Electrical Measuring Instruments

CHAPTER OVERVIEW

1. ELECTRICAL MEASURING INSTRUMENTS

Electrical energy is being used in the manufacture of many commodities. In order to ensure quality and efficiency, it is important that we should be able to measure accurately the electrical quantities involved. The instruments used to measure electrical quantities (*e.g.* current, voltage, power, energy *etc.*) are called electrical instruments. These instruments are generally named after the electrical quantity to be measured. Thus the instruments which measure current, voltage, power and energy are called ammeter, voltmeter, wattmeter and energymeter respectively. The accuracy, convenience and reliability of electrical instruments are mainly responsible for the widespread use of electrical methods of measurements. These days electrical methods of measurement are being widely used for the measurement of nonelectrical quantities *e.g.* moisture content of paper during manufacture, variations of strain in a structural member *etc*.

2. TYPES OF ELECTRICAL INSTRUMENTS

Electrical measuring instruments may be classified according to their functions as (*i*) indicating instruments (*ii*) integrating instruments and (*iii*) recording instruments.

(*i*) **Indicating instruments.** Those instruments which directly indicate the value of the electrical quantity *at the time* when it is being measured are called indicating instruments *e.g. ammeters, voltmeters* and *wattmeters*. In such instruments, a pointer moving over a graduated scale directly gives the value of the electrical quantity being measured. For example, when an ammeter is connected in the circuit, the pointer of the meter directly indicates the value of current flowing in the circuit at that time.

(*ii*) **Integrating instruments.** Those instruments which measure the total quantity of electricity (in ampere-hours) or electrical energy (in watt-hours) in a given time are called integrating instruments *e.g. ampere-hour meter* and *watt-hour meter*. In such instruments, there are sets of dials and pointers which register the total quantity of electricity or electrical energy supplied to the load.

(*iii*) **Recording instruments.** Those instruments which give a continuous record of the variations of the electrical quantity to be measured are called recording instruments. A recording instrument is merely an indicating instrument with a pen attached to its pointer. The pen rests lightly on a chart wrapped over a drum moving with a slow uniform speed. The motion of the drum is in a direction perpendicular to the direction of the pointer. The path traced out by the pen indicates the manner in which the quantity, being measured, has varied during the time of the record. Recording voltmeters are used in supply stations to record the voltage of the supply mains during the day. Recording ammeters are employed in supply stations for registering the current taken from the batteries.

3. PRINCIPLES OF OPERATION OF ELECTRICAL INSTRUMENTS

An electrical instrument essentially consists of a movable element and a scale to indicate or register the electrical quantity being measured. The movable element is supported on jewelled bearings and carries a pointer or sets of dials. The movement of the movable element is caused by utilising one or more of the following effects of current or voltage.

1. Magnetic effect ..... Moving-iron instruments
2. Electrodynamic effect ..... (*i*) Permanent-magnet moving coil
(*ii*) Dynamometer type
3. Electromagnetic-induction ..... Induction type instruments
4. Thermal effect ..... Hot-wire instruments
5. Chemical effect ..... Electrolytic instruments
6. Electrostatic effect ..... Electrostatic instruments

S. No.	Type	Effect	Suitable for	Instrument
1.	Moving-iron	Magnetic effect	d.c. and a.c.	Ammeter, Voltmeter
2.	Permanent-magnet moving coil	Electrodynamic effect	d.c. only	Ammeter, Voltmeter
3.	Dynamometer type	Electrodynamic effect	d.c. and a.c.	Ammeter, Voltmeter, Wattmeter
4.	Induction type	Electro-magnetic induction effect	a.c. only	Ammeter, Voltmeter, Wattmeter, Energy-meter
5.	Hot-wire	Thermal effect	d.c. and a.c.	Ammeter, Voltmeter
6.	Electrolytic meter	Chemical effect	d.c. only	Ampere-hour meter
7.	Electrostatic type	Electrostatic effect	d.c. and a.c.	Voltmeter only

The principles of operation of electrical instruments are given in the above table for facility of reference.

4. ESSENTIALS OF INDICATING INSTRUMENTS

An indicating instrument essentially consists of moving system pivoted in jewel bearings. A pointer is attached to the moving system which indicates on a graduated scale, the value of the electrical quantity being measured. In order to ensure proper operation of indicating instruments, the following three torques are required :

(*i*) Deflecting (or operating) torque
(*ii*) Controlling (or restoring) torque
(*iii*) Damping torque

(*i*) **Deflecting torque.** One important requirement in indicating instruments is the arrangement for producing deflecting or operating torque (T_d) when the instrument is connected in the circuit to measure the given electrical quantity. This is achieved by utilising the various effects of electric current or voltage mentioned in section 3. The deflecting torque causes the moving system (and hence the pointer attached to it) to move from zero position to indicate on a graduated scale the value of electrical quantity being measured. The actual method of producing the deflecting torque depends upon the type of instrument and shall be discussed while dealing with particular instrument.

(*ii*) **Controlling Torque.** If deflecting torque were acting alone, the pointer would continue to move indefinitely and would swing over to the maximum deflected position irrespective of the magnitude of current (or voltage or power) to be measured. This necessitates to provide some form of controlling or opposing torque (T_C). This controlling torque should oppose the deflecting torque and should increase with the deflection of the moving system. The pointer will be brought to rest at a position where the two opposing torques are equal *i.e.* $T_d = T_c$. The controlling torque performs two functions :

(*i*) It increases with the deflection of the moving system so that the final position of the pointer on the scale will be according to the magnitude of current (or voltage or power) to be measured.

(*ii*) It brings the pointer back to zero position when the deflecting torque is removed. If it were not provided, the pointer once deflected would not return to zero position on removing the deflecting torque.

The controlling torque in indicating instruments may be provided by one of the following two methods :

(*a*) By one or more springs ... *Spring control*

(*b*) By weight of moving parts ... *Gravity control*

The most common method of providing controlling torque is by the use of one or more springs as shown in Fig. 16.1. One or two spiral hair spring made of some nonmagnetic material is attached to the moving system of the instrument. With the deflection of the pointer, the spring is twisted in the opposite direction. This twist in the spring provides the controlling torque.

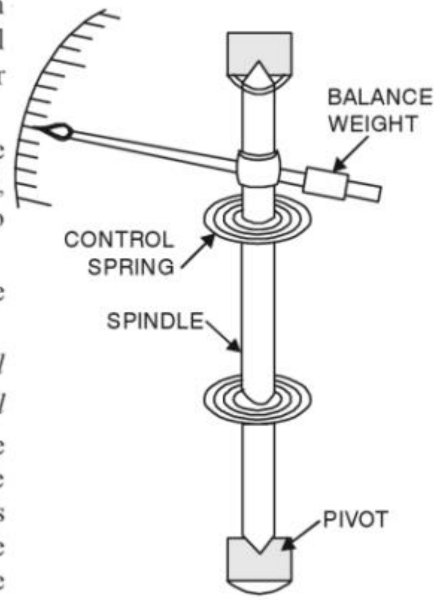


Fig. 16.1

In the gravity control a small adjustable weight W is attached to the moving system [See Fig. 16.2 (*i*)] which provides the necessary controlling torque. In the deflected position [See Fig. 16.2 (*ii*)], only the component $W \sin \theta$ provides the controlling torque.

$$T_C = W \sin \theta \times l = W l \sin \theta$$

or $$T_C \propto \sin \theta \text{ (for fixed } W \text{ and } l)$$

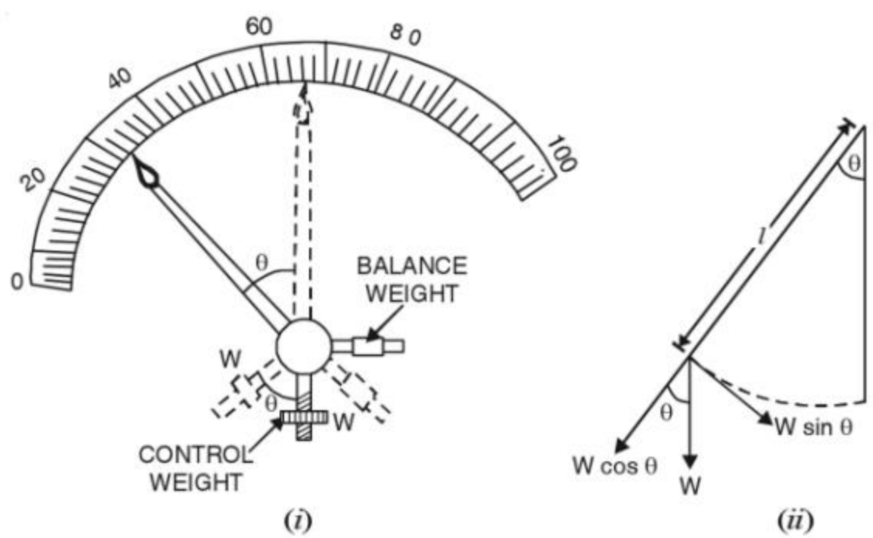


Fig. 16.2

(*iii*) **Damping torque.** If the moving system is acted upon by deflecting and controlling torques alone, then pointer, due to inertia, will oscillate about its final deflected position for quite some time before coming to rest. This is often undesirable because it makes difficult to obtain quick and accurate readings. In order to avoid these oscillations of the pointer and to bring it quickly to its final deflected position, a damping torque is provided in the indicating instruments. This damping torque acts only when the pointer is in motion and always opposes the motion. The position of the pointer when stationary is, therefore, not *affected by damping. The damping torque in indicating instruments can be provided by (*a*) air friction (*b*) fluid friction and (*c*) eddy currents.

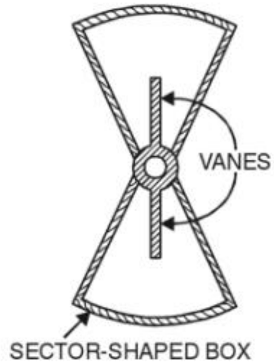


Fig. 16.3. Air friction damping

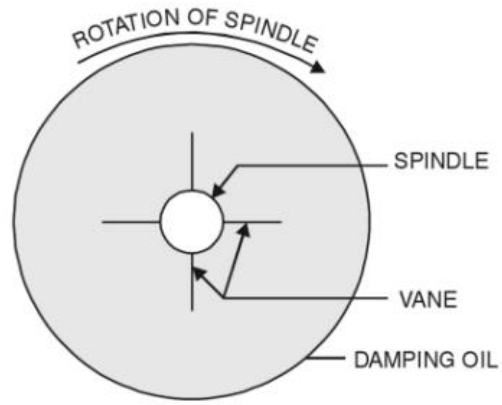
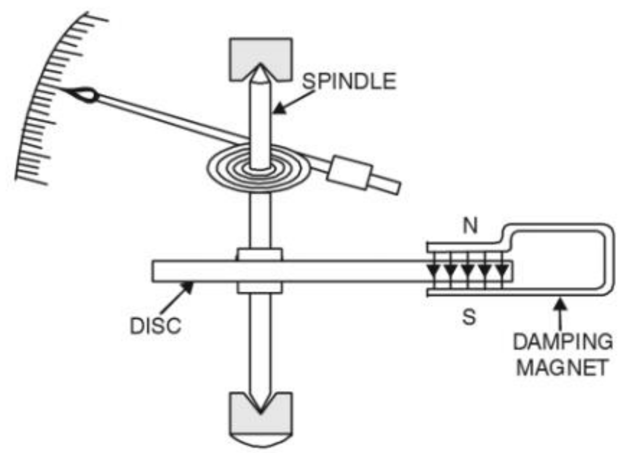


Fig. 16.4. Fluid friction damping



Eddy current damping
Fig. 16.5

In air friction damping (See Fig. 16.3), one or two light aluminium vanes are attached to the same spindle that carries the pointer. The vanes are permitted to swing in a sector-shaped closed box that is just large enough to accommodate the vanes. As the pointer moves, the vanes swing in the box, compressing the air in front of them. The pressure of compressed air in the vanes provides the necessary damping torque. In fluid friction damping [See Fig. 16.4], discs or vanes attached to the spindle of the moving system are kept immersed in a pot containing oil of high viscosity. As the pointer moves, the friction between the oil and vanes opposes motion of the pointer and thus necessary damping torque is provided. In eddy current damping [See Fig. 16.5], a thin *aluminium or copper disc attached to the moving system is allowed to pass between the poles of a permanent magnet. As the pointer moves, the disc cuts across the magnetic field and eddy currents are produced in the disc. These eddy currents react with the field of the magnet to produce a force which opposes motion (Lenz's law). In this way, eddy currents provide damping torque to reduce the oscillations of the pointer.

5. AMMETERS AND VOLTMETERS

The devices which measure current and potential difference in a circuit are called *ammeters* and *voltmeters* respectively. Before we discuss various types of ammeters and voltmeters, let us see how these meters are connected in a circuit.

(*i*) **Ammeter.** An ammeter is connected in series with the circuit element whose current we wish to measure. It is because only then current through the circuit element also goes through the ammeter. Thus in order to measure current through the resistor R in Fig. 16.6, we place an ammeter (A) in series with the resistor. An ammeter should have very low resistance so that on connecting it in the circuit there is a negligible change in the circuit resistance (and hence the circuit current).

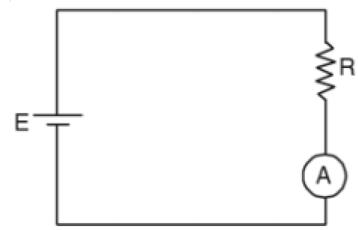


Fig. 16.6

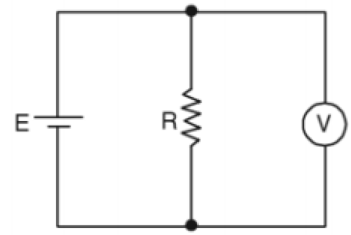


Fig. 16.7

(*ii*) **Voltmeter.** A voltmeter is connected in parallel with the circuit component across which potential difference is to be measured. It is because potential difference (or voltage) refers to two points. So to measure the potential difference between two points in a circuit, we connect two terminals of the voltmeter to those points. Thus to measure voltage across resistance R in Fig. 16.7, we connect the two terminals of the voltmeter (V) to the ends of the resistor R. The voltmeter should have a very high resistance so that on connecting it in the circuit, there is a *negligible change in the circuit resistance (and hence the circuit current).

6. TYPES OF AMMETERS AND VOLTMETERS

The basic principle of the ammeter and of the voltmeter is the same. Both are current operated devices *i.e.*, deflecting torque is produced when current flows through their operating coils. In the ammeter, the deflecting torque is produced by the current we wish to measure, or a certain fraction of that current. In the voltmeter, the deflecting torque is produced by a current which is proportional to the potential difference we wish to measure. Thus, the same instrument can be used as an ammeter or voltmeter with proper design.

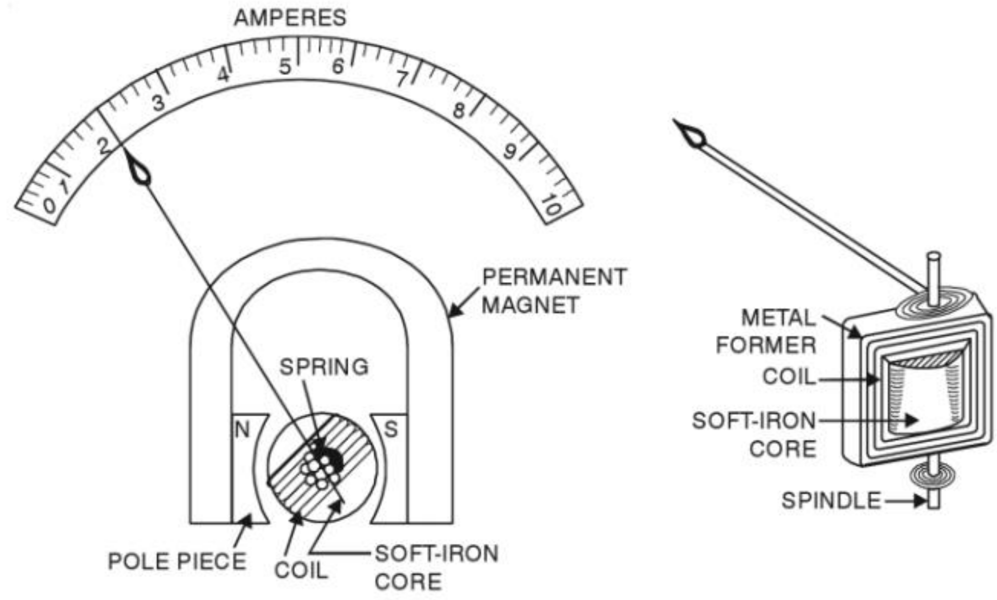
The following types of instruments are used for making voltmeters and ammeters :

(*i*) Permanent-magnet moving coil type
(*ii*) Dynamometer type
(*iii*) Moving-iron type
(*iv*) Hot-wire type
(*v*) Electrostatic type (for voltmeters only)
(*vi*) Induction type

The instrument at Sr. No. (*i*) can be used for d.c. work only whereas instrument at Sr. No. (*vi*) is employed for a.c. work only. However, instruments from Sr. No. (*ii*) to (*v*) can be used for both d.c. and a.c. measurements.

7. PERMANENT-MAGNET MOVING COIL INSTRUMENTS

These are suitable for d.c. work only. This type of instrument is based on the principle that when a current carrying coil is placed in a magnetic field, torque acts on the coil. Fig. 16.8 shows the various parts of a permanent-magnet moving coil instrument. It consists of a light rectangular coil of many turns of fine wire wound on an aluminium former inside which is an iron core as shown in Fig. 16.8 (*i*). The coil is delicately pivoted upon jewel bearings and is mounted between the poles of a permanent horse-shoe magnet. Attached to these poles are two soft-iron pole pieces which concentrate the magnetic field. The current is led into and out of the coil by means of two control hair-springs, one above and the other below the coil, as shown in Fig. 16.8 (*ii*). These springs also provide the controlling torque. The damping torque is provided by eddy currents induced in the aluminium former as the coil moves from one position to another.



(*i*) (*ii*)

Fig 16.8

Working. When the instrument is connected in the circuit to measure current or voltage, the operating current flows through the coil. Since the coil is carrying current and is placed in the magnetic field of the permanent magnet, a mechanical force acts on it. As a result, the pointer attached to the moving system moves in a clockwise direction over the graduated scale to indicate the value of current or voltage being measured. If the current in the coil is reversed, the deflecting torque will also be reversed since the direction of the field of the permanent magnet is the same. Consequently, the pointer will try to deflect below zero. Deflection in this direction (*i.e.*, reverse direction) is prevented by a spring "stop". Since the deflecting torque reverses with the reversal of current in the coil, such instruments can be used to measure direct current and voltage *only.

The magnetic field in the air-gap is radial due to the presence of soft-iron core. Therefore, when operating current flows through the coil, a constant deflecting torque T_d acts on the coil given by

$$T_d = BINA \text{ newton metre}$$

where B = flux density in Wb/m^2 ; I = current through the coil

N = Number of turns in coil ; A = Area of coil

Since the values of B, N and A are fixed.

$$T_d \propto I$$

The instrument is spring controlled so that $T_c \propto \theta$. The pointer will come to rest where $T_d = T_c$

$$\therefore \quad \theta \propto I$$

Thus the deflection is directly proportional to operating current. Hence such instruments have *uniform scale*.

Extension of range. The resistance of moving coil instrument and the current needed to produce full-scale deflection (f.s.d.) are very small. Typical values of these parameters may be :

Full-scale deflection current, I_g = 1 mA

Resistance of the meter, $G = 20\,\Omega$

This means that this instrument can read currents upto 1 mA and voltages upto 20 mV (= 1mA × 20 Ω). In order to measure large currents and voltages (*i.e.* to extend the range of the instrument) suitable means are provided.

(*i*) **Ammeter.** In order to measure large currents, a suitable low resistance S (called **shunt**) is connected in parallel with the instrument. *The shunted moving coil instrument is called an* **ammeter.** The value of shunt is chosen according to the maximum current we wish to measure. Suppose we want to measure I amperes at full-scale using a moving coil instrument having full-scale deflection current I_g and resistance G. This means that when circuit current is I, we want current I_g through the meter as shown in Fig. 16.9. For this purpose we connect a shunt S of suitable value so that $I - I_g$ current flows through it. Since the potential difference across the shunt is the same as across the meter,

$$(I - I_g)\,S = I_g G$$

$$\therefore \qquad S = \left(\frac{I_g}{I - I_g}\right) G$$

$$\text{Resistance of ammeter, } R_m = \frac{GS}{G + S}$$

Clearly, the value of R_m will be less than S. Since the value of S is very small, the ammeter resistance will be very low. Thus shunt has not only extended the current range but it has also lowered the resistance of the ammeter.

$$\text{Multiplying power of shunt, } n = \frac{I}{I_g} = \frac{G + S}{S}$$

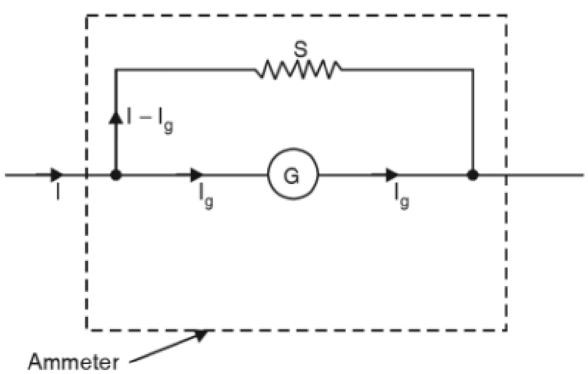


Fig. 16.9

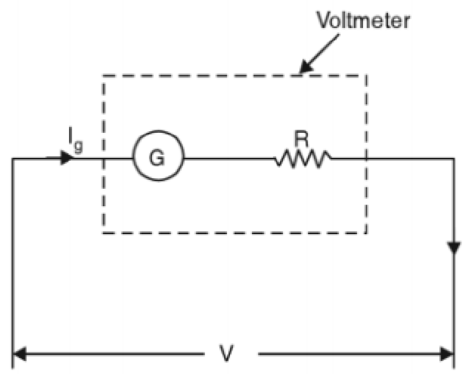


Fig. 16.10

(*ii*) **Voltmeter.** In order to measure large voltages, a suitable high resistance R (called **multiplier**) is used. *A moving coil meter in series with a high resistance is called a* **voltmeter.** The value of series resistance is chosen according to the maximum voltage we wish the measure. Suppose we want to read V volts at full-scale using a moving coil meter having full-scale deflection current I_g and resistance G. This means that when potential difference across the voltmeter is V volts, we want that current through the meter should be I_g as shown in Fig. 16.10. For this purpose, we connect a suitable high resistance R in series with the meter so that current through the meter is I_g. Referring to Fig. 16.10 and applying Ohm's law, we have,

$$I_g = \frac{V}{G+R}$$

or $$G + R = \frac{V}{I_g}$$

$\therefore$ $$R = \frac{V}{I_g} - G$$

Resistance of voltmeter, $R_m = G + R$

Since the value of R is large, the resistance of the voltmeter will be very high. Thus the series resistance has not only extended the voltage range but it has also increased the resistance of the voltmeter.

$$\text{Voltage amplification} = \frac{\text{Voltage to be measured}}{\text{Voltage across meter}} = \frac{V}{I_g G}$$

$$= \frac{I_g (G+R)}{I_g G} = \frac{G+R}{G} = 1 + \frac{R}{G}$$

Applications. Permanent-magnet moving coil instruments are acknowledged to be the best type for all d.c. measurements. They are very sensitive and maintain a high degree of accuracy over long periods. The chief applications of such instruments are :

(*a*) In the measurement of direct currents and voltages.

(*b*) In d.c. galvanometers to measure small currents.

(*c*) In ballistic galvanometers used mainly for measuring changes of magnetic flux linkages.

8. DYNAMOMETER TYPE INSTRUMENTS

These instruments can be used as ammeters or voltmeters but are generally used as wattmeters. They are suitable for d.c. as well as a.c. work. The operating principle of such instruments is that mechanical force exists between the current carrying conductors.

Fig. 16.11 shows the simplified diagram of a dynamometer type instrument. It essentially consists of a fixed coil and a moving coil. The fixed coil is split into two equal parts (*F*, *F*) which are placed close together and parallel to each other. The moving coil (*M*) is pivoted in between the two fixed coils and carries a pointer as shown in Fig. 16.11. The current is led into and out of the moving coil by means of two spiral hair-springs which also provide the controlling torque. *Air friction damping is provided by means of the aluminium vanes that move in the sector shaped chamber at the bottom of the instrument.

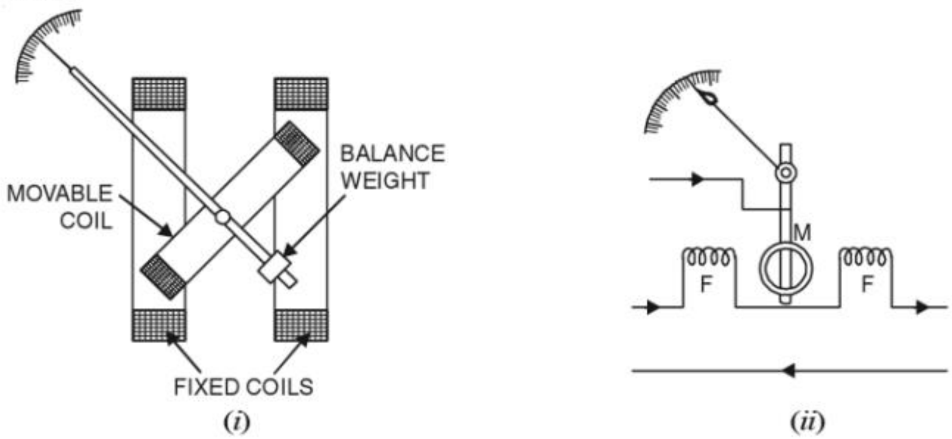


Fig. 16.11

Working. For use as an ammeter or voltemter, the fixed coils *FF* and the moving coil *M* are so connected that the same current flows through the two coils. Due to these currents, mechanical force exists between the coils. The result is that moving coil *M* moves the pointer over the scale. The pointer comes to rest at a position where deflecting torque is equal to the controlling torque. Since the polarity of the fields produced by both fixed and moving coils is reversed by the reversal of current, the deflection of the moving system is always in the same direction regardless of the direction of current through the coils. For this reason, dynamometer instruments can be used for both d.c. and a.c. measurements.

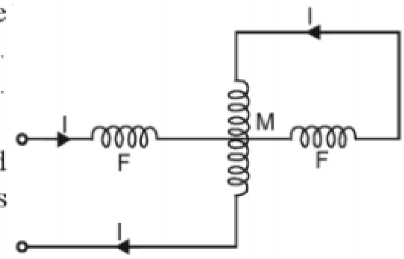


Fig. 16.12

The force of attraction or repulsion between the fixed and moving coils is directly proportional to the product of ampere-turns of fixed coils and the moving coil *i.e.*,

$$\text{Deflecting torque, } T_d \propto N_f I_f \times N_m I_m$$

Since N_m and N_f are constant,

$$\therefore \qquad T_d \propto I_f I_m$$

Since the instrument is spring-controlled, the controlling torque is proportional to the angular deflection θ *i.e.*,

$$T_C \propto \theta$$

In the steady position of deflection, $T_d = T_C$

$$\therefore \qquad \theta \propto I_f I_m$$

Thus deflection (θ) is directly proportional to the product of currents in the fixed coils and the moving coil.

(*i*) **As ammeter.** When the instrument is used as an ammeter, the fixed coils and the moving coil are connected in series so that the same current flows through the two coils as shown in Fig. 16.12. In that case, $I_f = I_m = I$ so that :

$$\theta \propto I^2$$

For measuring large currents, the moving coil is shunted ; the shunt being in series with the fixed coils as shown in Fig. 16.13. The fixed coils carry the main current while the moving coil carries a current proportional to the main current.

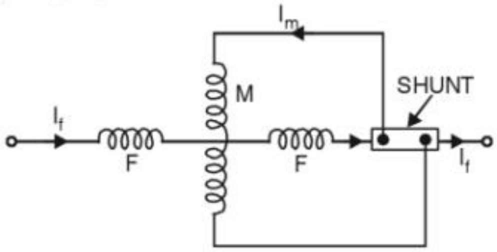


Fig. 16.13

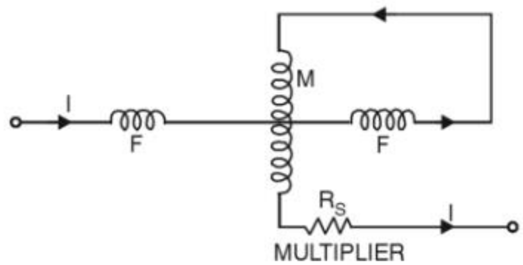


Fig. 16.14

(*ii*) **As voltmeter.** When the instrument is used as a voltmeter, both fixed coils and the moving coil are connected in series together with a high resistance R_S (called multiplier) having a negligible temperature co-efficient as shown in Fig. 16.14. Therefore, current in both the coils is the same and is proportional to the voltage V being measured.

$$\therefore \qquad \theta \propto V^2$$

It may be seen that whether the instrument is used as an ammeter or voltmeter, the deflection is directly proportional to the square of quantity (current or voltage) being measured. Hence the scale of dynamometer ammeter and voltmeter is not uniform ; being crowded at the beginning and open at the upper end of the scale.

Applications. It is clear from above that dynamometer ammeters and voltmeters are inferior to the permanent-magnet moving coil instruments and are seldom used for d.c. measurements. Their chief sphere of application is in a.c. measurements and particularly when the same instrument is required to read both direct and alternating currents as in the a.c. potentiometer.

9. MOVING IRON AMMETERS AND VOLTMETERS

This type of instrument is principally used for the measurement of alternating currents and voltages, though it can also be used for d.c. measurements. There are two types of moving-iron instruments *viz attraction type* and *repulsion type*.

(*i*) **Attraction type.** Fig. 16.15 shows the constructional details of an attraction type moving-iron instrument. It consists of a cylindrical coil or solenoid which is kept fixed. An oval-shaped soft-iron is attached to the spindle in such a way that it can move in and out of the coil. A pointer is attached to the spindle so that it is deflected with the motion of the soft-iron piece. The controlling torque is provided by one spiral spring arranged at the top of the moving element. The damping torque is provided by an aluminium vane, attached to the spindle, which moves in a closed air chamber.

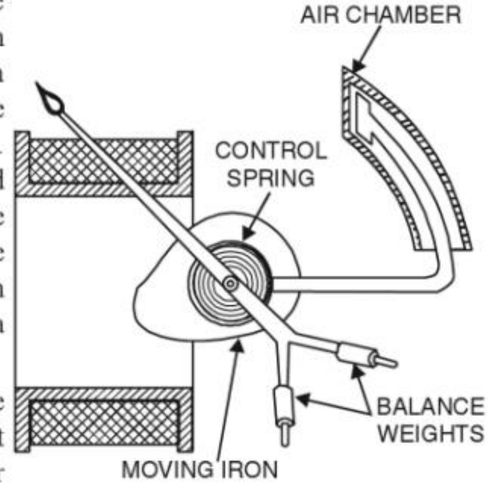


Fig. 16.15

Working. When the instrument is connected in the circuit to measure current or voltage, the operating current flowing through the coil sets up a magnetic field. In other words, the coil behaves like a magnet and therefore it attracts the soft-iron piece towards it. The result is that the pointer attached to the moving system moves from zero position. The pointer will come to rest at a position where deflecting torque is equal to the controlling torque. If current in the coil is reversed, the direction of magnetic field also reverses and so does the magnetism produced in the soft-iron piece. Hence, the direction of the deflecting torque remains unchanged. For this reason, such instruments can be used for both d.c. and a.c. measurements.

Deflecting torque. The force F pulling the soft-iron piece towards the coil is directly proportional to :

(*i*) field strength H produced by the coil

(*ii*) pole strength *m* developed in the iron piece

$\therefore \quad F \propto mH$

$\propto H^2 \qquad (\because m \propto H)$

$\therefore$ Instantaneous deflecting torque $\propto H^2$

If the permeability of iron is assumed constant, then,

$H \propto i$ where i is the instantaneous coil current.

$\therefore$ Instantaneous deflecting torque $\propto i^2$

Average deflecting torque, $T_d \propto$ mean of i^2 over a cycle

Since the instrument is spring controlled,

$$T_C \propto \theta$$

In the steady position of deflection, $T_d = T_C$

$\therefore \quad \theta \propto$ mean of i^2 over a cycle

$\propto I^2$ ...*for d.c.*

$\propto I^2_{r.m.s.}$ ...*for a.c.*

Since the deflection is proportional to the square of coil current, the scale of such instruments is non-uniform ; being crowded in the beginning and spread out near the finish end of the scale.

(*ii*) **Repulsion type.** Fig. 16.16 shows the constructional details of a repulsion type moving-iron instrument. It consists of two soft-iron pieces or vanes surrounded by a fixed cylindrical hollow coil which carries the operating current. One of these vanes is fixed and the other is free to move as shown in Fig. 16.16. The movable vane is of cylindrical shape and is mounted axially on a spindle to which a pointer is attached. The fixed vane, which is wedge-shaped and has a larger radius, is attached to the stationary coil. The controlling torque is provided by one spiral spring at the top of the instrument. It may be noted that in this instrument, springs do not provide the electrical connections. Damping is provided by air friction due to the motion of a piston in an air chamber.

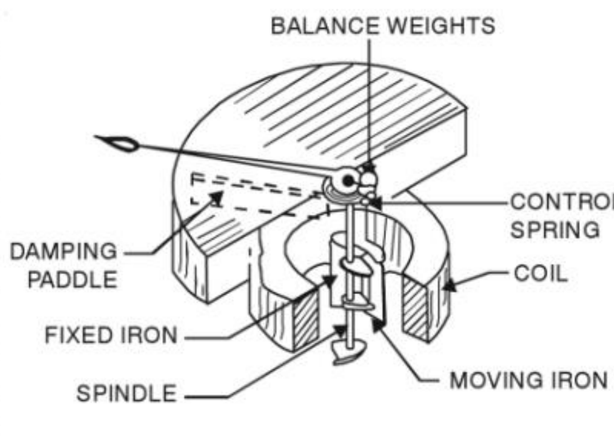


Fig 16.16

Working. When current to be measured or current proportional to the voltage to be measured flows through the coil, a magnetic field is set up by the coil. This magnetic field magnetises the two vanes in the same direction *i.e.*, similar polarities are developed at the same ends of the vanes. Since the adjacent edges of the vanes are of the same polarity, the two vanes repel each other. As the fixed vane cannot move, the movable vane deflects and causes the pointer to move from zero position. The pointer will come to rest at a position where deflecting torque is equal to the controlling torque provided by the spring. If the current in the coil is reversed, the direction of deflecting torque remains unchanged. It is because reversal of the field of the coil reverses the magnetisation of both iron vanes so that they repel each other regardless of which way the current flows through the coil. For this reason, such instruments can be used for both d.c. and a.c. applications.

Deflecting torque. The deflecting torque results due to the repulsion between the similarly charged soft-iron pieces or vanes. If the two pieces develop pole strengths of m_1 and m_2 respectively, then,

Instantaneous deflecting torque $\propto m_1 m_2 \propto H^2$

If the permeability of iron is assumed constant, then,

$$H \propto i \qquad \text{where } i \text{ is coil current.}$$

Instantaneous deflecting torque $\propto i^2$

$\therefore$ Average deflecting torque, $T_d \propto$ mean of i^2 over a cycle

Since the instrument is spring-controlled,

$$T_C \propto \theta$$

In the steady position of deflection, $T_d = T_C$

$$\therefore \qquad \theta \propto \text{mean of } i^2 \text{ over a cycle}$$

$$\propto I^2 \qquad \textit{...for d.c.}$$

$$\propto I^2_{r.m.s.} \qquad \textit{...for a.c.}$$

Thus, the deflection is proportional to the square of coil current as is the case with attraction type moving-iron instrument. Therefore, the scale of such instruments is also non-uniform ; being crowded in the beginning and spread out near the finish end of the scale. However, the non-linearity of the scale can be corrected to some extent by the accurate shaping (*e.g.* using tongue-shaped vanes) and positioning of iron vanes in relation to the operating coil.

Applications. The moving-iron instruments are primarily used for a.c. measurements *viz.*, alternating currents and voltages. They are not used to measure direct currents and voltages because their characteristics are inferior to permanent-magnet moving coil instruments.

10. EXTENDING RANGE OF MOVING-IRON INSTRUMENTS

As explained above, moving-iron instruments are used mainly on a.c. circuits. Therefore, range extension shall be discussed with reference to a.c. measurements.

(*i*) **Ammeter.** Shunts are not used to extend the range of moving-iron a.c. ammeters. It is because the division of current between the operating coil and the shunt varies with frequency (since reactance of the coil depends upon frequency). In practice, the range of moving-iron a.c. ammeter is extended by one of the following two methods :

(*a*) **By changing the number of turns** of the operating coil. For example, suppose that full-scale deflection is obtained with 400 ampere-turns. For full-scale reading with 100A, the number of turns required would be = 400/100 = 4.

Similarly, for full-scale reading with 50 A, the number of turns required is = 400/50 = 8. Thus the ammeter can be arranged to have different ranges by merely having different number of turns on the coil. Since the coil carries the whole of the current to be measured, it has a few turns of thick wire. The usual ranges obtained by this method are 0-250 A.

(*b*) For ranges above 0 – 250 A, a **current transformer** is used in conjunction with 0 – 5 A a.c. ammeter as shown in Fig. 16.17. The current transformer is a step-up transformer *i.e.*, number of secondary turns is more than the primary turns. The primary of this transformer is connected in series with the load and carries the load current. The a.c. ammeter is connected across the secondary of the transformer. Since in Fig. 16.17, the current transformer ratio is 10 : 1, it means that the line (or load) current is equal to 10 times the reading on the a.c. meter.

$$\text{Load current, } I_L = 3 \times 10 = 30 \text{ A}$$

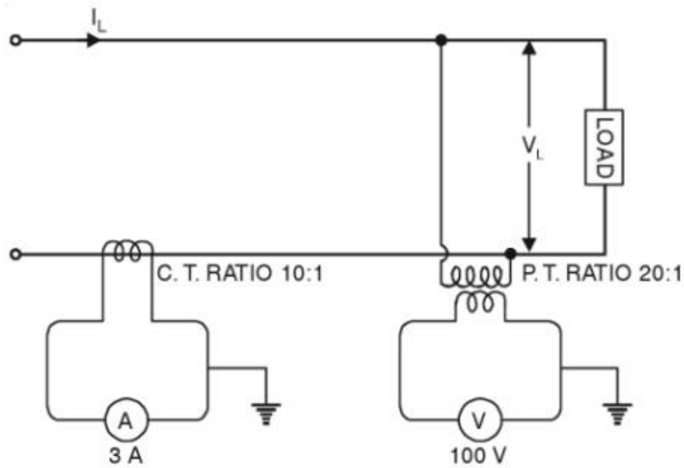


Fig. 16.17

(*ii*) **Voltmeter.** The range of a moving-iron a.c. voltmeter is extended by connecting a high resistance (multiplier) in series with it. For ranges higher than 0 – 750 V, where power wasted in the multiplier would be excessive, a 0 – 110 V a.c. voltmeter is used in conjunction with a **potential transformer** as shown in Fig. 16.17. The potential transformer is a stepdown transformer *i.e.* number of primary turns is more than the secondary turns. The primary of the transformer is connected across the load across which voltage is to be measured. The a.c. voltmeter is connected across the secondary. Since in Fig. 16.17, the potential transformer ratio is 20 : 1, the load voltage is equal to 20 times the reading on the a.c. voltmeter.

$\therefore$ Load voltage, $V_L = 100 \times 20 = 2000$ V

Note that both secondaries of the instrument transformers are grounded as a safety measure.

21. DYNAMOMETER WATTMETER

A dynamometer wattmeter is almost universally used for the measurement of d.c. as well as a.c. power. It works on the dynamometer prinicple *i.e.* mechanical force exists between two current carrying conductors or coils.

Construction. When a dynamometer instrument is used as a wattmeter, the fixed coils are connected in series with the load and carry the load current (I_1) while the moving coil is connected across the load through a series multiplier R and carries a current (I_2) proportional to the load voltage as shown in Fig. 16.35. The fixed coil (or coils) is called the *current coil* and the movable coil is known as *potential coil*. The controlling torque is provided by two spiral springs which also serve the additional purpose of leading current into and out of the moving coil. Air friction damping is provided in such instruments. A pointer is attached to the movable coil.

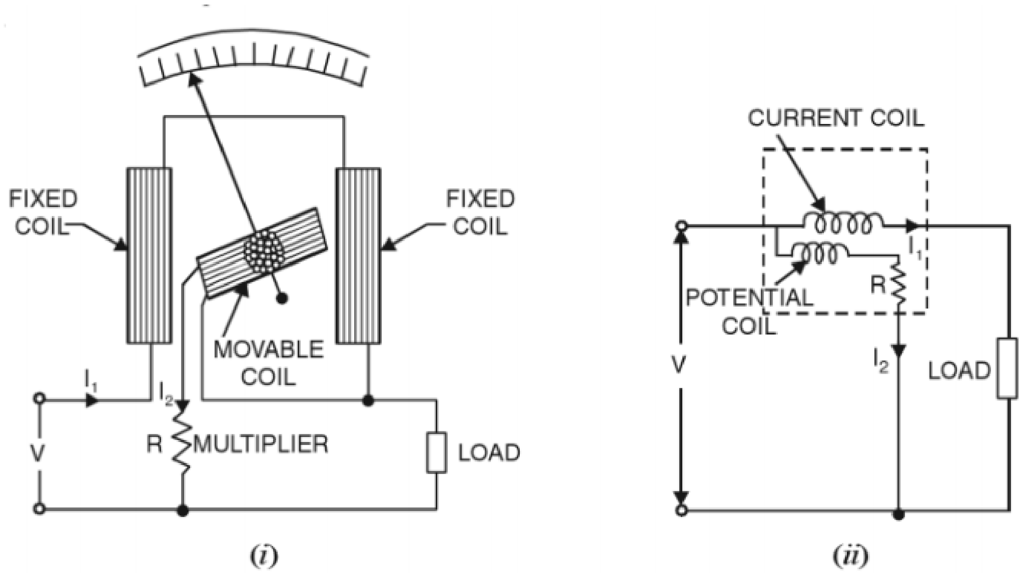


Fig. 16.35

Working. When the wattmeter is connected in the circuit to measure power (See Fig. 16.35), the current coil carries the load current and potential coil carries current proportional to the load voltage. Due to currents in the coils, mechanical force exists between them. The result is that movable coil moves the pointer over the scale. The pointer comes to rest at a position where deflecting torque is equal to the controlling torque. Reversal of current reverses currents in both the fixed coils and the movable coil so that the direction of deflecting torque remains unchanged. Hence, such instruments can be used for the measurement of d.c. as well as a.c. power.

Deflecting torque. We shall now prove that deflecting torque is proportional to load power in a d.c. as well as a.c. circuit.

(*i*) Consider that the wattmeter is connected in a d.c. circuit to measure power as shown in Fig. 16.35 (*ii*). The power taken by the load is VI_1.

$$\text{Deflecting torque, } T_d \propto I_1 I_2$$

Since I_2 is directly proportional to V,

$$\therefore \quad \text{Deflecting torque, } T_d \propto VI_1 \propto \text{load power}$$

(*ii*) Consider that the wattmeter is connected in an a.c. circuit to measure power. Suppose at any instant,current through the load is i and voltage across the load is v. Let the load power factor be $\cos\phi$ lagging. Then,

$$v = V_m \sin\theta$$
$$i = I_m \sin(\theta - \phi)$$

Instantaneous deflecting torque $\propto$ vi

The pointer cannot follow the rapid changes in the instantaneous power owing to the large inertia of the moving system. Hence the instrument indicates the mean or average power.

$\therefore$ Average deflecting torque, $T_d \propto$ Average of vi over a cycle

$$\propto \frac{1}{2\pi}\int_0^{2\pi} V_m I_m \sin\theta \sin(\theta - \phi)\, d\theta$$

$$\propto \frac{V_m I_m}{2}\cos\phi \propto VI\cos\phi$$

$$\therefore \qquad T_d \propto \text{load power}$$

Thus whether the instrument is used to measure d.c. or a.c. power, deflecting torque is proportional to load power.

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

In the steady position of deflection, $T_d = T_C$

$\therefore \qquad \theta \propto$ load power

Hence such instruments have uniform scale.

Errors. A wattmeter may not give true reading due to several of errors such as (*i*) error due to connection of potential coil circuit (*ii*) error due to inductance of potential coil (*iii*) error due to capacitance in potential coil circuit (*iv*) error due to stray fields and (*v*) errors due to eddy currents.

23. SINGLE PHASE INDUCTION WATTHOUR METER

Single phase induction watthour meters (or energy meters) are extensively used for the measurement of electrical energy in a.c. circuits. One can find such meters installed in homes. An induction watthour meter is essentially an induction wattmeter with control spring and pointer removed but brake magnet and counting mechanism provided.

Construction. Fig. 16.39 shows the various parts of a single-phase induction watthour meter.

(*i*) It consists of (*a*) two a.c. electromagnets ; the series magnet and shunt magnet (*b*) an aluminium disc or rotor placed between the two electromagnets (*c*) brake magnet and (*d*) counting mechanism.

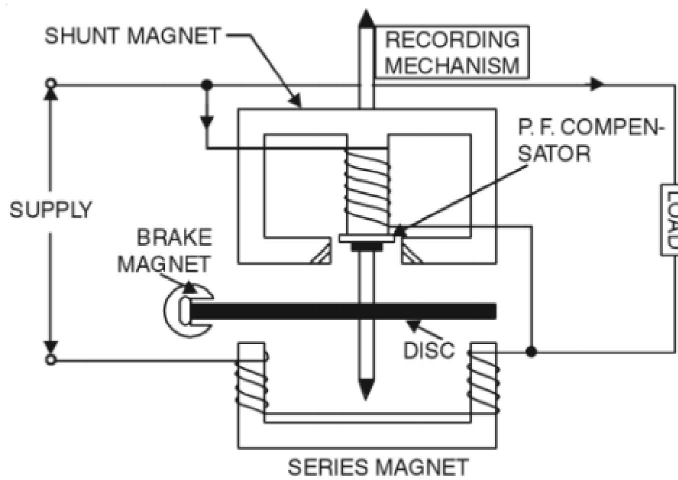


Fig. 16.39

(*ii*) The shunt magnet is wound with a fine wire of many turns and is connected across the supply so that it carries current proportional to the supply voltage. Since the coil of shunt magnet is highly *inductive, the current (and hence the flux) in it lags the supply voltage by 90°.

The series magnet is wound with a heavy wire of few turns and is connected in series with the load so that it carries the load current. The coil of this magnet is highly non-inductive so that angle of lag or lead is determined wholly by the load.

(*iii*) A thin aluminium disc mounted on the spindle is placed between the shunt and series magnets so that it cuts the fluxes of both the magnets.

(*iv*) The braking torque is obtained by placing a permanent magnet near the rotating disc so that the disc rotates in the field established by the permanent magnet. Eddy currents induced in disc produce a braking or retarding torque that is proportional to the disc speed.

(*v*) A short-circuited copper loop (also known as power factor compensator) is provided on the central limb of the shunt magnet. By adjusting the position of this loop, the shunt magnet flux can be made to lag behind the supply voltage exactly by 90°.

Frictional compensation is obtained by means of two adjustable short-circuited loops placed in the leakage gaps of the shunt magnet. Geared to the rotating element is counting mechanism which indicates the energy consumed directly in kilowatthours (*KWh*).

Theory. When induction watthour meter is connected in the circuit to measure energy, the shunt magnet carries current proportional to the supply voltage and the series magnet carries the load current. Therefore, expression for the driving torque is the same as for induction wattmeter. Referring back to the phasor diagram in Fig. 16.38.

$$\begin{aligned}\text{Driving torque, } T_d &\propto \phi_v \phi_C \sin\theta \\ &\propto VI \sin(\sin 90^\circ - \phi) \\ &\propto VI\cos\phi \\ &\propto \text{power}\end{aligned}$$

The braking torque is due to the eddy currents induced in the aluminium disc. Since the magnitude of eddy currents in proportional to the disc speed, the braking torque will also be proportional to the disc speed *i.e.*,

$$\text{Braking torque, } {}^{**}T_B \propto n \qquad (i.e.\ \text{disc speed})$$

$$\text{For steady speed of rotation, } T_d = T_B$$

$$\therefore \qquad \text{Power} \propto n$$

Multiplying both sides by t, the time for which power is supplied,

$$\text{Power} \times t \propto nt$$

or

$$\text{Energy} \propto N$$

where N (= nt) is the total number of revolutions in time t.

The counting mechanism is so arranged that the meter indicates kilowatthours (*kWh*) directly and not the revolutions.

Meter Constant. We have seen above that :

$$N \propto \text{Energy}$$

or

$$N = K \times \text{Energy}$$

where K is a constant called meter constant.

$$\therefore \qquad \text{Meter constant, } K = \frac{N}{\text{Energy}} = \frac{\text{No. of revolutions}}{\text{kWh}}$$

Hence the number of revolutions made by the disc for 1 kwh of energy consumption is called **meter constant.**

The meter constant is always written on the name plates of the energy meters installed in homes, commercial and industrial establishment. If the meter constant of an energy meter is 1500 rev/kWh, it means that for consumption of 1 kWh, the disc will make 1500 revolutions.