Module 10

Measuring Instruments

Lesson 44

Study of Single Phase Induction Type Energy Meter or Watt-hour Meter

Objectives

- To understand the basic construction and different components of a single phase induction type energy meter.
- Explain basic principle and development of torque expressions for energy meter.
- To study the errors involve in the energy meter.
- Use of instrument transformers for extension of Instrument range.
- Understanding the basic theory of shielded-pole shunt magnet.

L.44.1 Introduction

An instrument that is used to measure either quantity of electricity or energy, over a period of time is known as energy meter or watt-hour meter. In other words, energy is the total power delivered or consumed over an interval of time t may be expressed as:

$$W = \int_0^t v(t)\ i(t)\ dt$$

If $v(t)$ is expressed in volts, $i(t)$ in amperes and t in seconds, the unit of energy is joule or watt second. The commercial unit of electrical energy is kilowatt hour (KWh). For measurement of energy in a.c. circuit, the meter used is based on "electro-magnetic induction" principle. They are known as induction type instruments. The measurement of energy is based on the induction principle is particularly suitable for industrial or domestic meters on the account of lightness and robustness of the rotating element. Moreover, because of smallness of the variations of voltage and frequency in supply voltage, the accuracy of the induction meter is unaffected by such variations. If the waveform of the supply is badly distorted, the accuracy, however, is affected. Basically, the induction energy meter may be derived from the induction watt-meter by substituting for the spring control and pointer an eddy current brake and a counting train, respectively. For the meter to read correctly, the speed of the moving system must be proportional to the power in the circuit in which the meter is connected.

L.44.2 Construction of induction type energy meter

Induction type energy meter essentially consists of following components

(a) Driving system (b) Moving system (c) Braking system and (d) Registering system.

- Driving system: The construction of the electro magnet system is shown in Fig. 44.1(a) and it consists of two electromagnets, called "shunt" magnet and "series" magnet, of laminated construction.

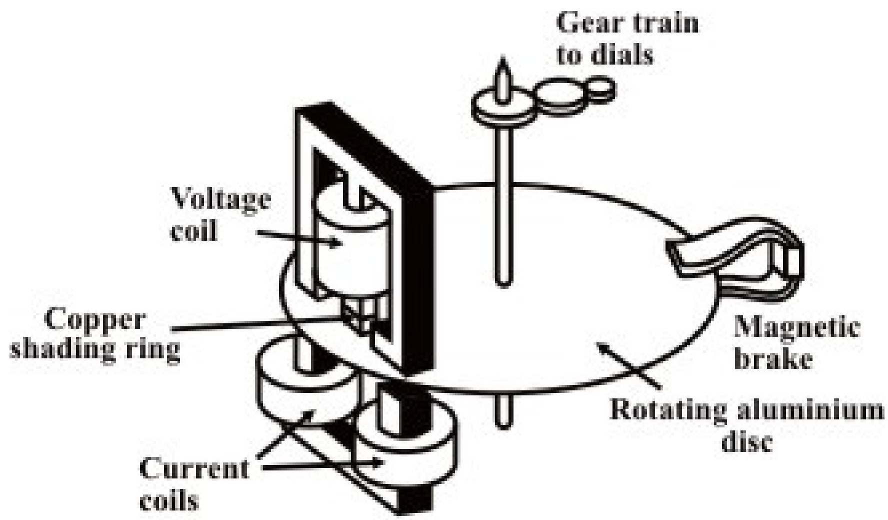

Fig. 44.1(a): Watt-hour meter.

A coil having large number of turns of fine wire is wound on the middle limb of the shunt magnet. This coil is known as "pressure or voltage" coil and is connected across the supply mains. This voltage coil has many turns and is arranged to be as highly inductive as possible. In other words, the voltage coil produces a high ratio of inductance to resistance. This causes the current, and therefore the flux, to lag the supply voltage by nearly 90^0. An adjustable copper shading rings are provided on the central limb of the shunt magnet to make the phase angle displacement between magnetic field set up by shunt magnet and supply voltage is approximately 90^0. The copper shading bands are also called the power factor compensator or compensating loop. The series electromagnet is energized by a coil, known as "current" coil which is connected in series with the load so that it carry the load current. The flux produced by this magnet is proportional to, and in phase with the load current.

- Moving system: The moving system essentially consists of a light rotating aluminium disk mounted on a vertical spindle or shaft. The shaft that supports the aluminium disk is connected by a gear arrangement to the clock mechanism on the front of the meter to provide information that consumed energy by the load. The time varying (sinusoidal) fluxes produced by shunt and series magnet induce eddy currents in the aluminium disc. The interaction between these two magnetic fields and eddy currents set up a driving torque in the disc. The number of rotations of the disk is therefore proportional to the energy consumed by the load in a certain time interval and is commonly measured in killowatt-hours (Kwh).

- Braking system: Damping of the disk is provided by a small permanent magnet, located diametrically opposite to the a.c magnets. The disk passes between the magnet gaps. The movement of rotating disc through the magnetic field crossing the air gap sets up eddy currents in the disc that reacts with the magnetic field and exerts a braking torque. By changing the position of the brake magnet or diverting some of the flux there form, the speed of the rotating disc can be controlled.

- Registering or Counting system: The registering or counting system essentially consists of gear train, driven either by worm or pinion gear on the disc shaft, which turns pointers that indicate on dials the number of times the disc has turned. The energy meter thus determines and adds together or integrates all the instantaneous power values so that total energy used over a period is thus known. Therefore, this type of meter is also called an "integrating" meter.

L44.2 Basic operation

Induction instruments operate in alternating-current circuits and they are useful only when the frequency and the supply voltage are approximately constant. The most commonly used technique is the shaded pole induction watt-hour meter, shown in fig.44.1 (b).

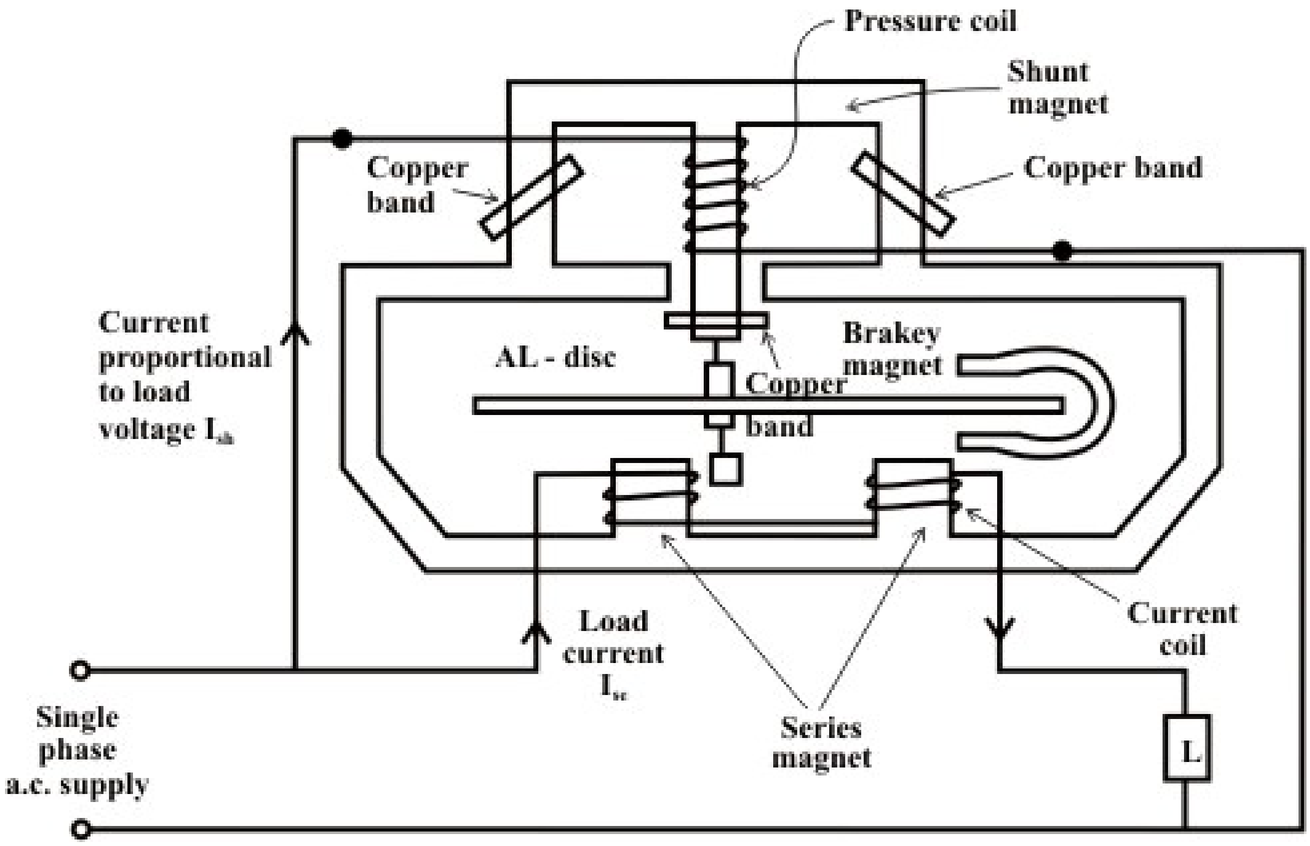

Fig. 44.1(b)

The rotating element is an aluminium disc, and the torque is produced by the interaction of eddy currents generated in the disc with the imposed magnetic fields that are produced by the voltage and current coils of the energy meter.

Let us consider a sinusoidal flux $\phi(t)$ is acting perpendicularly to the plane of the aluminium disc, the direction of eddy current i_e by Lenz's law is indicated in figure Fig.44.2. It is now quite important to investigate whether any torque will develope in aluminium disc by interaction of a sinusoidally varying flux $\phi(t)$ and the eddy currents i_e induced by itself.

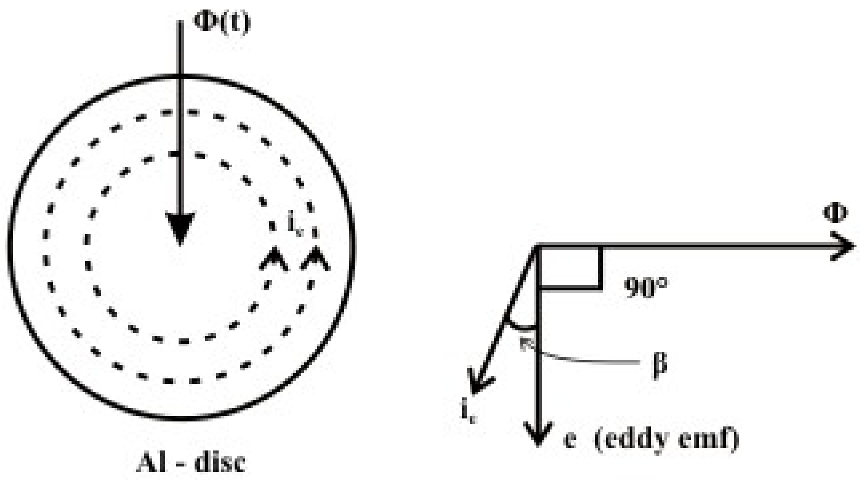

Fig. 44.2: Eddy currents in aluminium disc due to time-varying flux.

$$T_{d(av.)} \propto \phi\, I_e \cos\left(\angle \phi, I_e\right) = \phi\, I_e \cos(90^0 + \beta)$$
$$\propto \phi\, I_e \sin(\beta) \simeq 0 \qquad (44.1)$$

where ϕ and I_e are expressed in r.m.s and $\beta \simeq 0$ (because the reactance of the aluminium disc is nearly equal to zero). Therefore, the interaction of a sinusoidally varying flux $\phi(t)$ and its own eddy current i_e (induced) cannot produce torque any on the disc.

So in all induction instruments we have two fluxes produce by currents flowing in the windings of the instrument. These fluxes are alternating in nature and so they induce emfs in a aluminium disc or a drum provided for the purpose. These emfs in turn circulate eddy currents in the disc.

As in an energy meter instrument, we have two fluxes and two eddy currents and therefore two torques are produced by

i) first flux(ϕ_1) interacting with the eddy currents (I_{e2}) generated by the second flux (ϕ_2), and

ii) second flux (ϕ_2) interacting with the eddy currents (I_{e1}) induced by the first flux (ϕ_1).

In the induction type single phase energy meter, the flux produced by shunt magnet (pressure or voltage coil current) Φ_{sh} lags behind the applied voltage V by almost 90°. The flux ϕ_{se} is produced by the load current I and Φ_{se} is in the direction of I (see Fig.44.3).

Let the supply voltage $v(t) = V_{max} \sin(\omega t)$ and load current $i(t) = I_{max} \sin(\omega t - \theta)$. So, the fluxes are :

(i) Flux generated by current coil

$$\Phi_{se} = k\, I_{\max} \sin(\omega t - \theta) = \Phi_{\max(se)} \sin(\omega t - \theta)$$

(ii) Flux generated by voltage coil

$$\Phi_{sh} = k' \int v(t) dt$$

$$= -k' \frac{V_{\max}}{\omega} \cos(\omega t) = \Phi_{\max(sh)} \sin(\omega t - 90^0)$$

(note: $v(t) = \frac{1}{k'} \frac{d(\Phi_{sh})}{dt}$ and k and k' are constants.)

The eddy e.m.f , induced by flux Φ_{se} is

$$e_{se} \propto -\frac{\mathrm{d}}{\mathrm{dt}}(\Phi_{se}) = -k\, I_{\max}\, \omega \cos(\omega t)$$

Eddy current generated in disc by the current coil

$$i_{se} \propto -\frac{k}{Z} I_{\max}\, \omega \cos(\omega t - \theta - \alpha) = \frac{k}{Z} I_{\max}\, \omega \sin(\omega t - (\theta + \alpha + 90^0)),$$

where Z is the eddy current path impedance and α is the phase angle. In general, the angle $\alpha = \tan^{-1} \frac{X}{R}$ is negligible because $X \simeq 0$.

Also, note that

$$e_{sh} \propto -\frac{\mathrm{d}}{\mathrm{dt}}(\phi_{sh}) = -k' \frac{V_{\max}}{\omega} \omega \sin(\omega t)$$

Eddy current generated in disc by the voltage coil

$$i_{sh} \propto -k' \frac{V_{\max}}{Z} \sin(\omega t - \alpha) = k' \frac{V_{\max}}{Z} \sin(\omega t + (180^0 - \alpha))$$

The instantaneous torque on the disc is then proportional to

$$\left(\Phi_{sh}\, i_{se} - \Phi_{se}\, i_{sh}\right) = \frac{k\,k'}{Z} V_{\max}\, I_{\max} \left(\cos(\omega t) \cos(\omega t - \theta - \alpha) - \sin(\omega t - \theta) \sin(\omega t - \alpha)\right) \quad (44.2)$$

where Φ_{sh} is the flux generated by the voltage coil, Φ_{se} is flux generated by the current coil, i_{sh} is the eddy current produced in the disc by the voltage coil, and i_{se} is the eddy current produced in the disc by the current coil. The relative phases of these quantities are shown in fig.44.3.

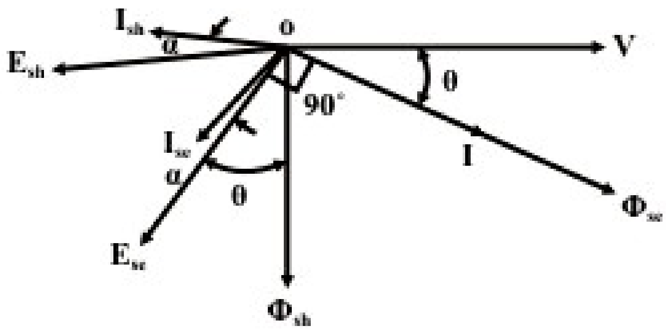

Fig. 44.3: Phasor diagram of fluxes and eddy currents in watt-hour meter.

The flux generated by the current coil is in phase with the current and flux generated by the voltage coil is adjusted to be exactly in quadrature with the applied voltage by means of the copper shading ring on the voltage or shunt magnet. Theory of shaded pole is discussed in Appendix. The average torque acting upon the disc

$$T_{d(av)} \propto \frac{k\,k'}{Z} V_{\max} I_{\max} \frac{1}{2}\left(\cos(\theta+\alpha)+\cos(\theta-\alpha)\right)$$

$$\propto \frac{k\,k'}{Z} V_{\max} I_{\max} \cos\alpha \cos\theta = \left(\frac{2\,k\,k'}{Z}\cos\alpha \right) VI\cos\theta \quad (44.3)$$

$$\propto VI\cos\theta = \text{power in the circuit}$$

One can write average torque expression directly from the phasor diagram shown in fig.44.3

$$T_{d(av)} \propto \left[\Phi_{sh(rms)} I_{se} \cos(\angle\Phi_{sh(rms)}, I_{se}) - \Phi_{se(rms)} I_{sh} \cos(\angle\Phi_{se(rms)}, I_{sh}) \right]$$

$$\propto \left[\Phi_{sh(rms)} I_{se} \cos(\theta+\alpha) - \Phi_{se(rms)} I_{sh} \cos(180+\alpha-\theta) \right]$$

$$\propto \left[k'V\,k\frac{I}{Z}\cos(\theta+\alpha) + k\,I\,k'\frac{V}{Z}\cos(\theta-\alpha) \right]$$

$$\propto \left(\frac{2\,k\,k'}{Z}\cos\alpha \right) VI\cos\theta$$

$$\propto VI\cos\theta = \text{power in the circuit}$$

where $\Phi_{sh}, \Phi_{se}, I_{sh}, I_{se}, V,$ *and* I are all expressed as r.m.s.

Remarks : (i) The torque expression shows that for a large torque the eddy current path resistance must be low which in turn the value of $\cos\alpha$ will be nearly equal to 1. Consideration of the torque-weight ratio shows that the choice of aluminium disc will be superior to copper and further it can be improved by properly selecting aluminium disc thickness. (ii) Note, that the torque expression does not involve ωt and it has same value at all instants of time. (iii) The resultant torque will act on the disc in such away so that it will move from the pole with the leading flux towards the pole with lagging flux.

Opposing or Brake Torque:

Now the breaking torque is produced by the eddy currents induced in the disc by its rotation in a magnetic field of constant intensity, the constant field being provided by the permanent magnet (called brake magnet, see fig. 44.1(a) & (b)). The eddy current i_b produced in the aluminium–disc by the brake magnet flux ϕ_b is proportional to the speed (N) of rotation of the disc N, as shown in fig.44.4.

Thus braking torque

$$\begin{aligned} T_b &\propto \Phi_b i_b \propto \Phi_b \frac{e_b}{r} \\ &\propto \Phi_b \frac{N\Phi_b}{r} \\ &\propto N\Phi_b^2 \end{aligned}$$

, where r = eddy current path resistance

Since Φ_b is constant, this implies that

$$T_b \propto N \qquad (44.4)$$

where N = speed of rotation of disc.
Now when the speed becomes steady, driving and braking torques become $T_d = T_b$ (see fig.44.4).

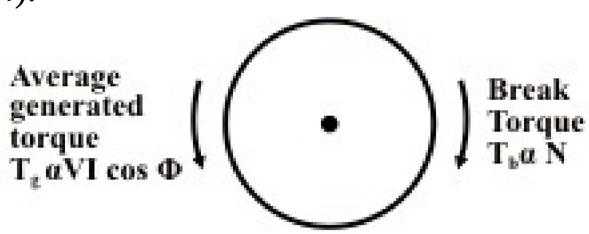

Fig. 44.4: Torque balance in a watt-hour meter.

Therefore, $V I \cos\theta \propto N$ i.e. speed of the disc is proportional to the power consumed by the load. The total number of revolution i.e. $\int N\,dt = \int V I \cos\theta\,dt \propto$ Energy consumed. This means that the speed of rotation of the disc is proportional to the average power. The integral of the number of revolutions of the disc is proportional to the total energy supplied.

The disc is connected via a gearing mechanism to a mechanical counter that can be read directly in watt-hours.

Remarks: (i) For a given disc and brake magnet, the braking torque varies with the distance of the poles from the center of the disc. The maximum braking torque occurs when the distance of the center of the pole faces from the center of the disc is equal to 83% of the radius of the disc. (ii) a movement of the poles of brake magnet towards the center of the disc reducing the braking torque (as the distance of brake magnet reduces from the center of the disc), and vise versa.

L44.3 Errors in the energy meter:

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

i 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.

ii 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.

iii 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 $1/4^{th}$ of full load at unity p.f.).

iv 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 180^0. 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.

(v) 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

$$K = \frac{\text{No. of revolutions}}{\text{kwh}}$$

In commercial meters the speed of the disc is of the order of 1800 revolutions per hour at full load

L.44.4 Extension of Instrument Range:

We have seen earlier M.C. instrument's range can be extended by properly designed non inductive shunts and multipliers in cases of ammeter and voltmeter respectively. Similarly for MI instruments shunts and multipliers can be designed for extension of range. Sometimes transformers are used in ac systems for the measurement of the basic quantities such as current, voltage and power. The transformers used in connection with the instruments for measurement purpose are **referred to as Instrument**

Transformers. They are classified as Current Transformer (C.T.) used for current measurement and potential Transformer (P.T.) used for voltage measurement. These transformers are used not only for extension of the range of the instrument, but also for isolating the instrument from a high current or voltage line. The advantages of these transformers are

- Single range instrument can be used to cover a wide range.
- Indicating instrument can be located at some distance from the circuit. This is a great advantage particularly for high voltage situation.
- By use of CT with split core or hinged core, the current in heavy current bus bar can be measured without breaking the circuit.

Appendix

Theory of shielded pole shunt magnet:

Fig. 44.5(a) shows that a shielding coil C (single turn) surrounds the pole face of the core of a magnet that is magnetized by the supply voltage V. The flux Φ at the pole face is taken as a reference vector in the phasor diagram as shown in fig. 44.5(b).

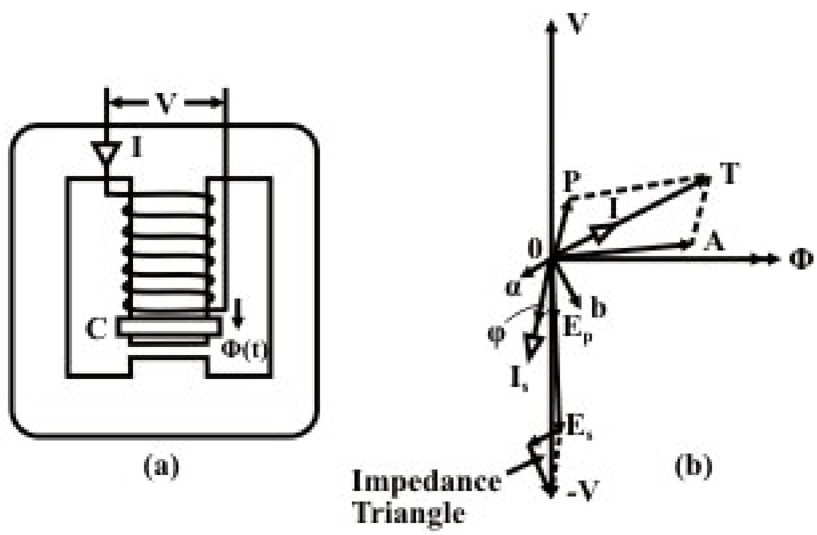

Fig. 44.5: Pasor diagram for shielded-pole shunt magnet.

No load magnetizing current I_0 and ampere turns $N I_0$ for the magnetic circuit are in same phase. The phasor OA = $N I_0$ represents magnetizing ampere-turns slightly in advance of the flux Φ owing to core loss in the magnetic circuit. The e.m.fs induced in exciting and shielding coils are represented by

OE_p and OE_s respetively and they are lagging by 90^0 with respect to the flux Φ. The current in shielding coil and also ampere-turns due to this coil are represented by the phasor OI_s. Hence, the effective ampere-turns to be provided by the exciting coil are represented by OT which is equal to the phasor sum of ampere-turms OA & OP. The phasor OP represents balancing ampere-turns due to the shielding coil C. The resultant exciting current is represented by OI. The applied voltage to the exciting coil is then can be found out by adding the induced e.m.f OE_p to the resistance and reactance voltage drops of the exciting coil. Now, in the induction energy meter, the applied voltage OV must lead the flux phasor Φ by 90^0. An inspection of phasor diagram shows that by adjusting the ampere-turns of the shielding coil one can obtain 90^0 phase difference between applied voltage OV and flux Φ. The ampere-turns of the shielding coil being effected either by alternation of the resistance of the shielding coil or by altering its axial position.

L44.5 Test your Understanding

Marks: 50

T.1 Describe fully the construction and principles operation of a single phase, induction type watt-hour meter, and explain the adjustments usually provided. [10]

T.2 State all possible source of errors that are involve in watt-hour meter and show how these are minimized in practice. [10]

T.3 Explain how one can prevent from registering the meter reading when shunt magnet is energized with the supply voltage and the load current flowing through series magnet is zero. [5]

T.4 A single phase $230V$ watt-hour meter has correctly adjusted having a meter constant of $500\ rev/kWh$. Determine the speed of the disc for current of $20A$ at a power factor lagging of 0.5. [5]
($Ans.\ 19.2\ r.p.m$)

T.5 The number of revolution per kWh for a $230V, 20A$ watt-hour meter is 1000. On test at half load, the time for 40 revolution of the disc is found to be 62 seconds. Determine the meter error at half load. [8]

(*Ans.* 0.97%, *fast*)

T.6 A single-phase induction watt-hour meter has its full-load ratings $240V, 10A$. Assuming the friction is accurately compensated at all power factors. If the phase angle between shunt magnet flux and applied voltage is 82^0 instead of 90^0, estimate the error introduced (i) at unity p.f (ii) at 0.8 lagging p.f. (iii) at 0.8 leading p.f . Prove any formula used. [4+4+4]
($Ans.(i)$ 0.97% (ii) 11.39%, $(slow)$ $(iii) -9.46\%$ ($fast$))

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