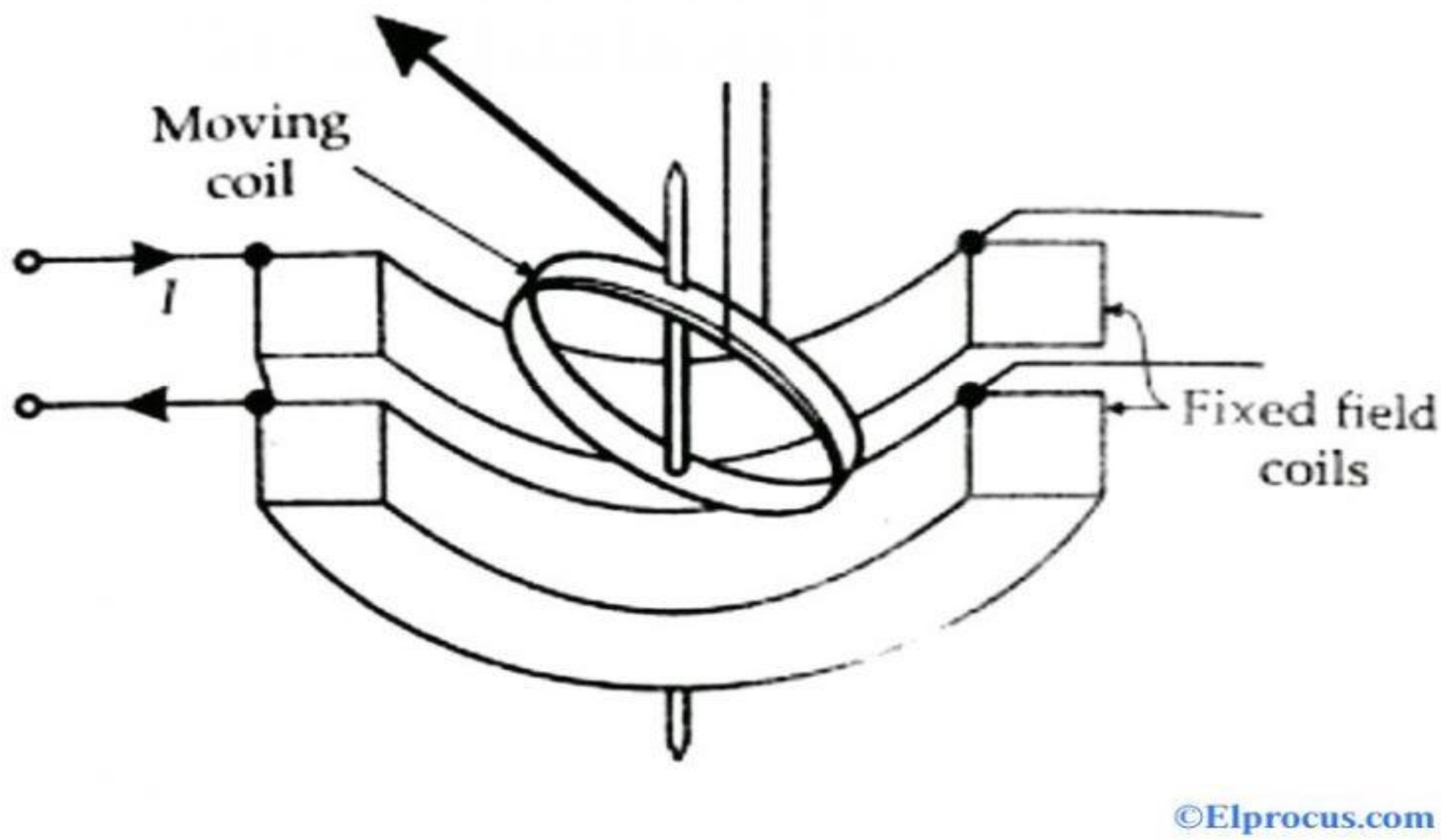
Chapter 13: Electrical Equipments

Wattmeter

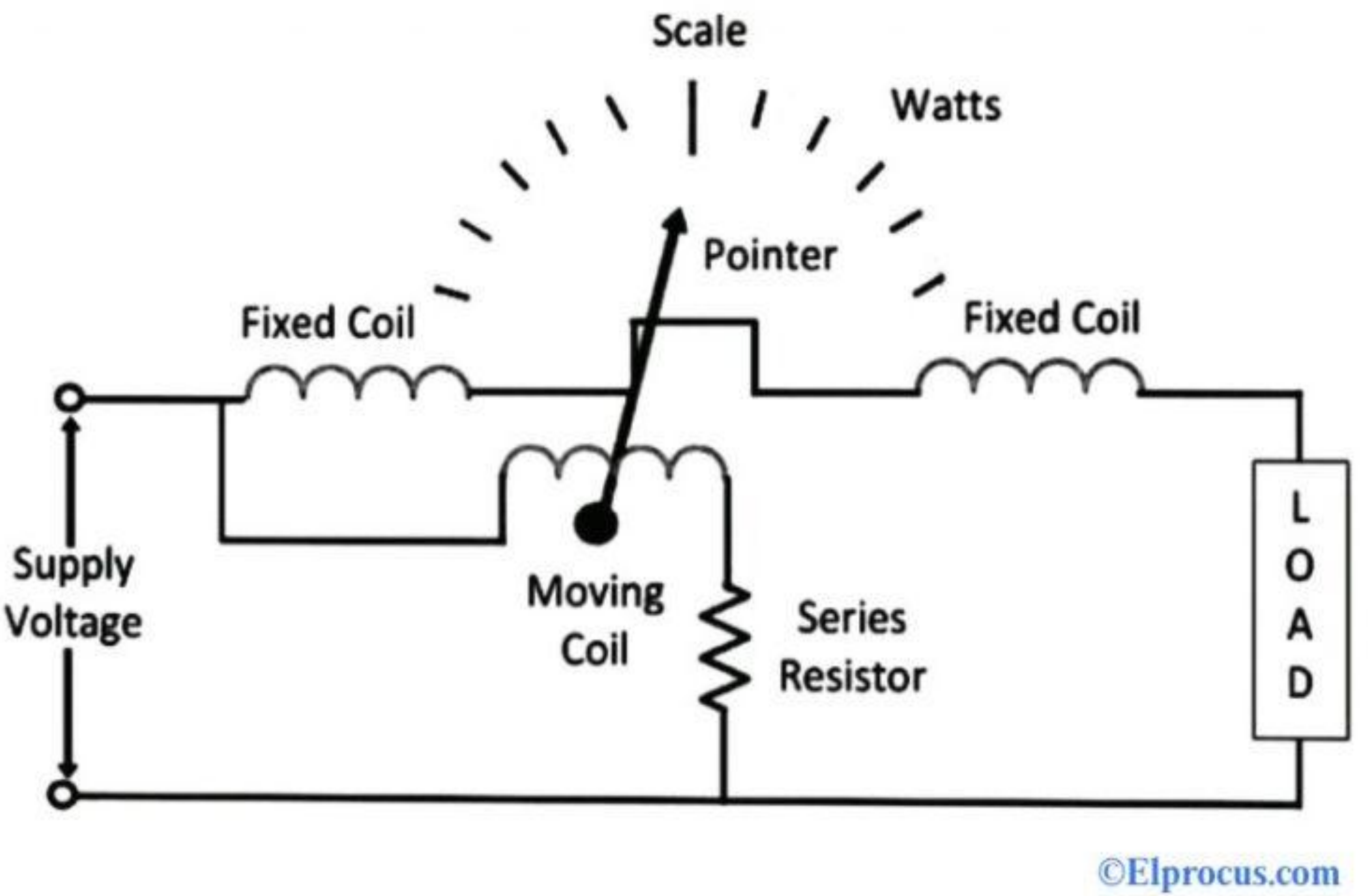
- An electrical instrument used to measure **electric power** in **watts** of any circuit is called **Wattmeter**.
- It consists of two coils like the **current coil** and **voltage coil**.
- The **current coil**, which is connected in **series** & **voltage coil** is connected in **parallel**.
- **Wattmeters** are mainly used in electrical circuit measurement, debugging, transmission, distribution of electrical power, power rating, consumption of electrical appliances, utility frequency measurement, home appliances and many more.
- These are classified into **three types**.
- They are **Electrodynamometer wattmeter**, **Induction type wattmeter**, **Electrostatic type wattmeter**.
- Let us discuss an overview of the **Electrodynamometer wattmeter** and **Induction type wattmeter**.

Electrodynamometer Wattmeter

- Electrodynamometer wattmeter is an instrument whose working is related to the reaction between magnetic fields of the fixed coil and moving coil which is connected across the voltage (current is directly proportional to voltage).



Construction and Working Principle



- The **Electrodynamometer wattmeter working principle** is very simple and easy.
- It is based on the theory of a current-carrying conductor experiences a magnetic force when it is placed in a magnetic field.
- Hence there will be a deflection of pointer that took place due to the mechanical force.
- It contains two coils such as **fixed coil** (**current coil**) and **moving coil** (**pressure coil** or **voltage coil**).
- The fixed coil is used to carry the current and connected in series with the load in any circuit.
- The moving coil carries the current directly proportional to the voltage and connected across the voltage.
- The value of current limited to a minimum value due to large non-inductive resistance connected in series.
- The circuit diagram is shown earlier.

- The construction of the Electrodynamometer wattmeter includes fixed coil, moving coil, control, damping, scales, and pointer. The construction of the Electrodynamometer wattmeter is shown earlier.

Fixed Coil

- It is connected in series with the load, which is considered as the current coil.
- To make construction easy and simple, it is divided into two parts.
- Those are two elements connected parallel to each other.
- It produces a uniform electric field, which is very essential for working.
- The current coil is designed in such a way that it carries approximately 20 Amperes.

Moving Coil

- Considered as pressure coil in this instrument, that is connected parallel with the supply voltage. So, that current flows directly proportional to supply voltage.
- A pointer is mounted on the moving coil with the help of spring to control the movement.
- The temperature increases when current flows through the coil. So, in order to control the flow of the current resistor is connected in series with the moving coil.

Control

- It provides controlling torque onto the instruments.
- Gravity control and spring control are the two types in this control system.
- Among these two Electrodynamometer wattmeters uses a spring control system as it helps in the pointer movement.

Damping

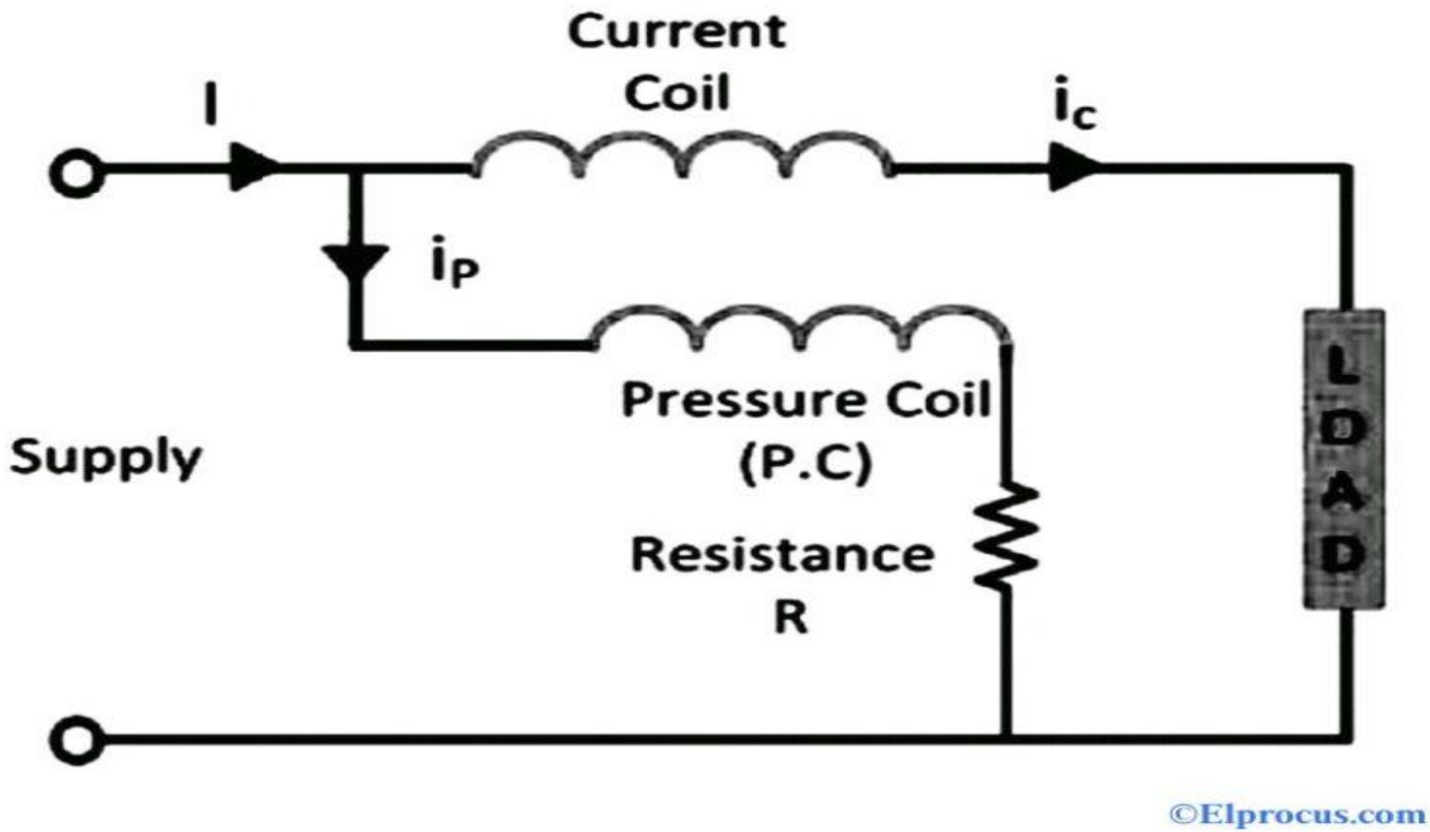
- The effect which reduces the pointer movement is called damping.
- In this, damping torque is produced because of the air friction.
- Other types of damping are not used as they destroy the useful magnetic flux.

Scales and Pointers

- It uses a linear scale as the moving coil moves linearly.
- The apparatus uses knife-edge pointers in order to remove parallax error caused due to oversights.

Theory of Electrodynamometer Wattmeter

- The circuit diagram of the Electrodynamometer wattmeter is shown below.



- The instantaneous torque acting on the pointer is given by,

$$T_1 = i_1 i_2 \, dM/d\theta$$

Where i_1 and i_2 are instantaneous currents in two coils.
- Let **V** and **I** are rms values of voltage and current being measured.
- The instantaneous voltage across the pressure coil is,

$$v = \sqrt{2}\, V \sin(\omega t)$$

- The current will be in phase with voltage if a purely resistive pressure coil is used.
- The value of the current is,

$$i_p = v/R_p = \sqrt{2}(V / R_p)\sin \omega t = \sqrt{2}\, I_p \,\mathrm{Sin}\, \omega t \quad \text{and} \quad I_p = V_p / R_p$$

- The current flowing through the **current coil** when it is **lagged** by the voltage in phase angle is, $i_p = \sqrt{2}\, I \sin(\omega t - \emptyset)$
- The current value is very small in the pressure coil. Hence it is considered as the total load current.
- The torque acting on the coil is,

$$T_i = \sqrt{2}\, I_p \sin(\omega t - \Phi) \; X \; \sqrt{2}\, I \sin(\omega t - \Phi) \, dM/d\theta$$

$$= I_p \, I \cos(\Phi - \cos(2wt - \Phi) dM/d\theta$$

- The average deflecting torque is integration of $T_i \, d(wt)$ from limit **0** to **T** over one **T** then $T_d = (V\, I / R_p) \cos\Phi \, dM/d\theta$
- Thus controlling torque exerted by spring: $Tc = K\,\theta$

where **K = Spring Constant** and **θ = final steady deflection.**

- Since the moving system of the **Electrodynamometer Type Wattmeter** cannot follow the rapid variations in torque (the torque has a double frequency, component), it will take up a position at which the average **deflection torque** is equal to the **restoring torque** of the springs.

$$K\theta = I_p I \cos\phi . dM / d\theta$$

$$\text{or deflection,}\ \theta = I_p I \cos\phi .(dM / d\theta) / K$$

$$= (VI \cos\phi / R_p K) dM / d\theta$$

$$= K_1 VI \cos\phi . dM / d\theta$$

$$= (K_1 dM / d\theta) P$$

where **P** = power being measured = **VI cos Ø** and $\mathbf{K_1 = 1/R_pK}$

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.

Principle

- However, it differs from induction ammeter or voltmeter in so far that two separate coils are used to produce the rotating magnetic field in place of one coil with phase split arrangement.
- **Figure (b)** shows the physical arrangement of the various parts of an induction wattmeter.

Construction

- **Figure (a)** shows the principal parts of an induction wattmeter.

Figure a

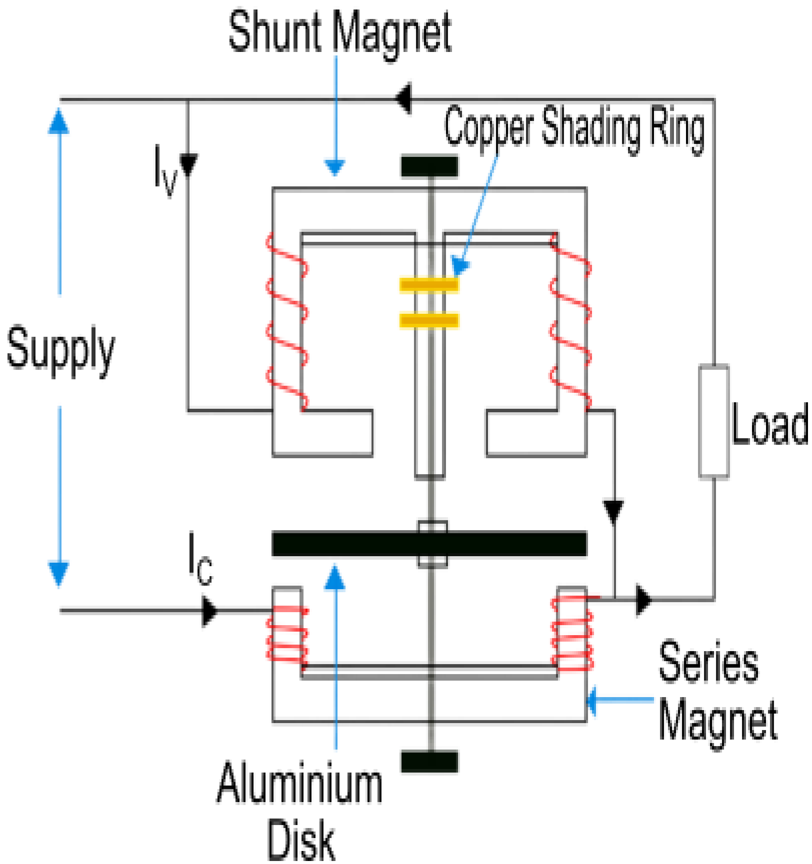
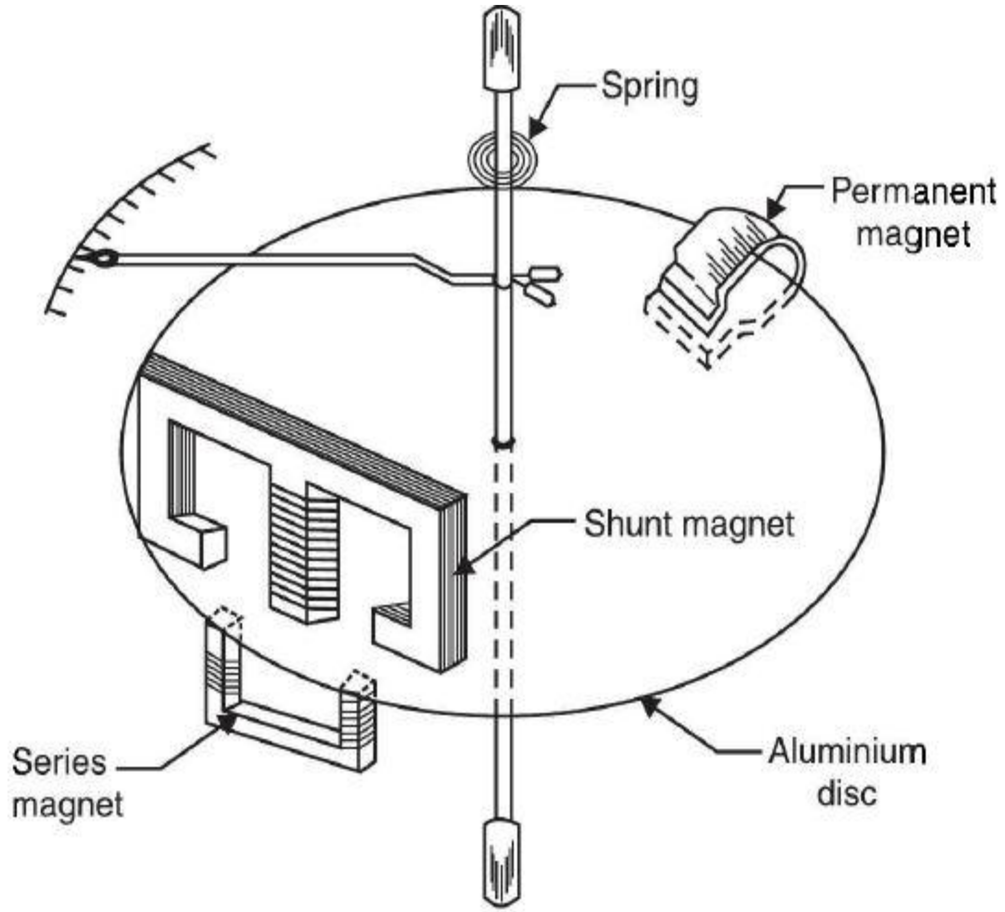


Figure b



- (i) 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 coil of this magnet is made **highly inductive** so that the current (and hence the flux produced) in it **lags** behind the supply voltage by **90^0**.
- The other electromagnet, called **series magnet** is connected in series with the supply and carries the load current.
- The coil of this magnet is made highly non-inductive so that angle of **lag** or **lead** is wholly determined by the load.
- (ii) 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 [**See Fig. (b**)].
- Two or more closed copper rings (called **shading rings**) are provided on the central limb of the shunt magnet.
- By adjusting the position of these rings, the shunt magnet flux can be made to lag behind the supply voltage by exactly **90^0**.

Working.

- When the wattmeter is connected in the circuit [**See Fig. (a)**] to measure a.c. power, the shunt magnet carries current proportional to the supply voltage and the series magnet carries the load current.
- The two fluxes produced by the magnets induce eddy currents in the aluminium disc.
- The interaction between the fluxes and eddy currents produces the deflecting torque on the disc, causing the pointer connected to the moving system to move over the scale.
- The pointer comes to rest at a position where deflecting torque is equal to the controlling torque.
- Let **V** = supply voltage

  $\mathbf{I_v}$ = current carried by shunt magnet

  $\mathbf{I_c}$ = current carried by series magnet (= load curent I)

  cos Φ = lagging power factor of the load

- The phasor diagram is shown in **Fig. (c).**
- The current $\mathbf{I_v}$ in the shunt magnet lags the supply voltage **V** by **90°** and so does the flux $\mathbf{\Phi_v}$ produced by it.
- The current $\mathbf{I_c}$ in the series magnet is the load current and hence **lags** behind the supply voltage **V** by **Φ**.
- The flux $\mathbf{\Phi_C}$ produced by this current (i.e., $\mathbf{I_c}$) is in phase with it.
- It is clear that phase angle **θ** between the two fluxes is (**90° - Φ**) i.e.,

$$\theta = 90° - \phi$$

$$\therefore \text{ Mean deflecting torque, } T_d \propto \phi_V \phi_C \sin\theta \quad ...$$

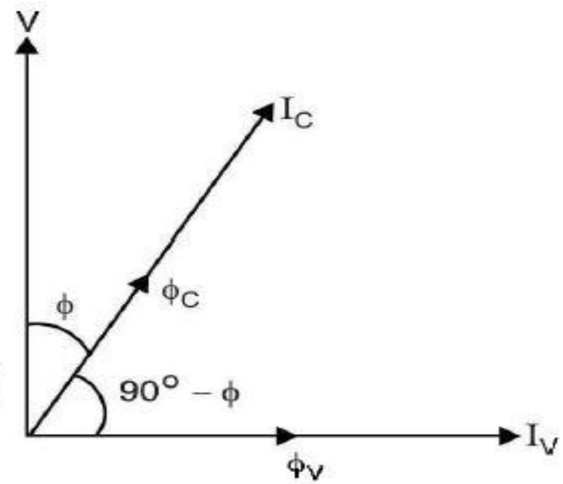
$$\propto VI \sin(90° - \phi)$$

$$\propto VI \sin(90° - \phi)$$

$$[\because \phi_V \propto V \text{ and } \phi_C \propto I]$$

$$\propto VI \cos\phi$$

$$\propto \text{a.c. power}$$



Since the instrument is spring controlled, $T_C \propto \theta$

For steady deflected position, $T_d = T_C$.

$$\therefore \quad \theta \propto \text{a.c. power}$$

Hence such instruments have uniform scale.

Energy Meter

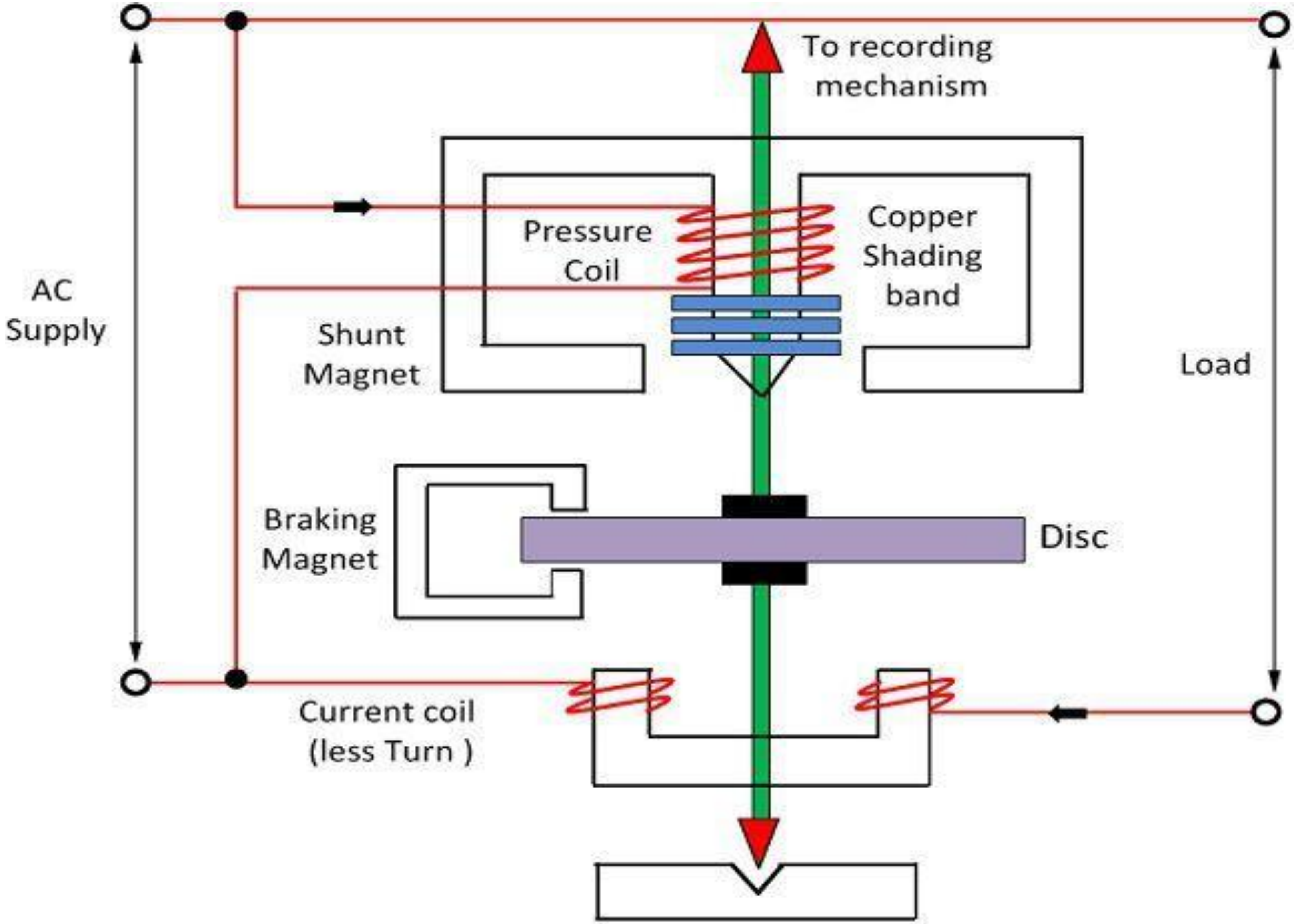
- The **meter** which is used for **measuring** the **energy utilises** by the **electric load** is known as the energy meter.
- The **energy** is the total **power consumed** and utilised by the load at a **particular interval** of **time**.
- It is used in **domestic** and **industrial** AC circuit for measuring the power consumption.
- The meter is less **expensive** and **accurate**.
- **3** basic **types**:
  - **Electrolytic Energy Meter** – depends on electrolytic action.
  - **Clock Meter** – functions as in clock mechanism.
  - **Motor Meter** – works as if they are small motors, several types:
    - **Mercury Motor Meter**
    - **Commutator Motor Meter**
    - **Induction Type Motor Meter** – most common for ac energy meter.

Construction and Working Principle of Energy Meter

- The construction of the single phase energy meter is shown in the figure below.
- The energy meter has four main parts. They are the:
  - Driving System
  - Moving System
  - Braking System
  - Registering System

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.



Induction Type Energy Meter

- The series electromagnet is excited by the load current flow through the **current coil**.
- The coil of the shunt electromagnet is directly connected with the supply and hence carry the current proportional to the shunt voltage.
- This coil is called the **pressure coil**.
- The centre limb of the magnet has the **copper band**.
- These bands are adjustable.
- The main function of the copper band is to align the flux produced by the shunt magnet in such a way that it is exactly perpendicular to the supplied voltage.

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.
- When the devices consume power, the aluminium disc starts rotating, and after some number of rotations, the disc displays the unit used by the load.
- The number of rotations of the disc is counted at particular interval of time.
- The disc measured the power consumption in kilowatt hours.

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.
- This braking torque opposes the movement of the disc, thus reduces their speed.
- The permanent magnet is adjustable due to which the braking torque is also adjusted by shifting the magnet to the other radial position.

Registration (Counting Mechanism)

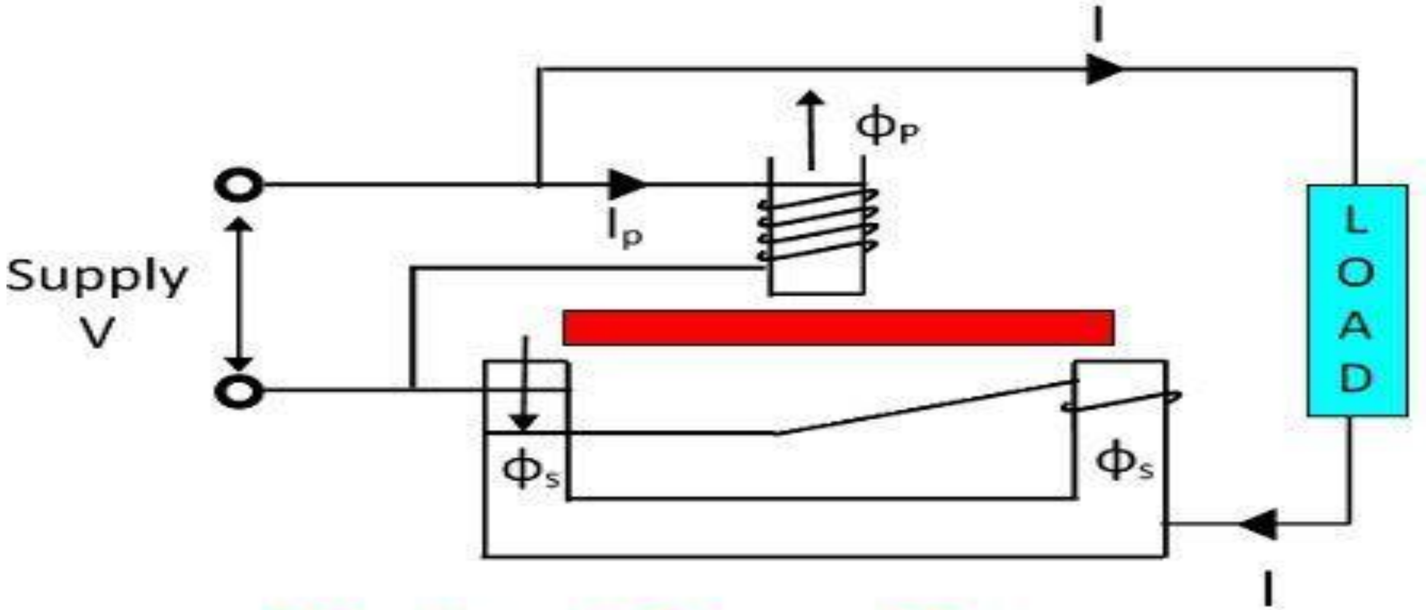
- The main function of the registration or counting mechanism is to record the number of rotations of the aluminium disc.
- Their rotation is directly proportional to the energy consumed by the loads in the kilowatt hour.
- The rotation of the disc is transmitted to the pointers of the different dial for recording the different readings.
- The reading in kWh is obtained by multiply the number of rotations of the disc with the meter constant.
- The figure of the dial is shown below.

Working of the Energy Meter

- The energy meter has the aluminium disc whose rotation determines the power consumption of the load.
- The disc is placed between the air gap of the series and shunt electromagnet.
- The shunt magnet has the pressure coil, and the series magnet has the current coil.
- The **pressure coil** creates the magnetic field because of the supply voltage, and the current coil produces it because of the current.
- The field induces by the voltage coil is **lagging** by **90^o** on the magnetic field of the current coil because of which eddy current induced in the disc.
- The interaction of the eddy current and the magnetic field causes torque, which exerts a force on the disc. Thus, the disc starts rotating.
- The force on the disc is proportional to the current and voltage of the coil.
- The permanent magnet controls their rotation.
- The permanent magnet opposes the movement of the disc and equalises it on the power consumption.
- The cyclometer counts the rotation of the disc.

Theory of Energy Meter

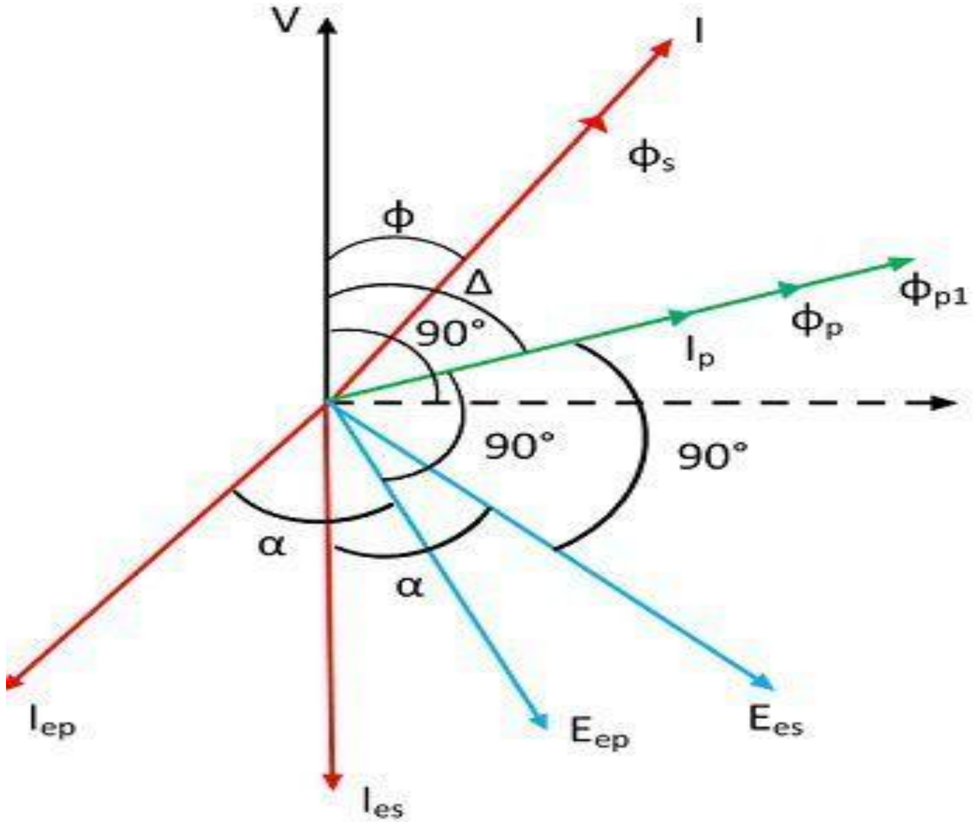
- The pressure coil has the number of turns which makes it more inductive.
- The reluctance path of their magnetic circuit is very less because of the small length air gap.
- The current $\mathbf{I_p}$ flows through the pressure coil because of the supply voltage, and it lags by 90^o.



Working of Energy Meter

- The $\mathbf{I_p}$ produces the two $\mathbf{\Phi_p}$ which is again divided into $\mathbf{\Phi_{p1}}$ and $\mathbf{\Phi_{p2}}$.
- The major portion of the flux $\mathbf{\Phi_{p1}}$ passes through the side gap because of low reluctance.
- The flux $\mathbf{\Phi_{p2}}$ goes through the disc and induces the driving torque which rotates the aluminium disc.
- The flux $\mathbf{\Phi_p}$ is proportional to the applied voltage, and it is lagged by an angle of $\mathbf{90^o}$.
- The flux is alternating and hence induces an eddy current $\mathbf{I_{ep}}$ in the disc.
- The load current passes through the current coil induces the flux $\mathbf{\Phi_s}$.
- This flux causes the eddy current $\mathbf{I_{es}}$ on the disc.
- The eddy current $\mathbf{I_{es}}$ interacts with the flux $\mathbf{\Phi_p}$, and the eddy current $\mathbf{I_{ep}}$ interacts with $\mathbf{\Phi_s}$ to produce the another torque.
- These torques are opposite in direction, and the net torque is the difference between these two.

- The phasor diagram of the energy meter is shown in the figure below.



Phasor Diagram of Energy Meter

- Let
  V – applied voltage
  I – load current
  Ø – the phase angle of load current
  $\mathbf{I_p}$ – pressure angle of load
  Δ – the phase angle between supply voltage and pressure coil flux
  f – frequency
  Z – impedance of eddy current
  ∝ – the phase angle of eddy current paths
  $\mathbf{E_{ep}}$ – eddy current induced by flux
  $\mathbf{I_{ep}}$ – eddy current due to flux
  $\mathbf{E_{ev}}$ – eddy current due to flux
  $\mathbf{I_{es}}$ – eddy current due to flux

- The net driving torque of the dis is expressed as

$$T_d \propto \emptyset_1\emptyset_2\frac{f}{Z}sin\beta cos\alpha = K_1\emptyset_1\emptyset_2\frac{f}{Z}sin\beta cos\alpha$$

  where $\mathbf{K_1}$ – constant, $\mathbf{\Phi_1}$ and $\mathbf{\Phi_2}$ are the phase angle between the fluxes.
- For energy meter, we take $\mathbf{\Phi_p}$ and $\mathbf{\Phi_s}$.
- **β** – phase angle between fluxes $\mathbf{\Phi_p}$ and $\mathbf{\Phi_p}$ = (**Δ – Φ**), therefore

$$Driving\ Torque, T_d = K_1\emptyset_1\emptyset_2\frac{f}{Z}\sin(\Delta - \emptyset)\,cos\alpha$$

$$But\ \emptyset_p \propto V, and\ \emptyset_p \propto I$$

$$T_d \propto K_2VI\frac{f}{Z}\mathrm{Sin}(\Delta - \emptyset)cos\alpha$$

- If **f**, **Z** and **α** are constants,

$$T_d = K_3VIsin(\Delta - \emptyset)$$

- If **N** is steady speed, braking torque: $T_B = K_4 N$
- At steady state, the speed of the driving torque is equal to the braking torque.

$$K_4 N = K_3 VI(\Delta - \emptyset)$$

$$N = KVIsin(\Delta - \emptyset)$$

- If **Δ = 90º**, Speed = $N = KVIsin(90° - \emptyset) = KVIcos\emptyset$

$$= K \times power$$

- The speed of the rotation is directly proportional to the power.

$$Total\ number\ of\ revolution = \int Ndt = \mathrm{K}\int VIsin(\Delta - \emptyset)$$

- If **Δ = 90º**, total number of revolutions:

$$= \mathrm{K}\int VIcos\emptyset dt$$

$$= \mathrm{K}\int power\ dt = K\ X\ energy$$

Frequency Meter

- *Frequency measurement is very important in many* applications, especially in AC power systems designed to run efficiently at one frequency only.
- If the AC is generated by an alternator, the **f** will be directly proportional to the shaft **N,** & **f** could be measured simply by measuring the **N** of the shaft.

Types of Frequency Meters

- The different types of frequency meters are : -
  - Mechanical resonance type
  - Electrical resonance type
  - Electrodynamometer type
  - Weston type
  - Ratiometer type
  - Saturable core type
- The frequency can also be measured and compared by other arrangements like counters, frequency bridges, stroboscopic methods and cathode ray oscilloscope.

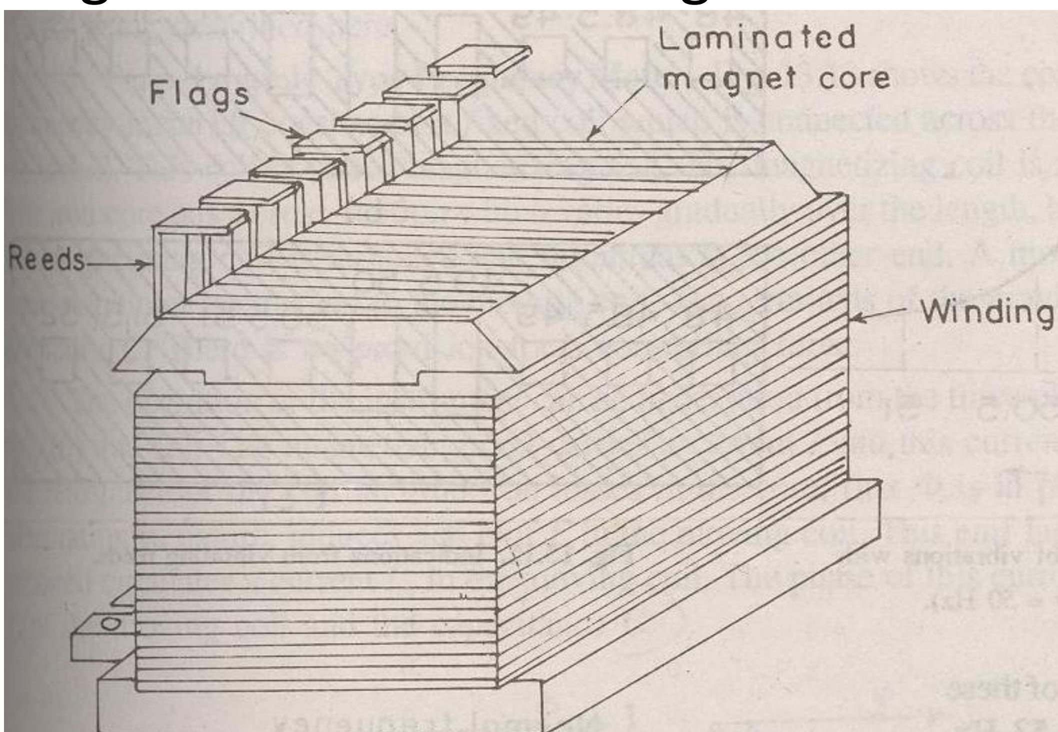
Mechanical Resonance Type Frequency Meter (Vibrating Reed Type)

Construction

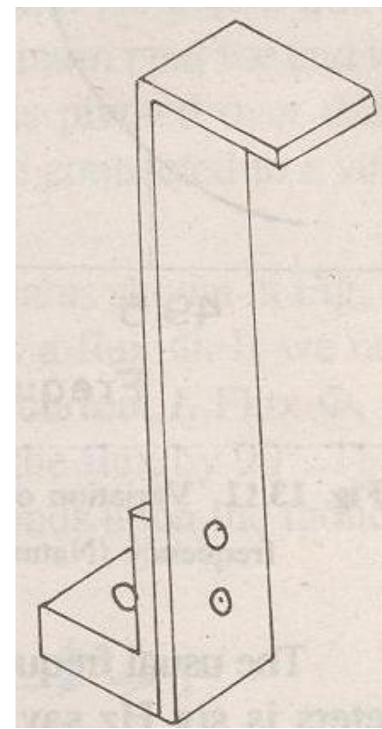
- This meter consists of a number of thin steel strips called **reeds** .
- These reeds are placed in a row, alongside and close to an electromagnet as shown in **Figure a**.
- The electromagnet has a laminated iron core and its coil is connected in series with a resistance, across the supply whose frequency is to be measured.
- The **reeds** are approximately about **4 mm wide** and **1/2 mm thic**k.
- All the reeds are **not exactly similar** to each other.
- They have either slightly different dimensions or carry different weights or flags at their tops.
- The **natural frequency** of vibration of the reeds depends upon their **weights** and **dimensions**.
- Since the **reeds** have different weights and sizes, their natural frequencies of vibration are different.
- The **reeds** are arranged in ascending order of natural frequency, the difference in frequency is usually **1/2 Hz**.

- Thus the natural frequency of first reed may be **47 Hz**, of the second **47.5 Hz**, of the next **48 H**z and so on.
- The **reeds** are fixed at the bottom end and are free at the top end.
- Since the **reeds** on a frequency meter are arranged to be viewed end on, they have a portion bent over at the free end to serve as a flag as shown in **Figure b**.
- The flags are painted white to afford maximum contrast against their black background.

a



b



Operation

- When the frequency meter is connected across the supply whose frequency is to be measured, the coil of electromagnet carries a current **i** which alternates at the supply frequency.
- The force of attraction between the reeds and the electromagnet is proportional to $\mathbf{i^2}$ and therefore this force varies at twice the supply frequency. ·
- Thus the force is exerted on the reeds every half cycle.
- All the reeds will tend to vibrate, but the reed whose natural frequency is equal to twice the frequency of supply will be in resonance and will vibrate most.
- Normally the vibration of other reeds is so slight as to be unobservable.
- The tuning in these meters is so sharp that as the excitation frequency departs from the resonant frequency the amplitude of vibration decreases rapidly becoming negligible for a frequency perhaps **1 to 2 %** away from resonance. This is clear from **Figure 12.11**.

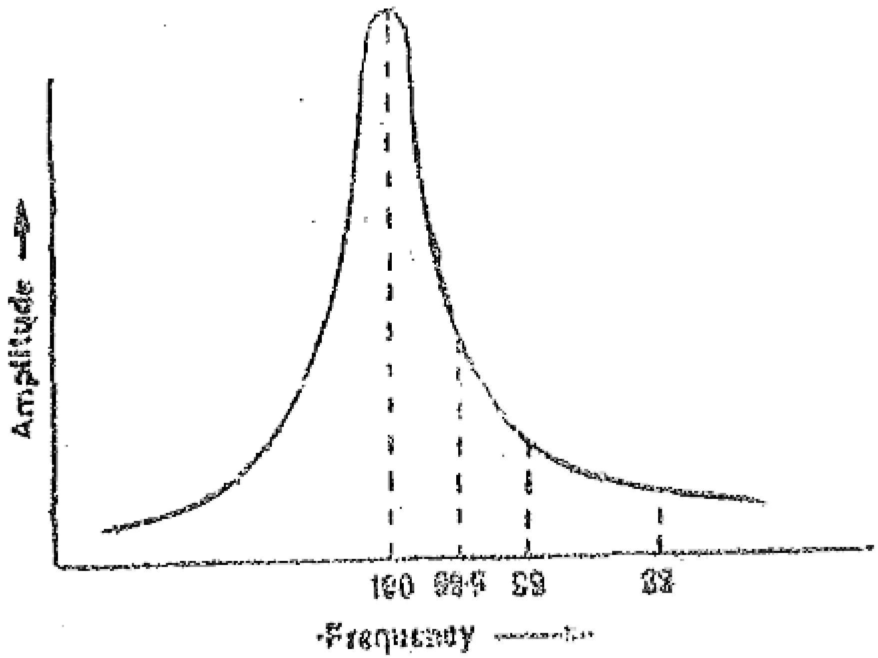


Fig. 12·11. Variation of amplitude of vibrations with frequency.

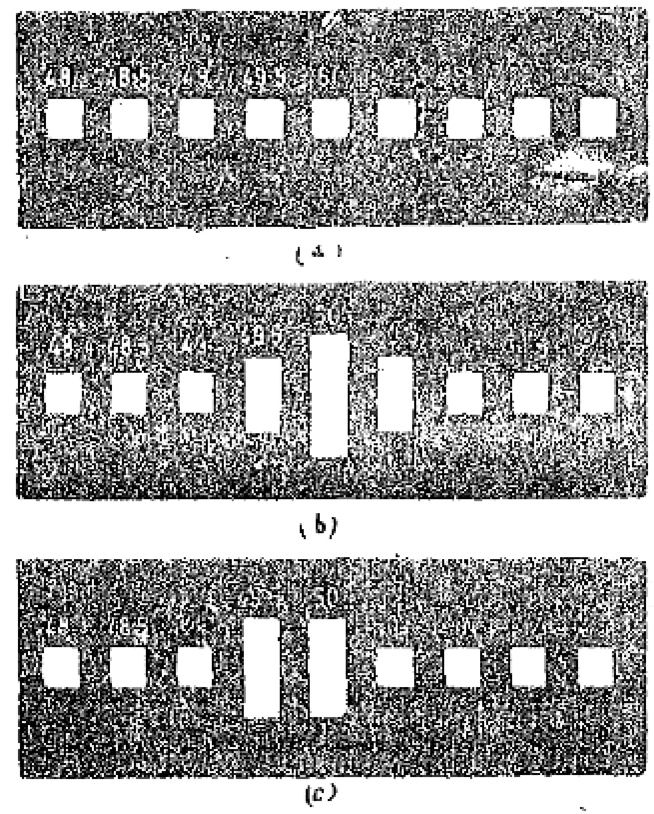


Fig. 12·12. Indications from vibrating reeds.

- When the **50 Hz** reed is vibrating with its maximum amplitude (when it is in resonance) some vibrations of **49·5 Hz** and **50·5 H**z reeds may be observed as shown in **Figure 12.12 b** but very little vibrations will be observed on **49 Hz** and **51 Hz** reeds.
- For a frequency exactly midway between that of the reeds, both will vibrate with amplitudes which are equal in magnitude, but considerably less than the amplitude which is at resonance.
- **Figure 12·12 c** shows the condition of vibrating reeds where the frequency is exactly midway between **49.5 Hz** and **50 Hz**.
- **Figure 12.12 a** shows the condition of the reeds when the frequency meter is unexcited i.e. is not connected to the supply.

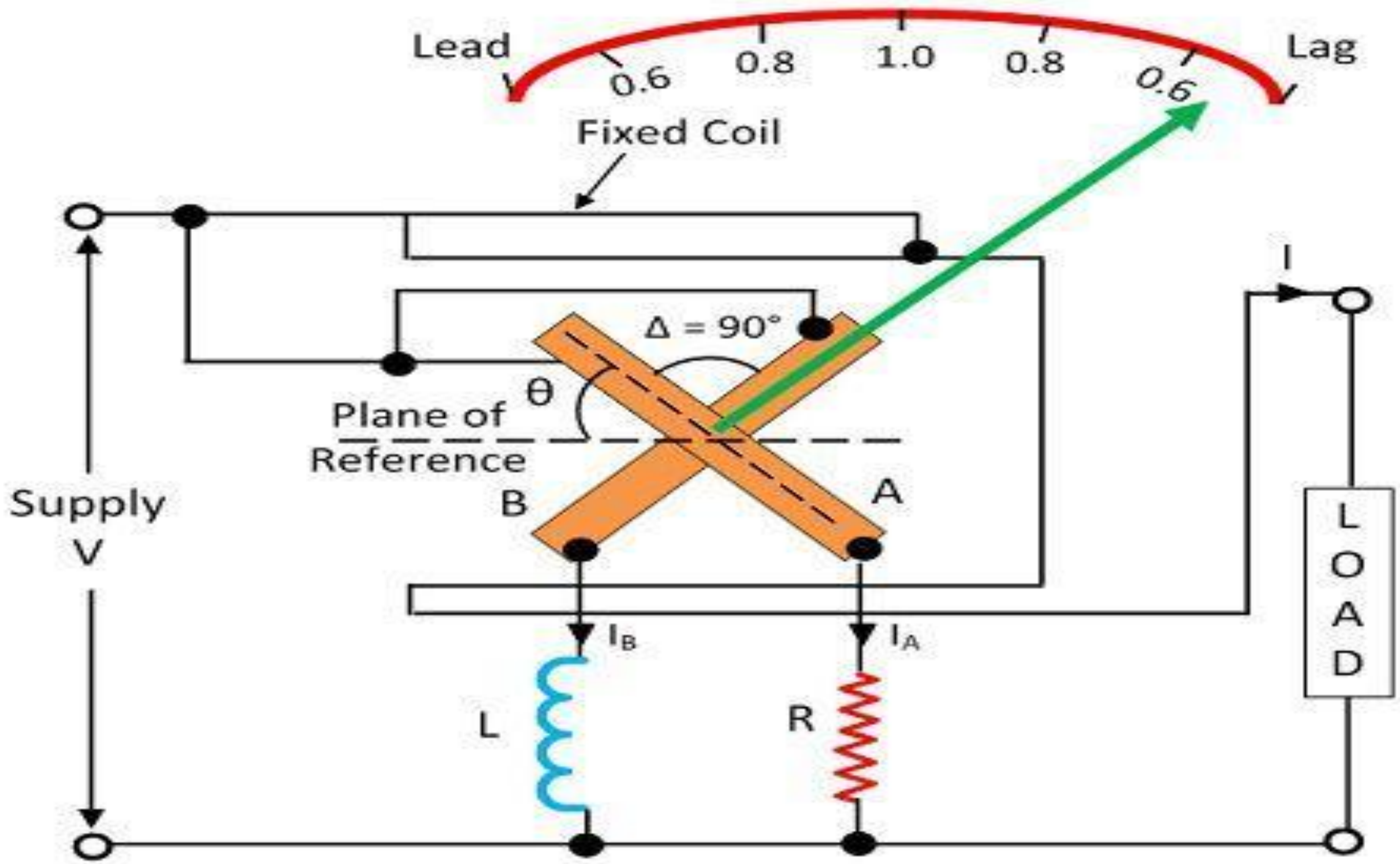
Power Factor Meter

- **Definition:** The power factor meter **measures** the **power factor** of a **transmission system**.
- The power factor is the cosine of the angle between the voltage and current.
- The power factor meter **determines the types of load** using on the line, and it also **calculates the losses** occur on it.
- The **power factor** of the **transmission line** is measured by dividing the product of voltage and current with the power.
- And the value of voltage current and power is easily determined by the voltmeter, ammeter and wattmeter respectively.
- This method gives high accuracy, but it takes time.
- The power factor of the transmission line is continuously changed with time.
- Hence it is essential to take the quick reading.
- The power factor meter takes a direct reading, but it is less accurate.
- The reading obtained from the power factor meter is sufficient for many purposes to expect precision testing.

- The power factor meter has the moving system called **pointer** which is in equilibrium with the two opposing forces.
- Thus, the **pointer** of the **power factor meter** remains at the same position which is occupied by it at the time of disconnection.
- The power factor meter is of two types.
- They are

1. **Electrodynamometer**
   - **Single Phase Electrodynamometer**
   - **Three Phases Electrodynamometer**
2. **Moving Iron Type Meter**
   - **Rotating Iron Magnetic Field**
   - **Number of Alternating Field**

Single Phase Electrodynamometer Power Factor Meter



Single Phase Electrodynamometer Type Power Factor Meter

- The construction of the single phase electrodynamometer is shown in the figure above.
- The meter has **fixed coil** which acts as a **current coil**.
- This coil is split into two parts and carry 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.
- The current in the **coil A** is **in phase** with the circuit while the current in the **coil B lag** by the voltage nearly equal to **90^o**.
- The connection of the moving coil is made through silver or gold ligaments which minimize the controlling torque of the moving system.

- The meter has two deflecting torque one acting on the **coil A**, and the other is on **coil B**.
- The windings are so arranged that they are opposite in directions.
- The pointer is in equilibrium when the torques are equal.
- Deflecting torque acting on the **coil A** is given as

$$\mathbf{T_A = KVIM_{max}\,Cos\Phi\,Sin\theta}$$

Where $\boldsymbol{\theta}$ – angular deflection from the plane of reference and $\mathbf{M_{max}}$ – maximum value of mutual inductance between the coils.

- The deflecting torque acting on **coil B** is expressed as

$$\mathbf{T_B = KVIM_{max}\,Cos(90^o - \Phi)\,Sin(90^o + \theta)}$$

$$\mathbf{T_B = KVIM_{max}\,Sin\Phi\,Cos\theta}$$

- The deflecting torque is acting on the clockwise direction.
- The value of maximum **mutual inductance** is same between both the deflecting equations.
- Hence at equilibrium: $\mathbf{T_A = T_B}$

$$\mathbf{KVIM_{max}\,Cos\Phi\,Sin\theta = KVIM_{max}\,Sin\Phi\,Cos\theta\text{ , thus, }\Phi = \theta.}$$

- This torque acts on anti-clockwise direction. The above equation shows that the deflecting torque is equal to the phase angle of the circuit.