy I_{se}

caused by induced emf E_{se} will be inphase with that emf. So, I_{se} also lags the current I by 90^0.
$\therefore$Angle between $\emptyset_{se}$ and $I_{se} = 90^0$

The flux $\emptyset_{sh}$ of shunt electromagnet induces emf E_{sh} in the disc. The emf causes the eddy current I_{sh} in the disc. Let us accurate that the disc is fully resistive. Hence eddy current I_{sh} caused by emf. E_{sh} will be inphase with that emf. So, E_{sh} also lags by 90^0.

Mathematical Derivation

The torque produced by interaction of $\emptyset_{se}, I_{se}$ and $\emptyset_{sh}$.

$T_1 = kI_{se}\emptyset_{sh}\cos\theta \ldots\ldots\ldots.(1)$

Torque produced by interaction of I_{sh} and $\emptyset_{se}$ is

$T_2 = kI_{sh}\emptyset_{se}(\cos(180^0 - \theta)) \ldots\ldots\ldots\ldots(2)$

The resultant deflecting torque is

$T_d = T_1 - T_2$

$or, T_d = kI_{se}\emptyset_{sh}\cos\theta - kI_{sh}\emptyset_{se}\cos(180^0 - \theta) = k[I_{se}\emptyset_{sh}\cos\theta - I_{sh}\emptyset_{se}\cos\emptyset]$

$or, T_d = k[k_1VI\cos\theta + k_2VI\cos\theta]$

$or, T_d = KVI\cos\theta\,[k_1 + k_2]$

$\therefore T_d \propto VI\cos\theta$

2.9 Energy meter: Types and Working Principle

Energy meter are integrating instruments used to measure quantity of electrical energy supplied to a load for a particular period of time. There are three types of energy meter. The energy is the total power consumed and utilized by the load at a particular interval of time. It is used in domestic and industrial AC circuit for measuring the power consumption. The meter is less expensive and accurate.

Construction: The energy meter has four main parts:

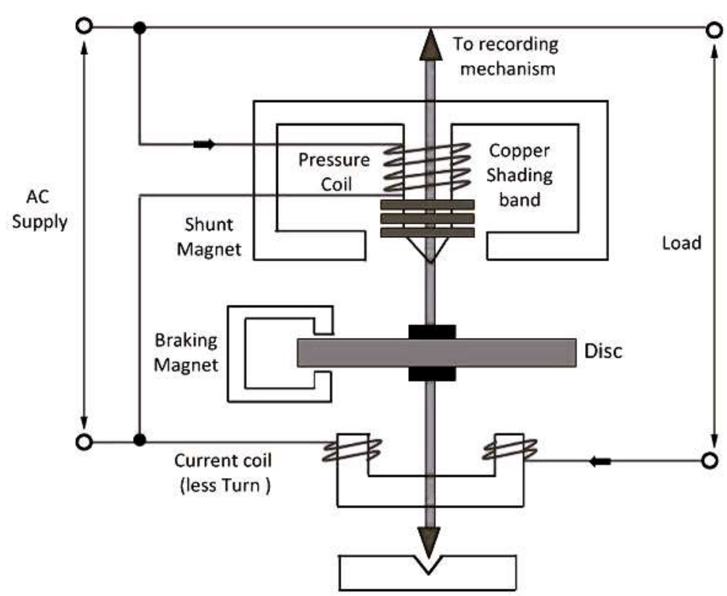


Fig: Single Phase Induction type energy meter

i) **Driving System:** The electromagnet is the main component of the driving system. It is the temporary magnet which is excited by the current flow through their coil. The core of the electromagnet is made up of silicon steel lamination. The driving system has two electromagnets. The upper one is called the shunt electromagnet, and the lower one is called series electromagnet.
ii) **Moving System:** The moving system is the aluminium disc mounted on the shaft of the alloy. The disc is placed in the air gap of the two electromagnets. The eddy current is induced in the disc because of the change of the magnetic field. This eddy current is cut by the magnetic flux. The interaction of the flux and the disc induces the deflecting torque.
iii) **Braking system:** The permanent magnet is used for reducing the rotation of the aluminium disc. The aluminium disc induces the eddy current because of their rotation. The eddy current cut the magnetic flux of the permanent magnet and hence produces the braking torque.
iv) **Registration System:** The main function of the registration or counting mechanism is to record the number of rotations of the aluminium disc. Their rotation is directly proportional to the energy consumed by the loads in the kilowatt hour.

Working:

An energy meter typically measures the product of voltage (V), current (I), and time (t) to determine the energy consumed. It consists of a current coil and a voltage coil, which are connected in series with the load. The voltage coil is connected across the load voltage, and the current coil is connected in series with the load current.

The energy consumed (E) by the load is given by the formula:

$$E = Power \times time$$

The power consumed by the load is given by:

$$P = VI\cos\emptyset$$

$Where, \emptyset\ is\ the\ phase\ angle\ between\ voltage\ and\ current$

Substituting the power formula into the energy consumption formula,
We get,

$$E = (VI\cos\emptyset) \times t$$

$$E = \int VI\cos\emptyset\, dt$$

Where the integral represents the energy consumed over time.

2.10 Power Factor Meter

A power factor meter is an electrical instrument used to measure the power factor of an AC circuit. The power factor is the ratio of real power (in watts) to apparent power (in volt-amperes) in an electrical system and is expressed as a value between 0 and 1 or as a percentage. Power factor meters are crucial for monitoring and optimizing power factor in electrical systems to ensure efficient power usage and minimize energy losses.

Construction:

The meter has fixed coil which acts as a current coil. This coil is split into two parts and carries the current under test. The magnetic field of the coil is directly proportional to the current flow through the coil. The meter has two identical pressure coils A and B. Both the coils are pivoted on the spindle. The pressure coil A has no inductive resistance connected in series with the circuit, and the coil B has highly inductive coil connected in series with the circuit.

Working:

A power factor meter typically measures the phase difference between the voltage and current in an AC circuit to determine the power factor. It consists of a synchronous motor or a moving coil mechanism connected to a pointer or digital display. The meter's movement responds to the phase difference between the voltage and current, indicating the power factor value directly.

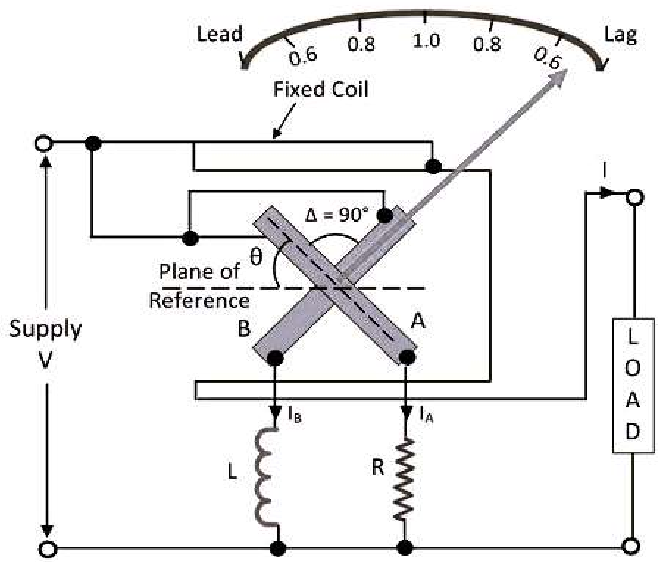


Fig: Single phase electrodynamometer type power factor meter

The power factor (PF) is calculated using the formula:

$PF = \cos \emptyset$

$Where, \emptyset\ is\ angle\ between\ voltage\ and\ curernt$

2.11 Instrument Transformer

Instrument Transformers are a type of transformer used in an AC system to measure electrical quantities such as voltage, current, power, energy, power factor, frequency. These are also equipped with protective relays to protect the power system. Instrument transformers have the basic function of reducing the AC System voltage and current. The current and voltage level of the power system is relatively high. It is very difficult and costly to design the measuring instruments to measure such high-level current and voltage

Working Principle

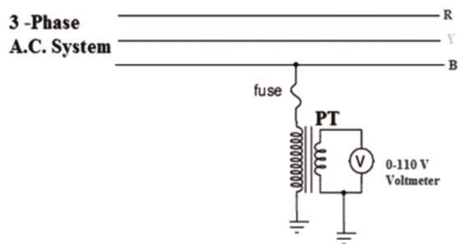
Mutual Induction: Instrument transformers operate based on the principle of mutual induction, where the primary winding (high voltage or current side) induces a voltage or current in the secondary winding (low voltage or current side). The turn’s ratio of the transformer determines the ratio between the primary and secondary voltages or currents.

Voltage Transformation: In a potential transformer, the primary winding is connected across the high voltage line, while the secondary winding is connected to the measuring or protection circuit. The voltage induced in the secondary winding is proportional to the voltage across the primary winding and is stepped down according to the turn’s ratio.

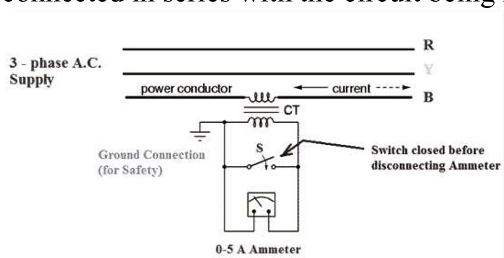
Current Transformation: In a current transformer, the primary winding carries the high current to be measured, while the secondary winding is connected to the measuring or protection circuit. The current induced in the secondary winding is proportional to the current flowing through the primary winding and is stepped down according to the turn's ratio.

Types of Instrument Transformers:

i. **Potential Transformer (PT) / Voltage Transformer (VT):** PTs are used to step down high voltages to a standardized low voltage (typically 120V or 240V) for measurement and protection purposes. They provide accurate voltage measurements for meters, relays, and control equipment. PTs are usually connected in parallel with the circuit being measured.



ii. **Current Transformer (CT)**: CTs are used to step down high currents to a standardized low current (usually 5A or 1A) for measurement and protection. They provide accurate current measurements for meters, relays, and protective devices. CTs are typically connected in series with the circuit being measured.



Applications:

- **Metering:** Instrument transformers are used in electricity metering systems to provide accurate measurements of voltage and current for billing purposes.
- **Protection:** CTs are widely used in protective relay systems to detect and respond to faults in electrical systems, such as over current, undercurrent, and earth fault conditions.
- **Control and Monitoring:** PTs and CTs are essential for control and monitoring systems in substations and industrial plants, providing data for analysis and decision-making.

Assignment