CHAPTER 8

ELECTRICAL EQUIPMENTS

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8.1 WATTMETER

Power is defined as the rate at which energy is transformed or made available. The power of a circuit at any instant is equal to the product of the current in the circuit and the voltage across its terminal at that instant. The power in a dc circuit is best measured by separately measuring quantities V and I and by computing power by formula $P = VI$. In the case of ac circuit the instantaneous power varies continuously as the current and voltage of though a cycle of values. If the voltage and current are both sinusoidal the average power over cycle is given by the expression $P = VI \cos \phi$ watts where V and I are the r.m.s. values of voltage and current. A wattmeter is a device used to measure how much electrical power a circuit is producing, expressed in watts. It uses resistance to move a piece of metal, which is carefully calibrated along a display with wattage numbers on it, the higher the wattage, the more the piece of metal will move. The wattmeter is an instrument for measuring the electric power in watts of any given circuit. Wattmeter is the combination of both ammeter and voltammeter. It consists of two coil current coil and pressure coil. The current coil is inserted in series with the line carrying current to be measured and the pressure coil in series with a high non-inductive resistance R is connected across the load or supply terminal. There are different types of wattmeter and they are given below:

8.1.1 Dynamometer Type Wattmeter

A dynamometer is a device for measuring force, moment of force (torque) or power.

For example; the power produced by an engine, motor or other rotating prime mover can be calculated by simultaneously measuring torque and rotational speed.

A dynamometer can also be used to determine the torque and power required to operate a driven machine such as a pump. In that case, motoring or driving dynamometer is used. A dynamometer that is designed to be driven is called an absorption or passive dynamometer. A dynamometer that can either drive or absorb is called a universal or active dynamometer.

Figure below show the dynamometer. The fixed coil (current coil) which is divided into two equal portion in order to provide uniform field. It is designed to handle the full load current. The moving coil is used as a pressure coil. The fixed coil carry the current through the circuit and the moving coil carries the current proportional to the voltage across the circuit. A high non-inductive resistance is connected in series with the moving coil in order to limit the current in the circuit. Since one flux is proportional to load current and the other is proportional to load voltage, the torque on the pointer or the moving coil is proportional to the power. The magnetic field of the fixed and moving coils reacts on one other causing the moving coil to turn about its axis.

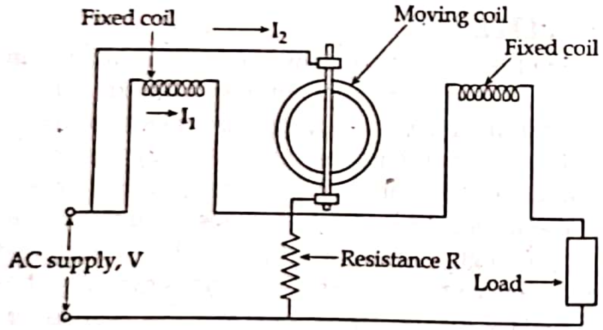


Figure: Dynamometer Type Wattmeter

The moving coil is carried on a pivoted spindle and the movement is spring controlled. The moving system carries a pointer and a damping vane, the latter moving in a sector-shaped box. The current coils are usually laminated when heavy current are to be carried. Damping is provided by light aluminum vanes moving in air dash pot.

Let, I_1 = Main circuit current flowing through the fixed coil

I_2 = Current proportional to the supply voltage

B = Flux density

V = Supply voltage

Since, $B \propto I_1$

and, $B = K_1 I_1$

where, K_1 is a constant.

Also, $I_2 \propto V$

so, $I_2 = K_2 V$

where, K_2 is another constant.

The deflecting torque is given by, $T_d \propto BI_2 \propto I_1 V$

$\therefore \quad T_d = KVI_1 = K \times \text{Power}$

where, K is a constant. In dc circuit the power is given by the product of the voltage and current. Hence the torque is directly proportional to power. In AC circuit the mean deflecting torque T_m is given by, $T_m \propto VI \cos\theta \propto$ true power.

8.1.2 Induction Type wattmeter

Figure below shows an induction type wattmeter. It consists of two laminated electromagnets. One of them is excited by the load current of main circuit, series or current magnets and its exciting coil (current coil) is connected in series with circuit. The other is excited by a current proportional to the voltage of the circuit called shunt magnet. It's exciting coil known as voltage of pressure coil is connected in parallel with the circuit. A thin aluminum disc is mounted in such a way that it cuts the fluxes of both magnets, and the deflecting torque is produced by the interaction between these fluxes and the eddy current which they induce in the disc.

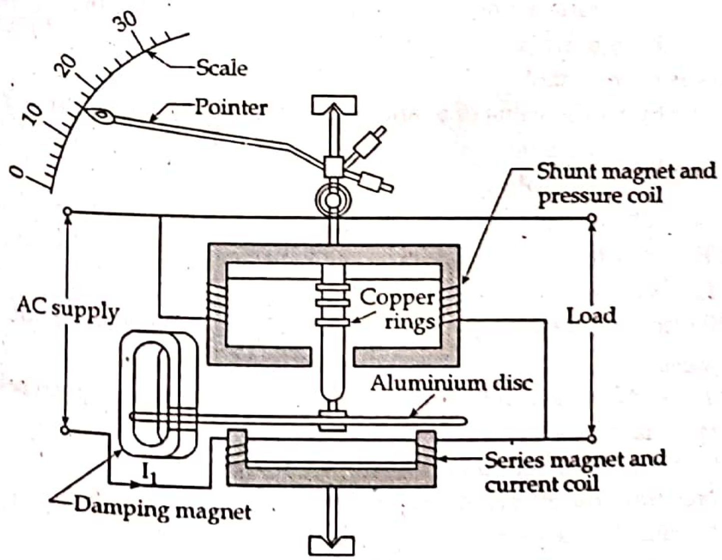


Figure: Induction Type wattmeter

The two or three copper rings are fitted on the central limb of the shunt magnet and can be adjust to make the resultant flux in the shunt magnet lag behind the applied voltage by 90°. The two pressure coils are joined in series and are so wound that both send the flux through the central limb in the same direction. The series magnet also carries two coils joined in series and are so wound that they magnetize their respective magnetic cores in the same direction. Desired phase shift between the two magnets fluxes can be obtained by adjusting the position of the copper shading rings. The controlling torque in induction wattmeter is provided by a spring fitted to the spindle of the moving system which also carries the pointer. The damping in these instruments is provided by the eddy current induced in the aluminum disc due to the fluxes produced by a permanent magnet.

The current coil carries the line current I_1 so that the flux produced by it is directly proportional to the line current I_1 and is in phase with it.

$$\phi_1 \propto I_1$$

The pressure coil of the shunt magnet is made highly inductive having an inductance L and negligible resistance. This is connected across the supply voltage V,

$$\phi_2 \propto I_2 \propto \frac{V}{\omega L}$$

where, $\omega = 2\pi f$

f = Supply frequency

ϕ_2 lags behind the supply voltage by 90°. Now let the load current I_1 lag behind V by an angle ϕ. Therefore the phase angle between ϕ_1 and ϕ_2,

$$\alpha = (90° - \phi)$$

The Deflection torque acting on the aluminum disc is given by,

$$T_d = K\omega\, \phi_1\phi_2 \sin\alpha$$

where, K is the constant

Now substituting the value of ϕ_1 and ϕ_2 in above equation we get,

$$T_d = K\omega\, I_1 \frac{V \sin(90° - \phi)}{\omega L}$$

or, $T_d = K'VI_1 \cos\phi$

where, K' is constant,

$\therefore$ $T_d \propto VI_1 \cos\phi \propto$ Power

The deflection torque is proportional to the power in the load circuit.

Advantages

Some of the advantages of the induction type wattmeter are given below:

1. Have large scales
2. Can handle current upto 100 amperes.
3. Free from the effects of stray fields.
4. Practically free from frequency errors.

Disadvantages

Some of the disadvantages are given below:

1. Scale is not uniform.

2. Temperature errors.
3. Used only when the frequency and the supply voltage are constant.

8.2 ENERGY METER

The meter which is used for measuring the energy utilizes by the electric load is known as the energy meter. It is also known as Watt- hour 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. Energy meter is an integrating instrument continuously measuring the integral value of either the total amount of energy in kilowatt hour (kWh) supplied to the load circuit in a given time. One kilowatt- hour is the quantity of electric energy needed to supply 1,000 watts of electricity for a time of one hour. One kWh is referred as one unit of energy.

Energy meters used for measurement of energy have moving systems that revolve continuously, unlike in indicating instruments where it deflects only through a fraction of a revolution. In energy meters, the speed of revolution is proportional to the power consumed. Thus, total number of revolutions made by the meter moving system over a given interval of time is proportional to the energy consumed. In this context, a term called meter constant, defined as the number of revolutions made per kWh, is used. Value of the meter constant is usually marked on the meter enclosure.

The energy meter can be broadly grouped into:

a) Electrolytic meters b) Clock meters c) Motor meters

Construction of Energy Meter

The construction of the single phase energy meter is shown in the figure below.

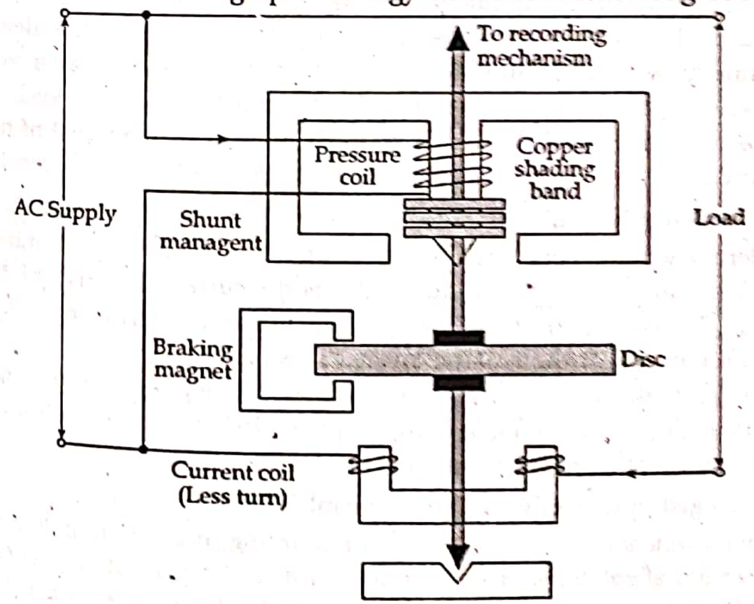


Figure: Induction type energy meter

The energy meter has four main parts. They are;

a) Driving System
b) Moving System
c) Braking System
d) Registering System

a) 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. 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.

b) 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 measure the power consumption in kilowatt hours.

c) 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.

d) Registering (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. Cyclometer Registers can also be used for this purpose. The figure of the dial is shown below.

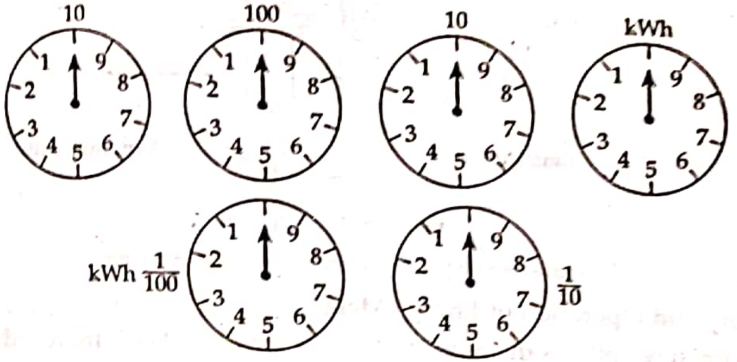


Figure: Pointer type register

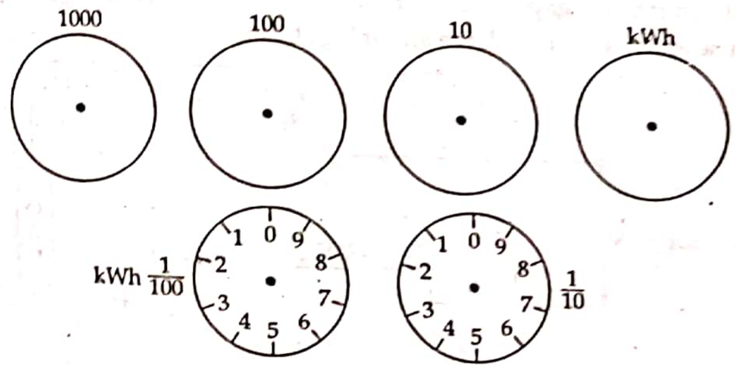


Figure: Cyclometer registers

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° 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 equalizes it on the power consumption. The cyclometer counts the rotation of the disc.

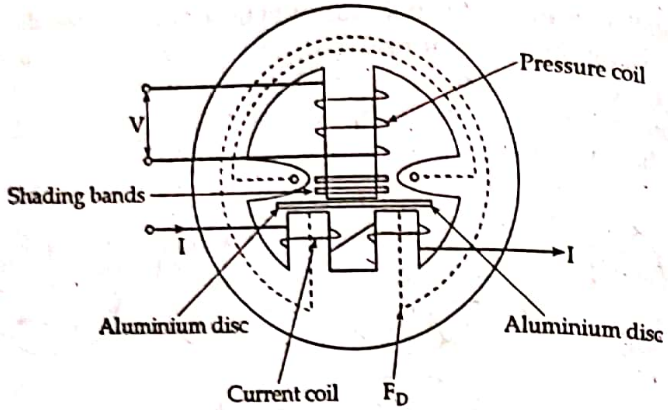


Figure: Single phase induction type energy meter

Theory and Operation 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 I_p flows through the pressure coil because of the supply voltage and it lags by 90°.

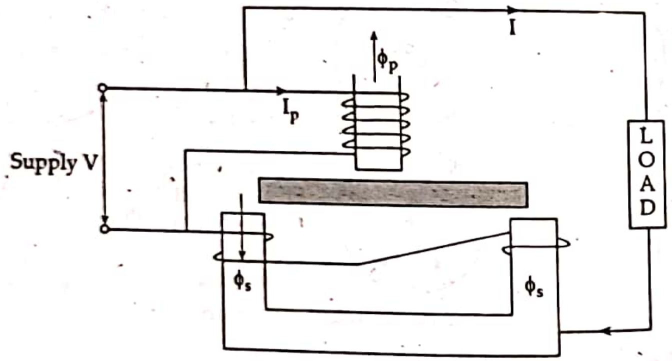


Figure: Working of energy meter

The I_p produces the two ϕ_p which is again divided into ϕ_{p1} and ϕ_{p2}. The major portion of the flux ϕ_{p1} passes through the side gap because of low reluctance. The flux ϕ_{p2} goes through the disc and induces the driving torque which rotates the aluminium disc. The flux ϕ_p is proportional to the applied voltage, and it is lagged by an angle of 90°. The flux is alternating and hence induces an eddy current I_{ep} in the disc. The load current passes through the current coil induces the flux ϕs. This flux causes the eddy current I_{es} on the disc. The eddy current I_{es} interacts with the flux ϕ_p, and the eddy current I_{ep} interacts with ϕ_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.

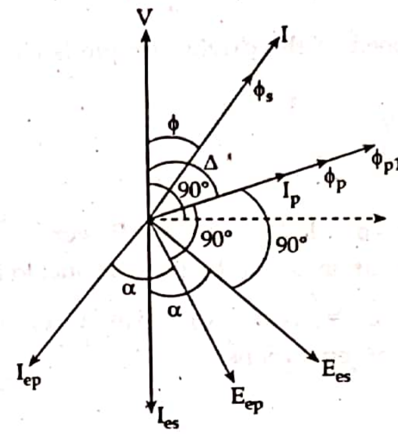


Figure: Phasor diagram of energy meter

Let, V = Applied voltage

I = Load current

ϕ = The phase angle of load current

I_p = Pressure angle of load

Δ = The phase angle between supply voltage and pressure coil flux

ϕ = Frequency

Z = Impedance of eddy current

$\propto$ = The phase angle of eddy current paths

E_{ep} = Eddy emf induced by flux ϕ_p

I_{ep} = Eddy current due to flux ϕ_p

E_{es} = Eddy emf induced by flux ϕ_s

I_{es} = Eddy current due to flux ϕ_s

The net driving torque of the disc is expressed as

$$T_d \propto \phi_1\phi_2 \frac{f}{Z} \sin\beta \cos\alpha = K_1 \phi_1\phi_2 \frac{f}{Z} \sin\beta \cos\alpha$$

where, K_1 = Constant

ϕ_1 and ϕ_2 are the phase angle between the fluxes. For energy meter, we take ϕ_p and ϕ_s. Thus, β-phase angle between fluxes ϕ_p and $\phi_s = (\Delta - \phi)$, therefore

Driving torque, $T_d = K_1\phi_1\phi_2 \frac{f}{Z} \sin(\Delta - \phi) \cos\alpha$

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

$$T_d \propto K_2 VI \frac{f}{Z} \sin(\Delta - \phi) \cos\alpha$$

If f, Z and α are constants,

$$T_d = K_3 VI \sin(\Delta - \phi)$$

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.

or, $K_4 N = K_3 VI\,(\Delta - \phi)$

$\therefore$ $N = KVI \sin(\Delta - \phi)$

If $\Delta = 90°$,

$N = KVI \sin(90° - \phi) = KVI \cos\phi = K \times \text{Power}$

Thus the speed of the rotation is directly proportional to the power.

Total number of revolution $= \int N dt = K \int VI \sin(\Delta - \phi)$

If $\Delta = 90°$, total number of revolutions

$= K \int VI \cos\phi \, dt$

$= K \int \text{Power}\, dt = K \times \text{Energy}$

Thus, total number of revolutions is proportional to the energy consumed.

Errors in the energy meter

Assuming the supply voltage and frequency constant, the induction type energy may have the following errors:

a) Speed error

Due to the incorrect position of the brake magnet, the braking torque is not correctly developed. This can be tested when meter runs at its full load current alternatively on loads of unity power factor and a low lagging power factor. The speed can be adjusted to the correct value by varying the position of the braking magnet towards the centre of the disc or away from the centre and the shielding loop. If the meter runs fast on inductive load and correctly on non-inductive load, the shielding loop must be moved towards the disc. On the other hand, if the meter runs slow on non-inductive load, the brake magnet must be moved towards the center of the disc.

b) Meter phase error

An error due to incorrect adjustment of the position of shading band results an incorrect phase displacement between the magnetic flux and the supply voltage (not in quadrature). This is tested with 0.5 p.f. load at the rated load condition. By adjusting the position of the copper shading band in the central limb of the shunt magnet this error can be eliminated.

c) Friction error

An additional amount of driving torque is required to compensate this error. The two shading bands on the limbs are adjusted to create this extra torque. This adjustment is done at low load (at about 1/4th of full load at unity p.f.)

d) Creep

In some meters a slow but continuous rotation is seen when pressure coil is excited but with no load current flowing. This slow revolution records some energy. This is called the creep error. This slow motion may be due to (a) incorrect friction compensation, (b) to stray magnetic field (c) for over voltage across the voltage coil. This can be eliminated by drilling two holes or slots in the disc on opposite side of the spindle. When one of the holes comes under the poles of shunt magnet, the rotation being thus limited to a maximum of 180°. In some cases, a small piece of iron tongue or vane is fitted to the edge of the disc. When the position of the vane is adjacent to the brake magnet, the attractive force between the iron tongue or vane and brake magnet is just sufficient to stop slow motion of the disc with full shunt excitation and under no load condition.

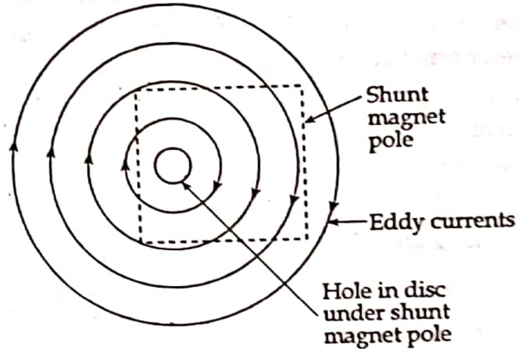


Figure: Creeping adjustment

e) Temperature effect

Energy meters are almost inherently free from errors due to temperature variations. Temperature affects both driving and braking torques equally (with the increase in temperature the resistance of the induced-current path in the disc is also increases) and so produces negligible error. A flux level in the brake magnet decreases with increase in temperature and introduces a small error in the meter readings. This error is frequently taken as negligible, but in modern energy meters compensation is adopted in the form of flux divider on the break magnet. Energy meter constant K is defined as $K = \dfrac{\text{Number of revolutions}}{\text{kWh}}$

In commercial meters the speed of the disc is of the order of 1,800 revolutions per hour at full load.

Advantages of induction type meters

Following are the advantages of induction type energy meters.

1. They are inexpensive as compared to moving iron type instruments.
2. They have high torque to weight ratio as compared to other instruments.

3. They retain their accuracy over wide range of temperature as well as loads.
4. Its construction simple and strong.
5. It requires less maintenance.
6. Its range can be extended with the help of instrument transformers.

Disadvantages of induction type meters

1. It can be only used for AC circuits.
2. The creeping can cause errors.
3. Lack of symmetry in magnetic circuit can cause errors.

Example 1

The meter constant of a 220 V, 5 A energy meter is 2,000 revolutions per kWh. The meter is tested at half load at rated voltage and unity power factor. The meter is found to make 3.4 revolutions in 116 seconds. Determine the meter error at half load.

Solution:

Actual energy consumed at half load during 166 seconds;

$$= VI \cos\phi \times t \times 10^{-3}$$

$$= 220 \times 2.5 \times \frac{116}{60 \times 60} \times 10^{-3}$$

$$= 17.72 \times 10^{-3} \text{ kWh}$$

Energy as recorded by the meter,

$$= \frac{\text{Number of revolutions made}}{\text{Meter constant (rev/kWh)}} = \frac{34}{2,000} = 17 \times 10^{-3} \text{ kWh}$$

$$\text{Hence, Error} = \left(\frac{17 - 17.72}{17.72}\right) \times 100 = -4.06\% \text{ (meter runs slower).}$$

Example 2

A 230 V, 5 A energy meter on full load unity power factor test makes 60 revolutions in 360 seconds. If the designed speed of the disc is 520 revolutions per kWh, find the percentage error.

Solution:

Actual energy consumed at full load during 360 S.

$$= VI \cos\phi \times t \times 10^{-3} = 230 \times 5 \times \frac{360}{60 \times 60} \times 10^{-3}$$

$$= 115 \times 10^{-3} \text{ kWh}$$

Energy as recorded by the meter,

$$= \frac{\text{Number of revolution made}}{\text{Meter constant (rev/kWh)}} = \frac{50}{520} = 115.385 \times 10^{-3} \text{ kWh}$$

$$\therefore \quad \text{Error} = \left(\frac{115.385 - 115}{115}\right) \times 100 = 0.34\% \text{ (meter runs faster)}$$

Example 3

An energy meter is design to have 80 revolutions of the disc per unit of energy consumed calculate the number of revolutions made by the disc when measuring the energy consumed by a load carrying 30 A at 230 V and 0.6 power factor. Find the percentage error if the meter actually makes 330 revolutions.

Solution:

Actual energy consumed by the load in one hour,

$$= VI \cos\phi \times t \times 10^{-3}$$

$$= 230 \times 30 \times 0.6 \times 1 \times 10^{-3}$$

$$= 4.14 \text{ kWh}$$

The meter makes 80 revolutions per unit of energy consumed *i.e.,* per kWh. Thus number of revolutions made by the meter be recorded 4.14 kWh is $4.14 \times 80 = 331.2$

In case the meter makes 330 revolutions, then error is given as,

$$\text{Error} = \left(\frac{330 - 331.2}{331.2}\right) \times 100 = -0.36\% \text{ (meter runs slower).}$$

8.3 FREQUENCY METER

The meters which are used in the circuit to indicate the frequency of the supply are called frequency meters. The frequency meters are classified based on the principle of operation as,

a) Mechanical resonance type frequency meter
b) Electrical resonance type frequency meter
c) Weston type frequency meter
d) Ratio meter type frequency meter
e) Saturable core frequency meter

The mechanical resonance type frequency meter is called vibrating reed type frequency meter. The electrical resonance type frequency meter is called ferrodynamic frequency meter.

A. Vibrating reed type frequency meter or mechanical resonance type frequency meter

This meter works on the principle of mechanized resonance. The meter consists of number of thin steel strips called reeds. The bottom of the reed is rigidly fixed to an electromagnet. The upper part of the reed is free and bent at right angles. An electromagnet has a laminated iron core which carries an excitation coil having large number of turns. This coil is connected across the voltage whose frequency is to be measured. The flags are painted white to have good visibility on the black background. The basic construction of this type of meter and construction of reed is shown is shown below.

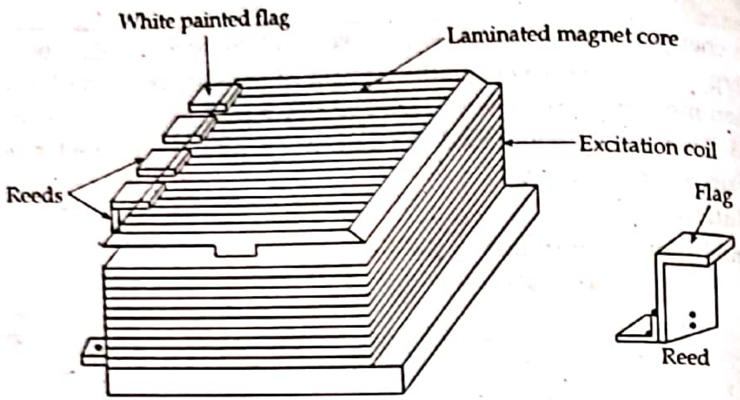


Figure: Vibrating reed type frequency meter

The reeds are manufactured such that their weight and dimensions are different. Hence, their natural frequencies of vibrations are different. The reeds are arranged in the ascending order of their natural frequencies and the natural frequencies are generally differ by half cycle. So, natural frequency of first reed may be 48 Hz, next may be 48.5 Hz, next may be 49 Hz and so on.

When meter is connected in the system, the coil carries current i which alternates at the supply frequency. This produces an alternating flux. This produces a force of attraction on the reeds which is proportional to square of the current i^2 and hence all the reeds vibrate with a force which varies at twice the supply frequency. But the reed whose natural frequency is twice the frequency of supply voltage will be in resonance and will vibrate most. The tuning in such meter is so precise that for a 1 to 2% change in the frequency way from resonating frequency, the amplitude of vibration decreases drastically and becomes negligible. Thus when a reed corresponding to 50 Hz is vibrating with maximum amplitude, other reeds vibrate but with negligible amplitudes which cannot be noticed. This is shown below.

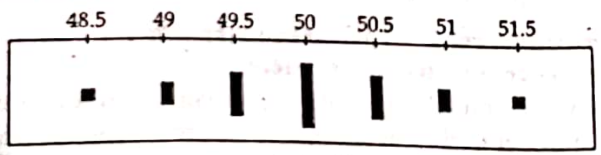


Figure: Vibrating reeds

The advantages of this frequency meter are that the reading is not affected by the change in the waveform of the supply voltage and simple mechanism. But if supply voltage is low, the vibrations may not be noticed. So, supply voltage should not be low for effective operation. One more limitations of the meter is that the difference in the frequencies of the adjacent reeds is 0.5 only. So reading corresponding to less than half

the frequency difference cannot be obtained. So, precise frequency measurements is not possible. The accuracy of the meter depends on the proper tuning of the reeds

B. Electrical resonance type frequency meter

Figure below shows the constructions of the electrical resonance type frequency meter.

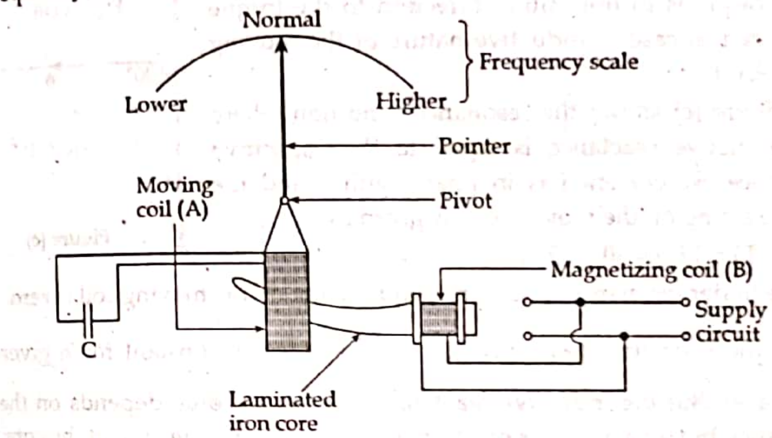


Figure: Electrical resonance type frequency meter

It consists of a laminated iron core-on one end of the core a fixed coil is wound which is called magnetizing coil. This coil is connected across the supply whose frequency is to be measured. On the same core, a moving coil is pivoted which carries a pointer. A capacitor C is connected across the terminals of the fixed coil.

Let, I = Current through magnetizing coil

ϕ = Flux in the iron core

The flux ϕ is assumed to be in phase with the current I. This flux induces the voltage in the moving coil which always lags flux ϕ by 90°.

Let, i = Current through moving coil.

The phase of the current i depends on the inductance of the moving coil and the capacitor C.

Consider the different cases and the corresponding Phasor diagrams to understand the working of the meter.

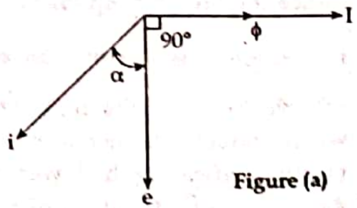


Figure (a)

In figure (a), the circuit of moving coil A is assumed to be inductive; hence current i lags the induced voltage e by angle α. Hence the torque acting on the moving coil is given by,

$$T_d \propto I\, i \cos(90° + \alpha) \qquad (1)$$

In figure (b), the circuit of moving coil A is assumed to be largely capacitive, hence current i leads the induced voltage e by angle β. Hence the torque acting on the moving coil is given by,

$$T_d \alpha I i \cos(90 - \beta) \quad (2)$$

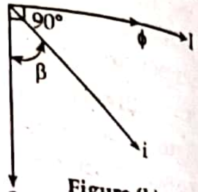


Figure (b)

This torque is in opposition direction to the torque produced in case of inductive nature of the moving coil circuit.

The figure (c) shows the resonance condition where the inductive reactance is equal to the capacitive reactance. So current i is in phase with e and the torque acting on the moving coil is given by,

$$T_d \alpha I i \cos 90° = 0$$

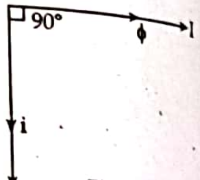


Figure (c)

Hence under resonance condition, torque acting on the moving coil is zero.

Now, the capacitive reactance $X_C = \frac{1}{\omega C} = \frac{1}{2\pi fC}$ is constant for a given frequency. But the inductive reactance $X_1 = \omega L$ not only depends on the frequency but also depends on the position of the moving coil on the core. Nearer the moving coil to the magnetizing coil, higher is its inductance. Thus for a given frequency, moving coil moves in such a way to achieve a position where $X_L = X_C$ and electrical resonance is achieved. At this position, torque on the moving coil is zero and the pointer indicates the corresponding frequency. The design of the instrument is such that for a normal frequency, the coil takes a mean position. The capacitor C is chosen such that the electrical resonance takes place at this mean position and pointer indicates the normal frequency.

If frequency is higher than the normal value,

Then, $X_C = \frac{1}{2\pi fC}$ decreases. Hence, $X_L = 2\pi fL$ must decrease in order to achieve resonance. So moving coil moves away from the magnetizing coil on the core and pointer moves to the right of the mean position, indicating higher frequency.

If frequency is lower than normal value, $X_C = \frac{1}{2\pi fC}$ increases. So to achieve $X_L = X_C$, the moving coil moves towards the magnetizing coil where inductance increases. Thus pointer moves to the left of the mean position indicating the lower frequency.

An important advantage of the instrument is that the great sensitivity is achieved as the inductance of the moving coil changes slowly with variation of its position on the core. This meter is also called ferrodynamic frequency meter.

C. Weston frequency meter

This is moving iron type instrument. It works on the changes in current distribution between two, parallel circuits, one of which is inductive and other non-inductive when the frequency changes. This is due to the fact that the on of the inductive circuit changes with the change in the frequency ($X_L = 2\pi fL$)

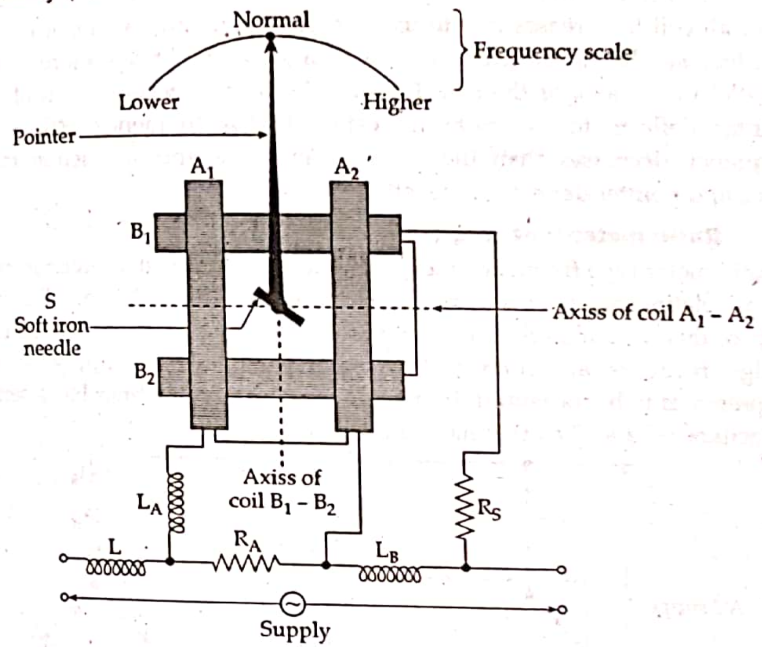


Figure: Weston frequency meter

It consists of two fixed coils, each divided in two parts $A_1 - A_2$ and $B_1 - B_2$. The axes of the two coils are mutually perpendicular to each other. At the center of the axes, a soft iron needle is pivoted which is thin and long. The needle carries a pointer and damping vanes. There is no controlling device to produce controlling torque.

The coil A is connected in series with an inductor L_A across a non-inductive resistance R_A. The coil B is connected in series with a non-inductive resistance R_B across an inductance L_B. The resistance R_A and L_B are in series with another L and the combination is across the supply voltage. The main purpose of inductor L is for damping out the harmonics in the wave form of the current. This eliminates the errors caused due to the harmonics.

When the meter is connected across the supply, both the coils carry currents. The two magnetic fields produced by the two currents are at right angles to each other. These fields act upon the soft iron needle causing its deflection. So position of needle and hence the pointer depends on the currents through the coils A and B. In practice, the values of R_A, R_B, L_A and L_B are so chosen that the equal currents flow through the coils and needle takes the mean position which indicates the normal frequency.

If the frequency increases above the normal value, then the reactance's L_A and L_B increase while non-inductive resistances R_A and R_B remain same so, impedance of the coil A increases. Hence the current through coil A is reduced. While voltage drop across R_A remains same. While the current through coil B increases due to its parallel combination with coil B more stronger so the needle moves in such a way that it lies more nearly parallel to the axis of the coil B. So needle tries to become vertical and pointer deflects to the right indicating higher frequency. When the frequency decreases than the normal value, the opposite action takes place and pointer deflects to the left.

D: Ratio meter type frequency meter

A ratio meter type frequency meter consists of a ratio meter which gives a linear relationship between the current ratio and the deflection. The two coils of this ratio meter are fed with rectifiers. The input sides of the two bridge rectifiers are connected to alternating current supply whose frequency is to be measured. Input side of one bridge rectifier has a series capacitance C and the other has series resistance R.

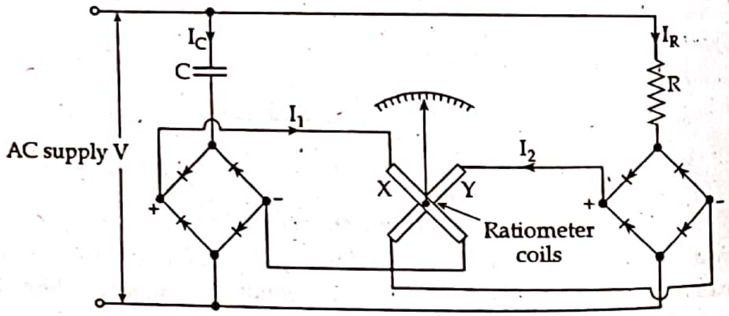


Figure: Ratio meter type frequency meter

Let V be the supply voltage and f be its frequency. Output current of bridge rectifier 1 is:

$$I_1 \propto I_C \propto 2\pi f VC$$

Output current of bridge rectifier 2 is:

$$I_2 \propto I_R \propto \frac{V}{R}$$

$\therefore$ Deflection, $\theta = k\left(\frac{I_1}{I_2}\right) = k_1 \frac{2\pi fVC}{V/R} = 2\pi k_1 CRf$

Now, C, k_1 and R are constants

$\therefore$ $\theta = k_2 f$

Thus the instruments has a linear scale of frequency in case the ratiometer is so designed that the deflection is directly proportional to the ratio of

two currents. If is clear from above that the supply voltage V does not appear in the expression for deflection. Thus the instrument may be used for a fairly wide range of voltage below the maximum specified. However, the voltage should not be to low otherwise distortions are introduced which make the meter read wrongly.

E. Saturable core type frequency meter

A saturable core frequency meter is shown below.

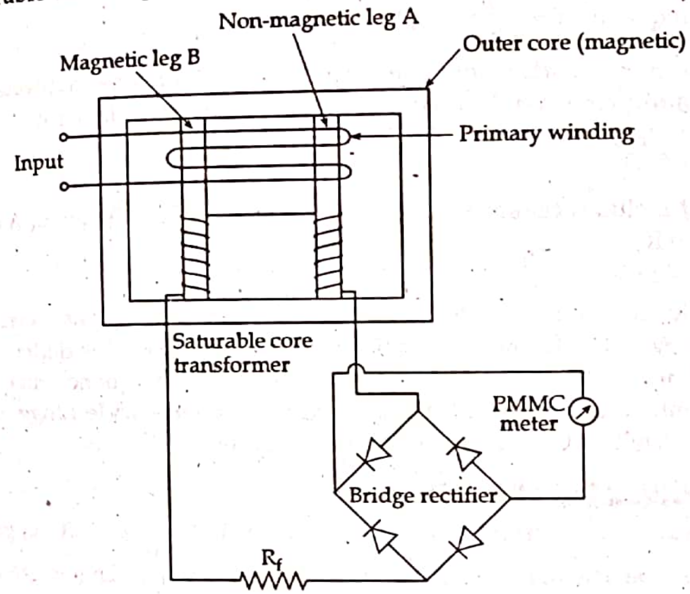


Figure: Staturable core frequency meter

This meter has a saturable core transformer as its primary detector. The core assembly consists of three parts viz;

i) An outer core which is made of magnetic material and has a sufficiently large cross section so that it does not saturate.

ii) A leg A made of non-magnetic material.

iii) A leg B which is made of magnetic material, the cross section of leg A being the same as that of B. The B saturates at low values of mmfs.

The primary (input) winding is wound both legs A and B. The secondary winding consists of two coils, one around leg A and the other around B. The two coils are connected in series. The emfs induced in these two coils oppose each other. When there is saturation, the rate of increase of induced voltage in the secondary coil over leg A will equal the rate of increase of induced voltage in secondary coil wound over magnetic leg B. Thus the rate of increase in these two coils will cancel, and the secondary output voltage will not be a function of the primary voltage but will be a function of frequency only.

Let, ϕ be the difference between the flux of leg A and B. Then the induced emf in the secondary winding is,

$$e = N\frac{d\phi}{dt}$$

and, The average secondary voltage per half cycle is,

$$E_{av} = \frac{\omega}{\pi}\int_0^{\pi/\omega} e\,dt = \frac{\omega}{\pi}\int_{-\phi_m}^{\phi_m} d\phi = 4\,Nf\phi_m$$

or, Frequency, $f = \frac{E}{4\,N\,\phi_m} = kE$

where, k is a constant after the magnetic leg B becomes saturate. The output of this circuit is rectified and the current in the dc meter is,

$$I_{av} = \frac{E_{av}}{R}$$

where, R includes the resistance of the bridge rectifier, the meter and the resistance R_1.

Hence, $f = kE\,I_{av}$

The deflection θ is directly proportional to current I_{av} as current is detected by a PMMC meter or deflection $\theta \propto I_{av} \propto f$. Thus the deflection of meter is proportional to the frequency. This type of frequency meter has the advantage that it can measure frequencies over a wide range and is especially well suited for use in tachometer system.

8.4 POWER FACTOR METER

On measuring the current, voltage and power in an ac circuit, its power factor can be calculate from the relation $\cos\phi = \frac{P}{VI}$. This method of determining the power factor of an electric circuit is however of low accuracy, has a number of disadvantages and is rarely used in practice. It is obviously desirable to have an instantaneous indication of the power factor of an ac circuit especially where this is varying continuously without having recourse to mathematical calculations of readings of several instruments. Power factor meter indicate directly, by a single reading, the power factor of the circuit to which they are connected. The accuracy obtained with the use of power factor meters is sufficient for most purposes other than high precision testing.

Power factor meters like wattmeters-have a current circuit and a pressure circuit. The current circuit carries the current in the circuit whose power factor is to be measured, or a definite fraction of this current. The pressure circuit is connected across the circuit whose power factor is to be measured and is usually split up into two parallel paths one inductive and the other non-inductive. The deflection of the instrument depends upon the phase difference between the main current and currents in the two paths of the pressure circuit *i.e.*, upon the power factor of the circuit. The deflection will be indicated by a pointer.

The moving system of power factor meter is perfectly balanced and there are no controlling forces. Hence when a power factor meter is disconnected from a circuit the pointer remains at the position which it occupied at the instant of disconnection. There are two types of power factor meters:

a) Electrodynamometer type
b) Moving iron type

A. Single phase electrodynamometer power factor meter

Construction

The construction of a single phase electrodynamometer type power factor meter is shown below

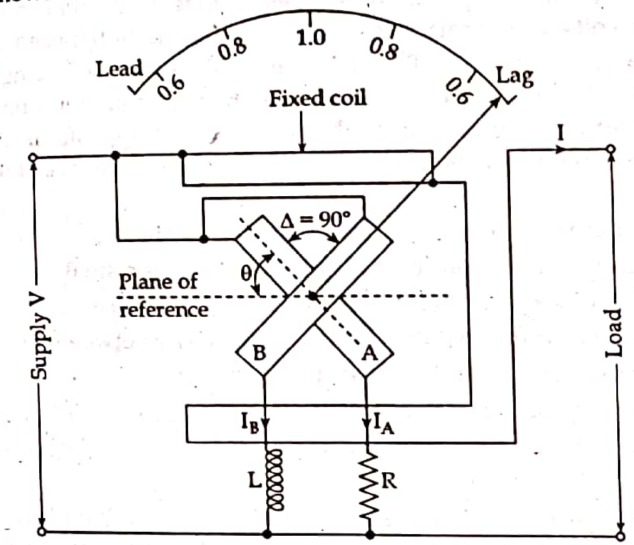


Figure: Single phase electrodynamometer type power factor meter

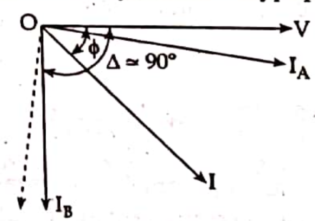


Figure: Phasor diagram

It consists of a fixed coil which acts the current coil. The coil is split up into two parts and carries the current of the circuit under test. Therefore, the magnetic field produced by this coil is proportional to the main current. Two identical pressure coils A and B pivoted on a spindle constitute the moving system. Pressure coil A has a non inductive resistance R connected in series with it and coil B has a high inductive choke coil L connected in series with it. The two coils are connected across the voltage of the circuit. The values of R and L are so adjusted that the two coils carry the same value of current through coil is in phase with the circuit voltage while that through coil B lags the voltage by an angle Δ which is nearly equal to 90°. The angle between the planes of coils is also made equal to Δ. There is no controlling device. Connections to moving coils are made by thin silver or gold ligaments which are externally flexible and thus give a minimum control effect on the moving system.

Theory

In order to simplify the problem, we assume that the current through coil B lags, the voltage by exactly 90°. Also that the angle between planes of coils is exactly 90°, (*i.e.*, $\Delta = 90°$). Now there will be two deflecting torques, one acting on coil A and other on coil B. The coil windings are so arranged that the torques due to the two coils are opposite in direction. Hence, the pointer will take up a position where there two torques are equal.

Let us consider the case of a lagging power factor of $\cos\phi$.

Deflecting torque acting on coil A, $T_A = KVI\, M_{max} \cos\phi \sin\theta$

where, θ = Angular deflection from the plane of reference

M_{max} = Maximum value of mutual inductance between the two coils

This torque say acts in the clockwise direction

Deflecting torque acting on coil B is,

$$T_B = KVI\, M_{max} \cos(90° - \phi) \sin(90° + \phi)$$
$$= KVI\, M_{max} \sin\phi \cos\theta$$

This torque acts in the anticlockwise direction. The value of M_{max} is the same in the two expressions, owing to similar constructions of the coils. The coils will take up such a position that the two torques are equal.

Hence at equilibrium,

$$T_A = T_B$$

or, $KVI\, M_{max} \cos\phi \sin\theta = KVI\, M_{max} \sin\phi \cos\theta$

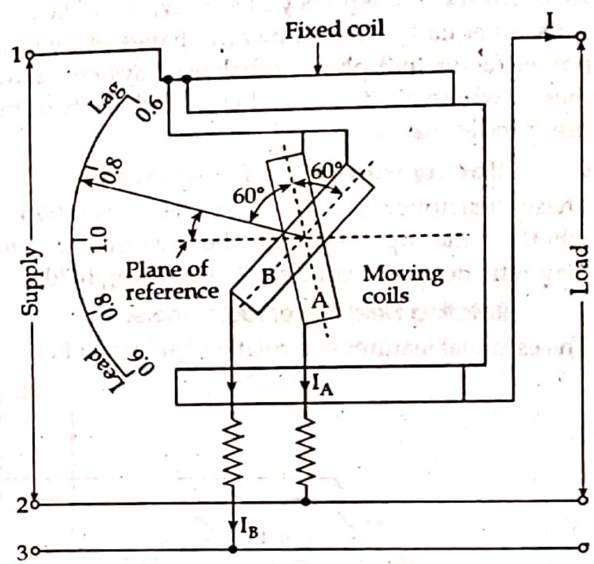
or, $\theta = \phi$

Therefore, the deflection of the instrument is a measure of phase angle of the circuit. The scale of the instrument can be calibrated in directly in terms of power factor. The instrument must be designed for and calibrated at the frequency of the supply on which it is to be used. In case the meter is used for any other frequency or if the supply contains harmonics it will give rise to serious errors in the indication on account change in the value of reactance of choke coil.

B. There phase electrodynamometer power factor method

Figure below shows the construction and connection of a 3 phase power factor meter. This meter is only use for balanced loads.

The two moving coils are so placed that the angle between their plane is 120°. They are connected across two different phase of the supply circuit. Each coil has a series resistance. There is no necessity for phase splitting by artificial means, since the required phase displacement between currents I_A and I_B in the two moving coils can be obtained from the supply itself as shown.



Theory

Voltage applied across coil A is V_{12} and as its circuit is resistive, current I_A is in phase with voltage V_{12}. Voltage applied across coil B is V_{13} and current I_B is in phase with V_{13} as the circuit of coil is resistive.

Let, ϕ = Phase angle of circuit

θ = Angular deflection from the plane of reference and

$V_1 = V_2 = V_3 = V$

Torque acting on coil A is,

$$T_A = KV_{12} I\, M_{max} \cos(30° + \phi) \sin(60° + \theta)$$
$$= \sqrt{3}\, KVI\, M_{max} \cos(30° + \phi) \sin(60° + \theta)$$

Torque acting on coil B is

$$T_B = KV_{13} I\, M_{max} \cos(30° - \phi) \sin(120° + \theta)$$
$$= \sqrt{3}\, KVI\, M_{max} \cos(30° - \phi) \sin(120° + \theta)$$

Torques T_A and T_B act in opposite directions and the moving system takes up a positions where $T_A = T_B$

$\therefore \quad \cos(30° + \phi) \sin(60° + \theta)$
$= \cos(30° - \phi) \sin(120° + \theta)$

On solving, $\theta = \phi$

Thus the angular deflection of the pointer from the plane of reference is equal to the phase angle of the circuit to which the meter is connected. The three phase power factor meter gives indication which are independent of

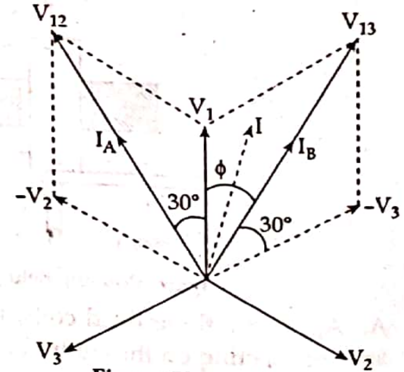


Figure: Phasor diagram

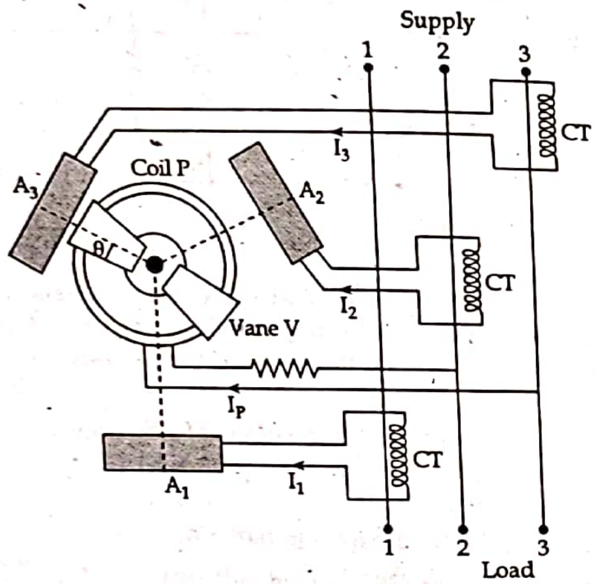
wave from and frequency of supply, since the currents in the two moving coils are equally affected by any change of frequency. For measurement of power factor in 3 phase unbalanced systems a two element power factor meter (where 2 sets of fixed coils and 2 sets of moving coils mounted on the spindle) has to be used.

C. Moving Iron power factor meter

These instruments may be divided into two categories according to whether the operation of the instrument depends upon a rotating magnetic field or a number of alternating fields.

I) Rotating Field Power factor meter

The essential features of a rotating field type of instrument are shown below.



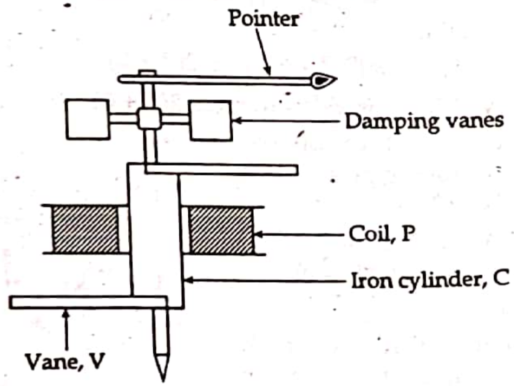


Figure: Rotating field moving iron power factor meter

A_1, A_2, A_3 are three fixed coils, with their axes displaced 120° from each and intersecting on the centre line of the instrument. These three coils are

connected respectively in lines 1, 2 and 3 of a three phase supply. Usually current transformers are used for the purpose. P is a fixed coil connected in series with a high resistance across one pair of lines say 2 and 3. There is an iron cylinder C inside coil P. Two sector shaped iron vanes are 180° apart. The spindle also carries damping vanes and a pointer. There are no control springs.

Theory

Coil P and the iron system, produce an alternating flux which interacts with the fluxes produced by coils A_1, A_2 and A_3. This causes the moving system to take up an angular position determined by the phase angle of the current. The theory of the moving iron instrument may be developed in a similar manner to that of the electrodynamometer type instruments if we consider the cylinder C and the vanes V, V to be magnetized by current I_P in coil P which is in phase with and proportional to the line voltage of the system. (This is very nearly true as coil P has a large resistance connected in series with it). Then if the effects of hysteresis and eddy currents are ignored, the iron cylinder, the vanes and the coil P are equivalent electromagnetically to a rectangular moving coil pivoted within coils A_1, A_2 and A_3, the center line of the moving coil being coincident with the axis of the iron vanes.

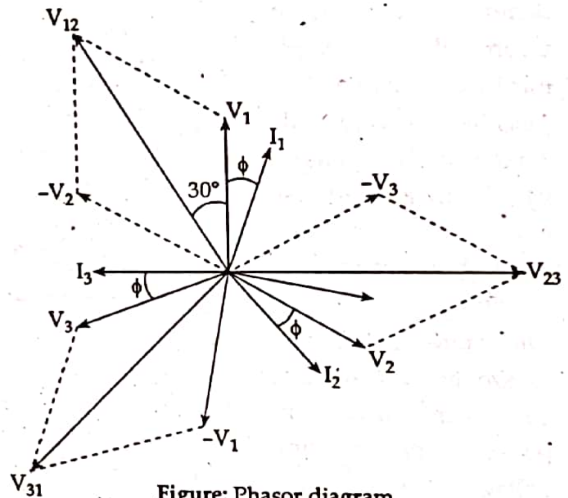


Figure: Phasor diagram

Now by arguments similar to those used for the electrodynamometer type of instrument, we can write the expression for total torque acting on the moving system due to currents in coil A_1, A_2 and A_3.

The total deflecting torque is,

$$T_d \propto I_1 I_p \cos(90° - \phi) \sin(90° + \theta) + I_2 I_P \cos(330° - \phi) \sin(210° + \theta) + I_3 I_p \cos(210° - \phi) \sin(330° + \theta)$$

For a steady deflection, the total torque must be zero

Also considering the system to be balanced *i.e.*, $I_1 = I_2 = I_3$, we have,

or, $$\cos(90° - \phi) \sin(90° + \theta) + \cos(330° - \phi) \sin(210° + \theta) + \cos(210° - \phi) \sin(330° + \theta) = 0$$

Solving above expression, we have,

$\therefore \quad \theta = \phi$

Therefore the deflection of iron vane from the reference axis is a direct measure of the phase angle between each line current and the corresponding phase voltage.

It may be noted that the three fixed coils A_1, A_2 and A_3 produce a rotating magnetic field and therefore owing to this there will be an induction motor action tending to drag the moving system continuously in the direction of the rotating magnetic field. This effect can be made negligibly small by using high resistivity metal for the moving irons so as to reduce the value of induced currents.

A single phase power factor meter based upon the principle outlined above, is possible if we provide 3 fixed coils displaced by 120° in space. These coils are connected through impedances to the lines.

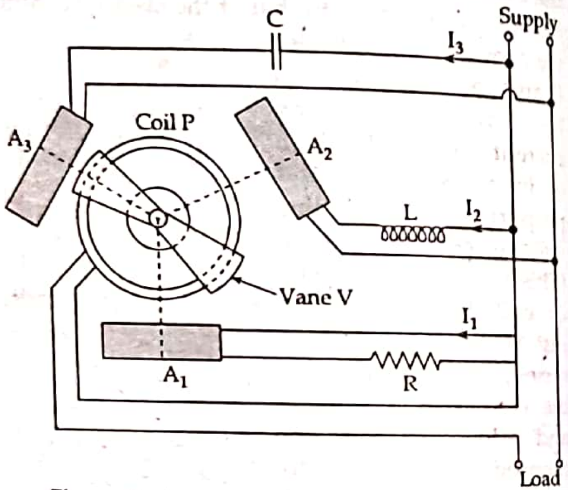


Figure: Single phase moving iron power factor meter

The value of R, L and C are chosen so that current in coil A_1 is in phase with the line voltage, current in coil A_2 lags by 60° and current in coil A_1 are reversed with respect to the connections of other coils so that the currents in the three coils are 120° out of phase with each other. Coil P is excited by the line current. The rest of the arrangement is similar to that described for the three phase wattmeter. The fixed coil assembly consisting of coils A_1, A_2 and A_3 has equal currents in each phase displaced 120° in time and since the coil axes are displaced 120° in space, a revolving field is produced which makes the system behave similarly to that for a balanced 3-phase supply.

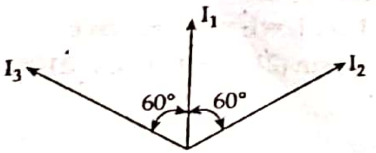


Figure: Before reversal of connections of coil A_1

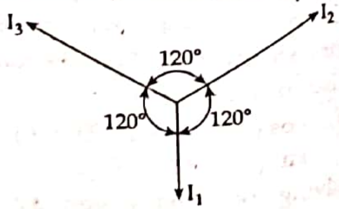


Figure: After reversal of connections of coil A_2

II) Alternating field power factor meter (Nalder Lipman Type)

This instrument is due to Lipman and is manufactured by M/S Nalder Brothers.

Construction

Figure below shows the construction of a Nalder Lipman type instrument used for balanced currents.

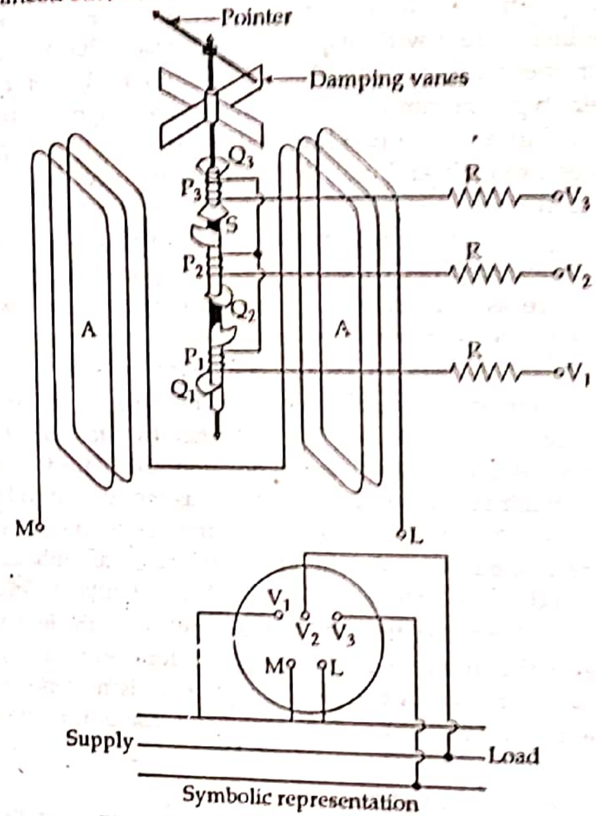


Figure: Nadler lipman power factor meter

The moving system comprises of three pairs of iron vanes and cylinders which are fixed to a common spindle. This spindle is pivoted in jewel bearings and carries damping vanes and a pointer. The iron vanes are sector shaped, the arc subtending an angle of 120°. The vanes forming each pair (which are magnetically connected to the same iron cylinder) are fixed 180° apart as in the rotating field instrument. The cylinders are separated on the spindle by distance pieces S. These distance pieces are made of a non-magnetic material. The axis of symmetry of the three pairs of values are displaced by 120° from each other. The iron cylinders and the vanes are magnetized by three fixed coaxial pressure coils P_1 P_2 and P_3. These pressure coils are mounted co-axially with the spindle and are excited by currents proportional to the phase voltage of the three phase system.

The current coil A is wound in two equal parts which are mounted parallel to each other on opposite sides of the spindle. Coil A is supplied with current proportional to the current in one of the lines of the three phase system. There are no control forces.

Theory

The angular position of the moving system is determined by the phase angle of the line current with respect to the phase voltage. The operation of this instrument can be analyzed in a similar manner as used for rotating field type instrument. The rotating field type instrument has three current coils and one pressure coil while the alternating field type has three pressure coils and one current coil. In one case there are three fluxes due to three line currents, displaced from each other by 120° in space as well as in time; together with a flux due to line voltage. In the second case, there are three fluxes due to three phase voltages, displaced by 120° in space as well as in time together with a flux due to a line current. Thus the relationship between angular deflection of the moving element and phase angle of the system is the same in both the cases.

The moving system deflects into such a position that the mean torque on one pair of vanes is neutralized by the other two torques, so that the resultant torque is zero. In this steady position, the deflection of the iron vane which is magnetized by the same phase as the current coil is equal to the phase angle of the circuit. The instrument as shown is used for balanced currents, but if can be modified for use on an unbalanced three phase circuit and for two phase and single phase circuits.

It may be noted here that the three coils together with their vanes and cylinders lie in the different planes and therefore no rotating magnetic field is produced. Hence in this instrument there is no tendency for the moving system to rotate continuously as in the case in rotating field type instrument.

Advantages of moving iron pf meter

i) The working forces are very large as compared with those in dynamometer type.

ii) The scale extends over 360°

iii) These instrument are simple and robust in construction.

iv) All the coils in moving iron instrument are fixed and therefore the use of ligaments is eliminated.

Disadvantages of moving iron pf meter

i) Errors are introduced in these meters owing to losses in iron parts. These losses are dependent upon the load and the frequency. They are less accurate than the dynamometer type.

ii) The calibration of these instruments is appreciably affected by variations in supply frequency, voltage and waveform.