9

Analog Ammeters, Voltmeters and Ohmmeters

9.1 INTRODUCTION

Analog ammeters and voltmeters are classed together as there are no fundamental differences in their operating principles. The action of all ammeters and voltmeters, with the exception of electrostatic type of instruments, depends upon a deflecting torque produced by an electric current. In an ammeter this torque is produced by a current to be measured or by a definite fraction of it. In a voltmeter this torque is produced by a current which is proportional to the voltage to be measured. Thus all analog voltmeters and ammeters are essentially current measuring devices.

The essential requirements of a measuring instrument are :

(*i*) That its introduction into the circuit, where measurements are to be made, does not alter the circuit conditions ;

(*ii*) The power consumed by them for their operation is small.

Ammeters are connected in series in the circuit whose current is to be measured. The power loss in an ammeter is I^2R_a, where I is the current to be measured and R_a, is the resistance of ammeter. Therefore, ammeters should have a low electrical resistance so that they cause a small voltage drop and consequently absorb small power.

Voltmeters are connected in parallel with the circuit whose voltage is to be measured. The power loss in voltmeters is V^2/R_v, where V is the voltage to be measured and R_v, is the resistance of voltmeter. Therefore, voltmeters should have a high electrical resistance, in order that the current drawn by them is small and consequently the power consumed is small.

Ohmmeters are used for measurement of resistance. They incorporate a source of emf and a current measuring device.

9.2 TYPES OF INSTRUMENTS

The main types of instruments used as ammeters and voltmeters are :

(*i*) Permanent magnet moving coil (PMMC)
(*ii*) Moving iron
(*iii*) Electro-dynamometer
(*iv*) Hot wire
(*v*) Thermocouple
(*vi*) Induction
(*vii*) Electrostatic
(*viii*) Rectifier.

Of these the permanent-magnet moving-coil type can be used for direct-current measurements only, and the induction type for alternating-current measurements only. The other types of meters can be used with either direct or alternating-currents.

The moving-iron and moving-coil types both depend for their action upon the magnetic effect of current. The former is the most generally used form of indicating instrument, as it is the cheapest. It can be used for either direct or alternating-current measurements and, if properly designed is very accurate. The permanent-magnet moving-coil instrument is the most accurate type for direct-current measurements, and instruments of this type are frequently constructed to have substandard* accuracy.

Electrodynamometer type of instruments are used both on a.c. as well as on d.c. Their calibration for both d.c. and a.c. is the same and hence they are very useful as "*transfer instruments*".

* The connotation, "substandard", is not used in the negative sense. It only implies a standard which is almost a secondary standard.

Thermal instruments have the advantage that their calibration is the same for both d.c. and a.c. They are particularly suited for alternating-current measurements since their deflection depends directly upon the heating effect of the alternating current, *i.e.*, upon the rms value of the current. Their readings are thus, independent of the frequency or wave-form of the current, and of any stray magnetic fields which may exist in their vicinity.

As voltmeters, electrostatic instruments have the advantage that their power consumption is exceedingly small. They can be made to cover a large range of voltage, and can be constructed to have substandard accuracy. Their main disadvantage is that the electrostatic principle is only directly applicable to voltage measurements.

The induction principle is more generally used for watt-hour meters than for ammeters and voltmeters owing to their comparatively high cost, and inaccuracy, of induction instruments of the latter types.

9.3 ERRORS IN AMMETERS AND VOLTMETERS

There are certain errors which occur in most types of instruments, while other errors occur only in those of particular type. The latter types of errors will be dealt with later, together with the instruments in which they occur.

Of the errors common to most types of instruments, friction and temperature errors are perhaps the most important. To reduce the effect of friction torque, and consequently the error produced by it the weight of the moving system must be made as small as possible compared with the operating force, *i.e.*, the ratio of torque to weight must be large. In high quality instruments the ratio of deflecting torque at full scale to weight of moving system is rarely much less than 0.01 Nm/kg. A vertical spindle is generally preferred to a horizontal one from the point of view of a small friction torque.

The most serious error is produced by the heat generated in the instrument, or by changes in ambient (room) temperature, is that due to a change in the resistance of the working coil. Such a change of resistance is of little importance in ammeters, but in voltmeters, in which the working current should be directly proportional to the applied voltage, it is essential that the resistance of the instrument remains as nearly constant as possible.

Thus, the power loss in the instrument should be small, and resistance coils which are likely to produce appreciable heating should be mounted, if possible, in such a position that they are well ventilated. In order to eliminate temperature errors, the working coil is wound with copper wire and is of comparatively low resistance. A high *"swamping resistance"* of material whose resistance temperature coefficient is small, is connected in series with the coil, so that, although the resistance of the coil may change considerably, the change in total resistance of circuit is small.

Other errors resulting from heating may be caused by expansion of the control spring, or of other parts of the instrument, although such errors are usually small. Lack of balance in the moving system and changes in the strength of permanent magnets (if used) are other possible sources of error which are common to several types of instruments.

9.4 PERMANENT MAGNET MOVING COIL INSTRUMENT (PMMC)

The permanent magnet moving coil instrument is the most accurate type for d.c. measurements. The working principle of these instruments is the same as that of the d'Arsonval type of galvanometers, the difference being that a direct reading instrument is provided with a pointer and a scale.

9.4.1 Construction of PMMC Instruments

The general constructional features of this instrument are shown in Fig. 9.1.

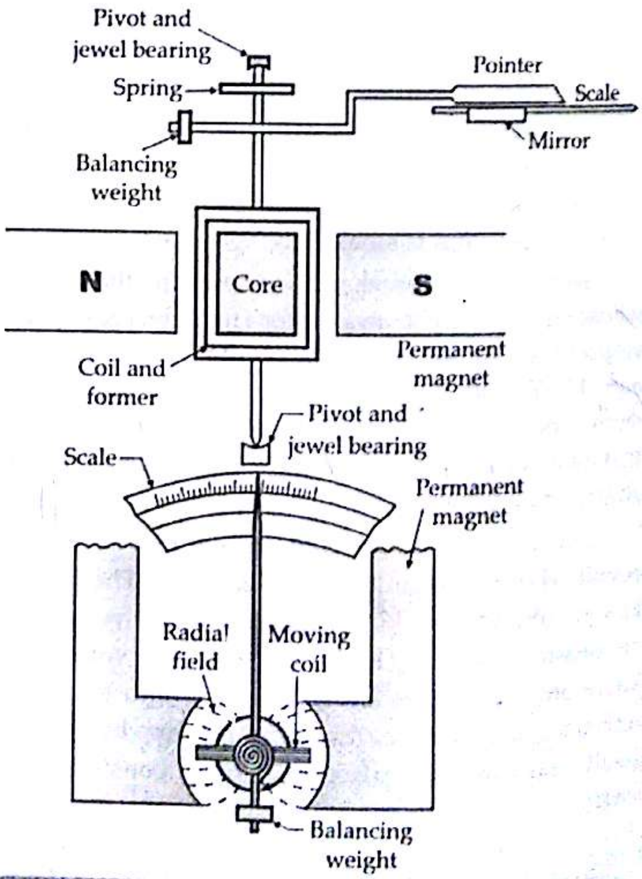


Fig. 9.1 Permanent magnet moving coil instrument.

Moving coil. The moving coil is wound with many turns of enamelled or silk covered copper wire. The coil is mounted on a rectangular aluminium former which is pivoted on jewelled bearings. The coils move freely in the field of a permanent magnet. Most voltmeter coils are wound on metal frames to provide the required electro-magnetic damping. Most ammeter coils, however, are wound on non-magnetic formers, because coil turns are effectively shorted by the ammeter shunt. The coil itself, therefore, provides electro-magnetic damping.

Magnet systems. There has been considerable development in materials for permanent magnets and, therefore, magnet assemblies have undergone a lot of change in the recent past. Old style magnet system consisted of a relatively long *U* shaped permanent magnets having soft iron pole pieces. Owing to development of materials like Alcomax and Alnico, which have a high coercive force, it is possible to use smaller magnet lengths and high field intensities. The flux densities used in PMMC instruments vary from 0.1 Wb/m^2 to 1 Wb/m^2. Thus in small instruments it is possible to use a small coil having small number of turns and hence a reduction in volume is achieved. Alternatively in instruments having a large scale length it is possible to increase the air gap length to accommodate large number of turns.

The movement of the coil is restricted in the above design. This is because no actual part of the coil is allowed to reach the extreme positions near the pole tips where, there is fringing field (owing to fringing the flux density near the pole tips is smaller than that at the centre and also the field is not radial). Thus the angular span of scale is restricted to 90°. In order to obtain longer movement of the pointer and a longer angular swing of the coil a concentric magnet construction as shown in Fig. 9.2 is used. Since the magnet is concentric type it produces a radial flux

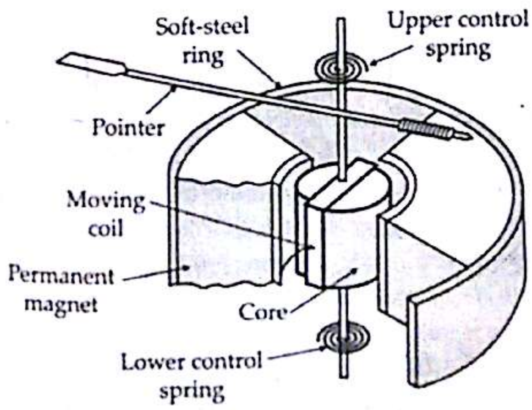


Fig. 9.2 Concentric magnet assembly.

pattern which extends over 250° or more. This type of construction is used for many panel type instruments and some portable instruments.

An air cored coil offset from the axis of rotation is used as shown in Fig. 9.3. The scale length of the instrument can be increased from 120° to 240° or even 300°, thereby giving better resolution of reading for the same scale range.

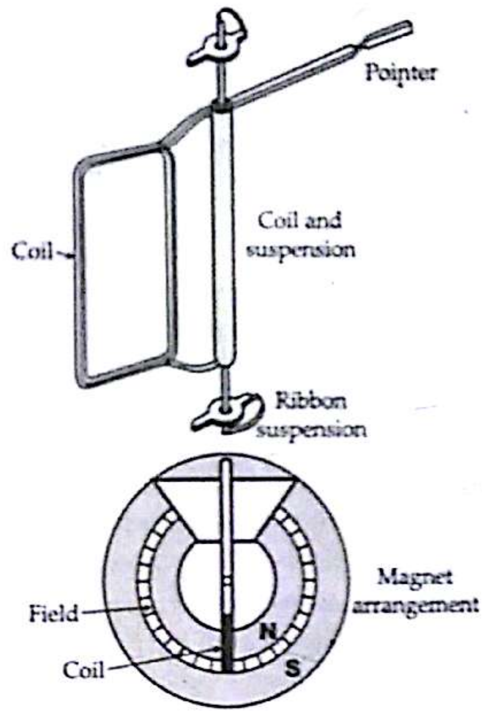


Fig. 9.3 Long scale moving coil instrument.

In recent years, with the development of improved magnetic materials like Alnico, it has become feasible to design a magnetic system in which the magnet itself serves as the core as shown in Fig. 9.4. The moving coil moves over the magnet. The active sides of the moving coil are located in the uniform radial field between pole pieces and the steel yoke.

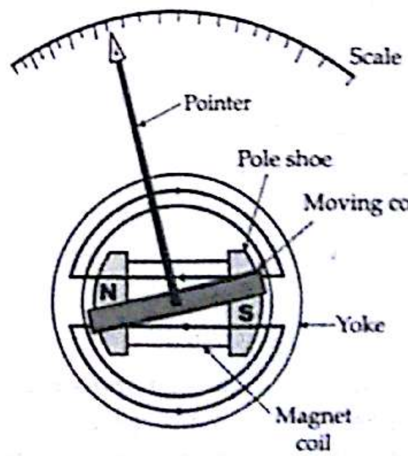


Fig. 9.4 Core magnet construction.

This arrangement has the obvious advantage of being relatively unaffected by the external magnetic fields. It also eliminates the magnetic shunting effects in steel panel construction, where several meters operating side by side may affect each other's readings. The need for magnetic shielding in the form of iron cases, is also eliminated by core magnet construction.

Control. When the coil is supported between two jewel bearings the control torque is provided by two phosphor bronze hair springs. These springs also serve to lead current in and out of the coil. The control torque is provided by the ribbon suspension as shown in Fig. 9.2. This method is comparatively new and is claimed to be advantageous as it eliminates bearing friction.

Damping. Damping torque is produced by movement of the aluminium former moving in the magnetic field of the permanent magnet.

Pointer and scale. The pointer is carried by the spindle and moves over a graduated scale. The pointer is of light-weight construction and, apart from those used in some inexpensive instruments has the section over the scale twisted to form a fine blade. This helps to reduce parallax errors in the reading of the scale.

In many instruments such errors may be reduced further by careful alignment of the pointer blade and its reflection in the mirror adjacent to scale. The weight of the instrument is normally counter balanced by weights situated diametrically opposite and rigidly connected to it.

9.4.2 Torque Equation

The torque for a moving coil instrument is derived in Art. 8.4 on page 198.

Deflecting torque $T_d = NBI\,dI = GI$ ...(9.1)

where G = a constant = $NBld$ ...(9.2)

The spring control provides a restoring (controlling) torque

$$T_c = K\theta \quad ...(9.3)$$

where K = spring constant.

For final steady deflection

$$T_c = T_d \text{ or } GI = K\theta$$

$\therefore$ Final steady deflection

$$\theta = (G/K)\,I \quad ...(9.4)$$

or current $I = (K/G)\theta$ ...(9.5)

As the deflection is directly proportional to the current passing through the meter (K and G being constants) we get a uniform (linear) scale for the instrument.

In micro-ammeters and low range milli-ammeters upto about 20 mA, the entire current to be measured is sent through the moving coil. This is because instrument springs serve as current leads to the moving coil. Their current carrying capacity limits the current which can be safely carried to about 20 mA. For higher currents (usually above 20 mA) the moving coil is shunted to bypass current around the coil and the spring. D.C. ammeters are normally designed to have a voltage drop of nearly 50 mV to 100 mV for full scale deflection. Voltmeters on their own have a range of 0-50 mV or 0-100 mV. However, voltmeters having higher ranges use a moving coil together with sufficient series resistance (known as multiplier) to limit the instrument current to the desired value. Most d.c. voltmeters are designed to produce full scale deflection with a current of 20, 10, 5 or 1 mA. Normally a value of 1 mA is used.

Thus, excluding low range current measuring instruments, most d.c. ammeters are actually 50 mV (or 100 mV) millivoltmeters operated with a suitable shunt, while voltmeters are low range milli-ammeters operated with a suitable series resistance.

Example 9.1 *A permanent magnet moving coil instrument has a coil of dimensions 15 mm × 12 mm. The flux density in the air gap is 1.8×10^{-3} Wb/m^2 and the spring constant is 0.14×10^{-6} Nm/rad. Determine the number of turns required to produce an angular deflection of 90 degrees when a current of 5 mA is flowing through the coil.*

Solution. Deflection, $\theta = 90° = \pi/2$ rad.

At equilibrium, $T_d = T_c$ or $NBld\,I = K\theta$.

$\therefore$ Number of turns, $N = \dfrac{K\theta}{Bld\,I}$

$$= \frac{0.14 \times 10^{-6} \times \pi/2}{18 \times 10^{-3} \times 15 \times 10^{-3} \times 12 \times 10^{-3} \times 12 \times 10^{-3} \times 5 \times 10^{-3}}$$

$$= 136.$$

Example 9.2 *A moving coil voltmeter with a resistance of 20 Ω gives a full scale deflection of 120° when a potential difference of 100 mV is applied across it. The moving coil has dimensions of 30 mm × 25 mm and is wound with 100 turns. The control spring constant is 0.375×10^{-6} Nm/deg. Find the flux density in the air gap. Find also the diameter of copper wire of coil winding if 30 percent of instrument resistance is due to coil winding. The specific resistance for copper = 1.7×10^{-8} Ωm.*

Solution. Voltage across instrument for full scale deflection = 100 mV.

Current in instrument for full scale deflection

$$I = \frac{V}{R} = \frac{100 \times 10^{-3}}{20} = 5 \times 10^{-3}\text{ A.}$$

Deflecting torque

$$T_d = NBldI$$
$$= 100 \times B \times 30 \times 10^{-3} \times 25 \times 10^{-3} \times 5 \times 10^{-3}$$
$$= 375 \times 10^{-6} B\text{ N-m.}$$

$\therefore$ Controlling torque for a deflection $\theta = 120°$,

$$T_c = K\theta = 0.375 \times 10^{-6} \times 120$$
$$= 45 \times 10^{-6}\text{ N-m.}$$

At final steady position,

$$T_d = T_c \quad \text{or} \quad 375 \times 10^{-6} B = 45 \times 10^{-6}.$$

$\therefore$ Flux density in the air gap

$$B = \frac{45 \times 10^{-6}}{375 \times 10^{-6}} = 0.12\text{ Wb/m}^2.$$

Resistance of coil winding

$$R_c = 0.3 \times 20 = 6\ \Omega$$

Length of mean turn

$$l_{mt} = 2(l + d) = 2(30 + 25) = 110\text{ mm.}$$

Let a be the area of cross-section of wire and ρ be the resistivity.

Resistance of coil, $R_c = N\rho\, l_{mt} / a$.

$\therefore$ Area of cross-section of wire,

$$a = \frac{100 \times 1.7 \times 10^{-8} \times 110 \times 10^{-3}}{6} \times 10^{6}$$
$$= 31.37 \times 10^{-3}\text{ mm}^2$$

Diameter of wire, $d = [(4/\pi)(31.37 \times 10^{-3})]^{1/2} = 0.2$ mm

Example 9.3 The coil of a moving coil voltmeter is 40 mm long and 30 mm wide and has 100 turns on it. The control spring exerts a torque of 240×10^{-6} N-m when the deflection is 100 divisions on full scale. If the flux density of the magnetic field in the air gap is 1.0 Wb/m^2, estimate the resistance that must be put in series with the coil to give one volt per division. The resistance of the voltmeter coil may be neglected.

Solution. Controlling torque at full scale deflection

$$T_c = 240 \times 10^{-6}\text{ N-m.}$$

Deflecting torque at full scale deflection

$$T_d = NBldI$$
$$= 100 \times 1 \times 40 \times 10^{-3} \times 30 \times 10^{-3} I$$
$$= 120 \times 10^{-3} I\text{ N-m.}$$

At final steady position,

$$T_d = T_c \quad \text{or} \quad 120 \times 10^{-3} I = 240 \times 10^{-6}.$$

$\therefore$ Current at full scale deflection, I

$$= 2 \times 10^{-3}\text{ A} = 2\text{ mA.}$$

Let the resistance of the voltmeter circuit be R

$\therefore$ Voltage across the instrument $= 2 \times 10^{-3} R$.

This produces a deflection of 100 divisions

$\therefore$ Volts per division $= 2 \times 10^{-3} R / 100$

This value should be equal to 1 in order to get 1 volt per division.

$$\therefore \quad 2 \times 10^{-3} R / 100 = 1$$

or

$$R = 50000\ \Omega = 50\text{ k}\Omega$$

9.4.3 Ammeter Shunts

The basic movement of a d.c. ammeter is a PMMC d'Arsonval galvanometer. The coil winding of a basic movement is small and light and can carry very small currents since the construction of an accurate instrument with a moving coil to carry currents greater than 100 mA is impracticable owing to the bulk and weight of the coil that would be required.

When heavy currents are to be measured, the major part of the current is bypassed through a low resistance called a "*shunt*". Figure 9.5 shows the basic movement (meter) and its shunt to produce an ammeter.

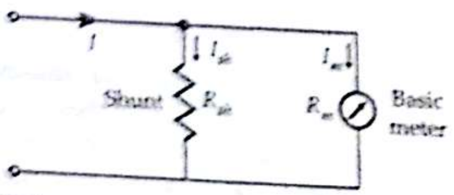


Fig. 9.5 Basic ammeter circuit.

The resistance of the shunt can be calculated using conventional circuit analysis. See Fig. 9.5,

where R_m = internal resistance of movement (*i.e.*, the coil) Ω ;

R_{sh} = resistance of the shunt ; Ω,

$I_m = I_{fs}$ = full scale deflection current of movement, A ;

I_{sh} = shunt current, A

I = current to be measured ; A.

Since the shunt resistance is in parallel with the meter movement, the voltage drops across shunt and movement must be the same.

or $\quad I_{sh} R_{sh} = I_m R_m$

$$\therefore \quad R_{sh} = I_m R_m / I_{sh} \qquad \text{...(9.6)}$$

But $\quad I_{sh} = I - I_m$

Therefore, we can write,

$$R_{sh} = I_m R_m / (I - I_m) \qquad \text{...(9.7)}$$

$$\therefore \quad I / I_m - 1 = R_m / R_{sh}$$

or

$$I / I_m = 1 + R_m / R_{sh} \qquad \text{...(9.8)}$$

This ratio of total current to the current in the movement is called *multiplying power of shunt.*

∴ Multiplying power

$$m = I / I_m \quad ...(9.9)$$

$$= 1 + R_m / R_{sh} \quad ...(9.10)$$

∴ Resistance of shunt

$$R_{sh} = R_m / (m-1) \quad ...(9.11)$$

The shunt resistance used with a d'Arsonval movement may consist of a coil of resistance wire within the case of the Instrument, or it may be external shunt having a very low resistance.

Construction of Shunts :

The general requirements for shunts are :

(*i*) The temperature co-efficient of shunt and instrument should be low and should be as nearly as possibly the same.

(*ii*) The resistance of shunts should not vary with time,

(*iii*) They should carry the current without excessive temperature rise,

(*iv*) They should have a low thermal electromotive force with copper.

'Manganin' is usually used for shunts of d.c. instruments as it gives low value of thermal emf with copper although it is liable to corrosion and is difficult to solder. 'Coustantan' is a useful material for a.c. circuits since its comparatively high thermal emf, being unidirectional, is ineffective on these circuits.

The construction of shunts is the same as that of low resistance standards explained in Art. 6.4. Shunts for low currents are enclosed in the meter casing but for currents above 200 A, they are mounted separately (so that heat produced can be effectively dissipated).

Example 9.4 *A 1 mA meter d'Arsonval movement with an internal resistance of 100 Ω is to be converted into a 0-100 mA ammeter. Calculate the shunt resistance required. What particulars should be specified on the shunt ?*

Solution. Shunt resistance

$$R_{sh} = I_m R_m / (I - I_m) = 1 \times 100 / (100-1) = 1.01\,\Omega.$$

Voltage drop across the shunt

$$= (1.0)\,(100) = 100 \text{ mV}.$$

Equivalent resistance of shunt and meter in parallel

$$= 100 \times 10^{-3} / (100 \times 10^{-3}) = 1.0\,\Omega.$$

Therefore the indications on the shunt should be :

(*i*) 100 mA, 100 mV (*ii*) 1.0 Ω, 100 mA or

(*iii*) 1.0 Ω, 100 mV.

Example 9.5 *Find the multiplying power of a shunt of 200 Ω resistance used with a galvanometer of 1000 Ω resistance. Determine the value of shunt resistance to give a multiplying power of 50.*

Solution. Multiplying power

$$m = 1 + R_m / R_{sh} = 1 \times 1000/200 = 6.$$

We have, $m = 1 + R_m / R_{sh}$

∴ Shunt resistance, $R_{sh} = \dfrac{R_m}{m-1} = \dfrac{1000}{50-1} = 20.4\,\Omega.$

Example 9.6 *A moving coil ammeter has a fixed shunt of 0.02 Ω. With a coil resistance of R = 1000 Ω and a potential difference of 500 mV across it, full scale deflection is obtained :*

(*a*) *To what shunted current does this correspond ?*

(*b*) *Calculate the value of R to give full scale deflection when shunted current I is*

(*i*) *10 A,* (*ii*) *75 A and*

(*c*) *With what value of R is 40% deflection obtained with I = 100 A ?*

Solution. (*a*) Current through shunt,

$$I_{sh} = 500 \times 10^{-3} / 0.02 = 25 \text{ A}.$$

Current through the meter to give full scale deflection

$$= 500 \times 10^{-3} / 1000 = 0.5 \times 10^{-3} \text{ A}.$$

(*b*) (*i*) Voltage across shunt for a current of 10 A

$$= 0.02 \times 10 = 0.2 \text{ V}.$$

∴ Resistance of meter for a current of 10 A to give full scale deflection

$$= 0.2 / (0.5 \times 10^{-3}) = 400\,\Omega.$$

(*ii*) Voltage across shunt for a current of 75 A

$$= 0.02 \times 75 = 1.5 \text{ V}.$$

Resistance of meter for a current of 75 A to give full scale deflection

$$= 1.5 / (0.5 \times 10^{-3}) = 3000\,\Omega.$$

(*c*) Now 40 percent deflection is obtained with 100 A.

∴ Current to give full scale deflection

$$= 100 / 0.4 = 250 \text{ A}.$$

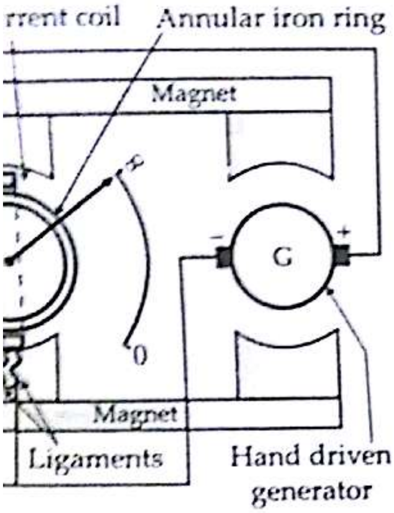
Voltage across shunt for a current of 250 A

$$= 0.02 \times 250 = 5.0 \text{ V}$$

Resistance of meter for a current of 100 A to give 40 percent of full scale deflection

$$= 5.0 / (0.5 \times 10^{-3}) = 10{,}000\,\Omega$$

Example 9.7 *A simple shunted ammeter using a basic meter movement with an internal resistance of 1800 Ω and a full scale deflection current of 100 μA is connected in a* es from the '∞' position of the resistance scale. The ds around) the extension H



of the two voltage coils V_1 ered as though the coils ariable stiffness, being very he scale where the current in ge (on account of unknown , and very weak near the ∞ current in the current coil is of unknown resistance R_x

presses the low resistance pens up the high resistance a great advantage since this used as "*insulation tester*" as are quite high.

of the instrument can be elector switch. This can be 'R' connected in series with oltages, usually 500, 1000 or hand cranked generator G. orporated in the generator slips at a predetermined voltage is applied to the voltage provides a test of ulation as well as a measure since it is sufficient to cause breakdowns are indicated ointer off scale at zero end. m supplies magnetic fields

9.9 MOVING IRON (M.I.) INSTRUMENTS

The most common ammeters and voltmeters for laboratory or switch-board use at power frequencies are the moving iron instruments. These instruments can be constructed to measure current and voltage to an accuracy needed in most engineering works and still be cheap as compared with any other type of a.c. instrument of same accuracy and ruggedness.

The general principle of working of a moving iron instrument (which is strictly relevant to attraction type of moving iron instruments) can be explained as under :

A plate or vane of soft iron or of high permeability steel forms the moving element of the system. This iron vane is so situated that it can move in a magnetic field produced by a stationary coil. The coil is excited by the current or voltage under measurement. When the coil is excited, it becomes an electromagnet and the iron vane moves in such a way so as to increase the flux of the electromagnet. This is because the vane tries to occupy a position of minimum reluctance. Thus the force produced is always in such direction so as to increase the inductance of coil (this is because inductance is inversely proportional to reluctance of magnetic circuit of the coil).

9.9.1 General Torque Equation of Moving Iron Instruments

An expression for the torque of a moving iron instrument may be derived by considering the energy relations when there is a small increment in current supplied to the instrument. When this happens there will be a small deflection $d\theta$ and some mechanical work will be done. Let T_d be the deflecting torque.

$\therefore$ Mechanical work done $= T_d \cdot d\theta$

Alongside there will be a change in the energy stored in the magnetic field owing to change in inductance.

Suppose the initial current is I, the instrument inductance L and the deflection θ. If the current increases by dI then the deflection changes by $d\theta$ and the inductance by dL. In order to affect an increment dI in the current there must be an increase in the applied voltage given by

$$e = \frac{d}{dt}(LI) = I\frac{dL}{dt} + L\frac{dI}{dt}.$$

The electrical energy supplied

$$e\,I\,dt = I^2 dL + ILdI$$

The stored energy changes from

$$= \frac{1}{2} I^2 L \text{ to } \frac{1}{2}(I + dI)^2 (L + dL).$$

Hence the change in stored energy,

$$= \frac{1}{2}(I^2 + 2\,IdI + dI^2)(L + dL) - \frac{1}{2} I^2 L$$

Neglecting second and higher order terms in small quantities this becomes $ILdI + \frac{1}{2} I^2 dL$

From the principle of the conservation of energy,

$$\boxed{\text{Electrical energy supplied} = \text{increase in stored energy} + \text{mechanical done work}}$$

$$I^2 dL + ILdI = ILdI = \frac{1}{2} I^2 dL + T_d\, d\theta$$

Thus $\quad T_d\, d\theta = \frac{1}{2} I^2 dL$

or $\boxed{\text{Deflecting torque } T_d = \frac{1}{2} I^2 \frac{dL}{d\theta}}$ ...(9.51)

T is in newton-metre, I in ampere, L in henry, and θ in radian.

The moving system is provided with control springs and it turns the deflecting torque T_d is balanced by the controlling torque

$$\boxed{T_c = K\theta.}$$

where K = control spring constant ; Nm/rad,

θ = deflection ; rad.

At equilibrium (or final steady) position,

$$T_c = T_d \quad \text{or} \quad K\theta = \frac{1}{2} I^2 \frac{dL}{d\theta}.$$

$\therefore$ $\boxed{\text{Deflection } \theta = \frac{1}{2}\frac{I^2}{K}\frac{dL}{d\theta}}$ ...(9.52)

Hence the deflection is proportional to square of the rms value of the operating current. The deflecting torque is, therefore, unidirectional (acts in the same direction) whatever may be the polarity of the current.

9.9.2 Classification of Moving Iron Instruments

Moving iron instruments are of *two* types :

(*i*) Attraction type.

(*ii*) Repulsion type.

1. ***Attraction type.*** Figure 9.24 shows the constructional details of an attraction type moving iron instrument. The coil is flat and has a narrow slot like opening. The moving iron is a flat disc or a sector eccentrically mounted. When the current flows through the coil, a magnetic field is produced and the moving iron moves from the weaker field outside the coil to the stronger field inside it or in other words, the moving iron is attracted in. The controlling torque is provided by springs but gravity control can be used for panel type of instruments which are vertically mounted.

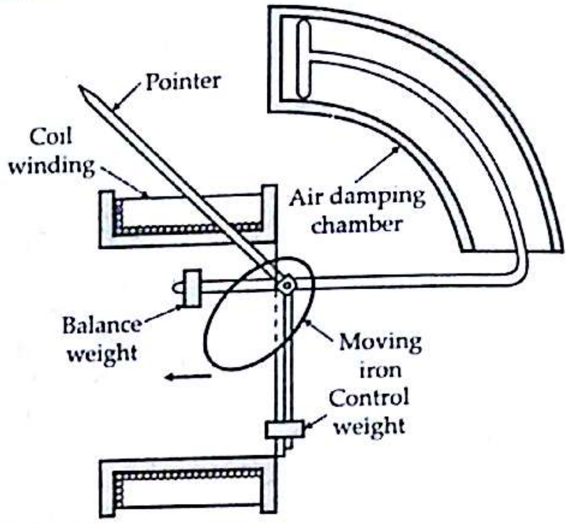


Fig. 9.24 Attraction type moving iron instrument.

Damping is provided by air friction with the help of a light aluminium piston (attached to the moving system) which moves in a fixed chamber closed at one end as shown in Fig. 9.24 or with the help of a vane (attached to the moving system) which moves in a fixed sector shaped chamber as shown in Fig. 7.17(*b*) on page 187.

2. ***Repulsion type.*** In the repulsion type, there are two vanes inside the coil one fixed and other movable. These are similarly magnetised when the current flows through the coil and there is a force of repulsion between the two vanes resulting in the movement of the moving vane.

Two different designs are in common use :

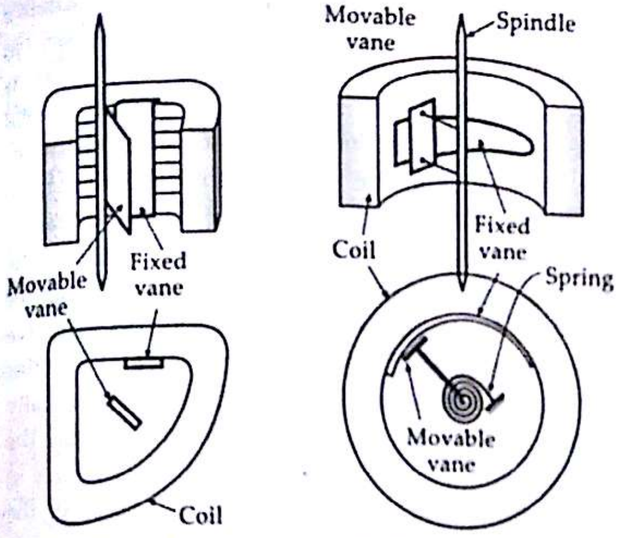
(Vane)

(*i*) *Radial Vane Type*. In this type, the vanes are radial strips of iron. The strips are placed within the coil as shown in Fig. 9.25(*a*). The fixed vane is attached to the coil and the movable one to the spindle of the instrument.

(*ii*) *Co-axial Vane Type*. In this type of instrument, the fixed and moving vanes are sections of co-axial cylinders as shown in Fig. 9.25(*b*).

The controlling torque is provided by springs. Gravity control can also be used in vertically mounted instruments. The damping torque is produced by air friction as in attraction type instruments.

The operating magnetic field in moving iron instruments is very weak and therefore eddy current damping is not used in them as introduction of a permanent magnet required for eddy current damping would distort the operating magnetic field.



(a) Radial vane type. (b) Co-axial vane type.

Fig. 9.25 Replusion type moving iron instruments.

It is clear that whatever may be the direction of the current in the coil of the instrument, the iron vanes are so magnetised that there is always a force of attraction in the attraction type and repulsion in the repulsion type of instruments. Thus moving iron instruments are unpolarised instruments *i.e.*, they are independent of the direction in which the current passes. Therefore, these instruments can be used on both a.c. and d.c.

9.9.3 Shape of Scale of Moving Iron Instruments

The deflection in a moving iron instrument is given by

$$\theta = \frac{1}{2}\frac{I^2}{K}\frac{dL}{d\theta} \qquad \text{(See Eqn. 9.52)}$$

Thus the angular deflection is proportional to the square of the operating current, and the instrument has a square law response. The deflection is in terms of rms value of current or voltage. As the deflection is proportional to square of current, it is evident that the scale of such an instrument is non-uniform.

If there is no saturation, the change of inductance with angle of deflection is uniform *i.e.*, $dL/d\theta$ = a constant. Therefore the instrument exhibits a pure square law response. For such an instrument the scale can be easily laid as the measured quantity is proportional to the square root of deflection.

In actual instruments $dL/d\theta$ is not constant and is usually a function of angular position of the moving iron and thus the scale is distorted from the square law in a manner dependent upon the way in which inductance varies with angle of deflection. This variation can be controlled by suitable design *i.e.*, by choosing proper dimensions, shape and position of iron vanes. Thus it is possible to design and construct an instrument with a scale which is very nearly uniform over a considerable part of its length. The necessary condition relating to $dL/d\theta$ against θ for linearization may be obtained from Eqn. 9.52 which gives :

$$\frac{dL}{d\theta} = \frac{2K\theta}{I^2}$$

For a linear scale $I = C\theta$ where C is a constant.

$$\therefore \quad \frac{dL}{d\theta} = \frac{2K}{C^2\theta} \quad \text{or} \quad \theta \cdot \frac{dL}{d\theta} = \text{constant.}$$

Thus for a linear scale product $\theta \frac{dL}{d\theta}$ should be a constant.

This is not possible as it requires $dL/d\theta$ to be infinite at $\theta = 0$. In practice the scale is made linear from the maximum deflection down to about 1/10th of the maximum deflection. The plot of $dL/d\theta$ against θ over the range is a rectangular hyperbola as shown in Fig. 9.26.

It is also possible to design and construct an instrument in which a small portion of the range, which is of particular interest or importance, is expanded over a large part while the remainder of the scale is compressed into a relatively small space. It is clear from the torque equation (Eqn. 9.52) that the portion of scale near zero can never be expanded or made uniform since this would require that the initial value of $dL/d\theta$ infinite.

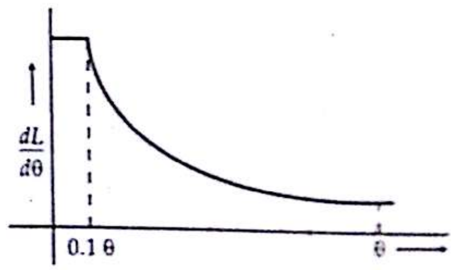


Fig 9.26 Variation of $dL/d\theta$ v/s θ.

The deflecting torque is proportional to the square of current multiplied by the rate of change of inductance with angle. The scale is compressed at its lower end because I^2 is small relative to full scale value and somewhat compressed at its higher end because in this range the rate of change of inductance with angle (*i.e.*, $dL/d\theta$) decreases rapidly (See Fig. 9.26). The scale is usable over about 80° of its length.

$$=(2500/2512.25)\times 125 = 124.4 \text{ V}.$$

$$\text{Hence, error} = \frac{124.4-125}{125}\times 100 = -0.48\%$$

9.10 ELECTRODYNAMOMETER (EELECTRODYNAMIC) TYPE INSTRUMENTS

The necessity for the a.c. calibration of moving iron instruments as well as other types of instruments which cannot be correctly calibrated requires the use of a transfer type of instrument. A *transfer instrument* is one that may be calibrated with a d.c. source and then used without modification to measure a.c. This requires the transfer type instrument to have same accuracy for both d.c. and a.c., which the electro-dynamometer instruments have. This is necessary since all measurements, and hence the calibration of all indicating instruments, must eventually be referred to standards of voltage and resistance. These standards are precision resistors and the Weston standard cell (which is a d.c. cell). It is obvious, therefore, that it would be impossible to calibrate an a.c. instrument directly against the fundamental standards.

The calibration of an a.c. instrument may be performed as follows : The transfer instrument is first calibrated on d.c. This calibration is then transferred to the a.c. instrument on alternating current, using operating conditions under which the latter operates properly.

Electrodynamic instruments are capable of service as transfer instruments. Indeed, their principal use as ammeters and voltmeters in laboratory and measurement work is for the transfer calibration of working instruments and as standards for calibration of other instruments as their accuracy is very high.

Electrodynamometer type of instruments are used as a.c. voltmeters and ammeters both in the range of power frequencies and lower part of the audio frequency range. They are used as watt-meters, varmeters and with some modification as power factor meters and frequency meters.

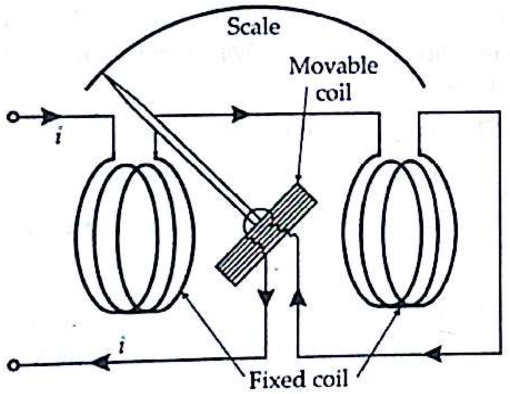


Fig. 9.33 Electrodynamometer type instrument.

9.10.1 Operating Principle of Electrodynamometer Type Instrument

We can have an idea of the working principle of this instrument by taking up a permanent magnet moving coil instrument and considering how it would behave on a.c. It would have a torque in one direction during one half of the cycle and an equal effect in the opposite direction during the other half of the cycle. If the frequency were very low, the pointer would swing back and forth around the zero point. However, for an ordinary meter, the inertia is so great that on power frequencies the pointer does not go very far in either direction but merely stays (vibrates slightly) around zero. If, however, we were to reverse the direction of the flux each time the current through the movable coil reverses, a unidirectional torque would be produced for both positive and negative halves of the cycle. In electrodynamometer instruments the field can be made to reverse simultaneously with the current in the movable coil if the field (fixed) coil is connected in series with the movable coil.

9.10.2 Construction of Electrodynamometer Type Instrument

Fixed coils. The field is produced by a fixed coil. This coil is divided into two sections to give a more uniform field near the centre and to allow passage of the instrument shaft. The instrument as shown in Fig. 9.33 may be a milliammeter, or may become a voltmeter by the addition of a series resistance. The fixed coils are wound with fine wire for such applications.

Fixed coils are usually wound with heavy wire carrying the main current in ammeters and wattmeters. The wire is stranded where necessary to reduce eddy current losses in conductors. The coils are usually varnished and baked to form a solid assembly. These are then clamped in place against the coil supports. This makes the construction rigid so that there is no shifting or change in dimensions which might effect the calibration.

The mounting supports are preferably made out of ceramic, as metal parts would weaken the field of the fixed coil on account of eddy currents.

Moving coil. A single element instrument has one moving coil. The moving coil is wound either as a self-sustaining coil or else on a non-metallic former. A metallic former cannot be used as eddy currents would be induced in it by the alternating field. Light but rigid construction is used for the moving coil. It should be noted that both fixed and moving coils are air cored.

Control. The controlling torque is provided by two control springs. These springs act as leads to then moving coil.

Moving system. The moving coil is mounted on an aluminium spindle. The moving system also carries the counter weights and truss type pointer. Sometimes a suspension may be used in case a high sensitivity is desired.

Damping. Air friction damping is employed for these instruments and is provided by a pair of aluminium vanes, attached to the spindle at the bottom. These vanes move in sector shaped chambers. Eddy current damping cannot be used in these instruments as the operating field is very weak (on torque, on equating controlling torque with deflection torque we have GI = K.x where x is deflection thus current is given by

$$I = \frac{K}{G}.x$$

Since the deflection is directly proportional to the current therefore we need a uniform scale on the meter for measurement of current.

3.Moving Iron Instruments

Moving-iron **instruments** are generally used to measure alternating voltages and currents. In moving-iron instruments the movable system consists of one or more pieces of specially-shaped soft iron, which are so pivoted as to be acted upon by the **magnetic field** produced by the current in coil.
There are two general types of moving-iron instruments namely:

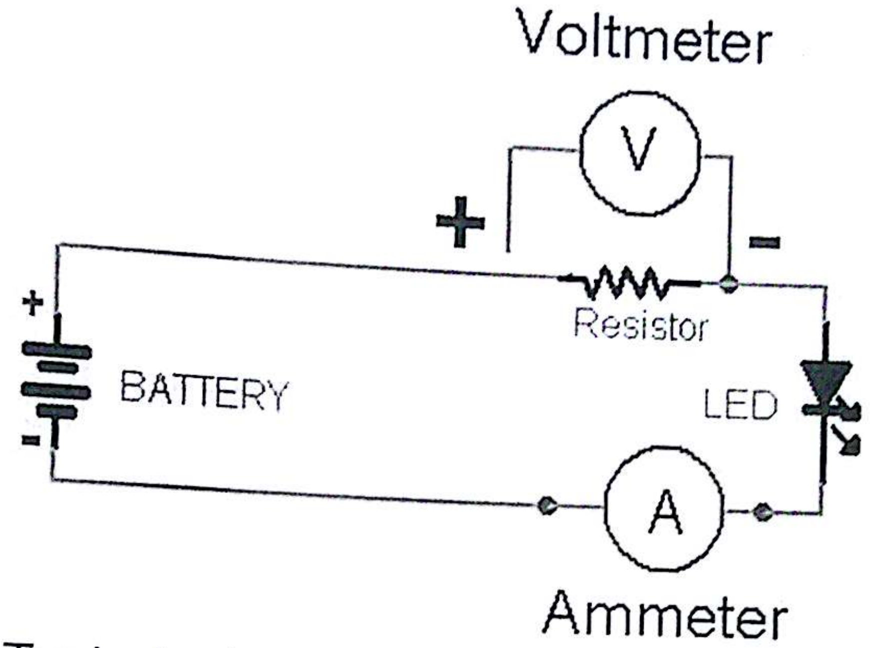
1. **Repulsion** (or double iron) type (figure 1)
2. **Attraction** (or single-iron) type (figure 2)

The brief description of different components of a moving-iron instrument is given below:

- **Moving element:** a small piece of soft iron in the form of a vane or rod.
- **Coil:** to produce the magnetic field due to current flowing through it and also to magnetize the iron pieces.
- **In repulsion type**, a **fixed** vane or rod is also used and magnetized with the same polarity.
- **Control torque** is provided by spring or weight (gravity).
- **Damping torque** is normally pneumatic, the damping device consisting of an air chamber and a moving vane attached to the instrument spindle.
- **Deflecting torque** produces a movement on an aluminum pointer over a graduated scale.

How it works?

The deflecting torque in any moving-iron instrument is due to forces on a small piece of magnetically 'soft' iron that is magnetized by a coil carrying the **operating current**. In repulsion type moving–iron instrument consists of two cylindrical soft iron vanes mounted within a fixed current-carrying coil.



Typical scheme of measuring el. current and voltage

One iron vane is held fixed to the coil frame and other is free to rotate, carrying with it the pointer shaft. Two irons lie in the magnetic field produced by the coil that consists of only few turns if the instrument is an ammeter or of many turns if the instrument is a voltmeter.

Current in the coil induces both vanes to become magnetized and repulsion between the similarly magnetized vanes produces a proportional rotation. The deflecting torque is proportional to the square of the current in the coil, making the instrument reading is a true 'RMS' quantity Rotation is opposed by a hairspring that produces the restoring torque. Only the fixed coil carries load current, and it is constructed so as to withstand high transient current.

Moving iron instruments having scales that are nonlinear and somewhat crowded in the lower range of calibration.

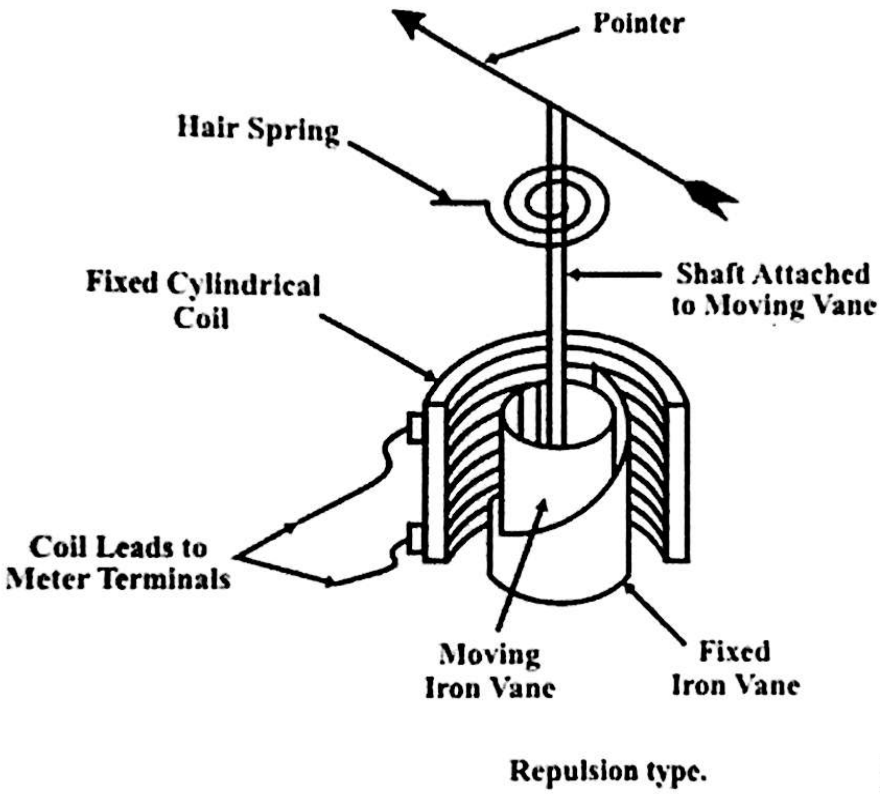


Figure 1 – Repulsion moving iron-instrument

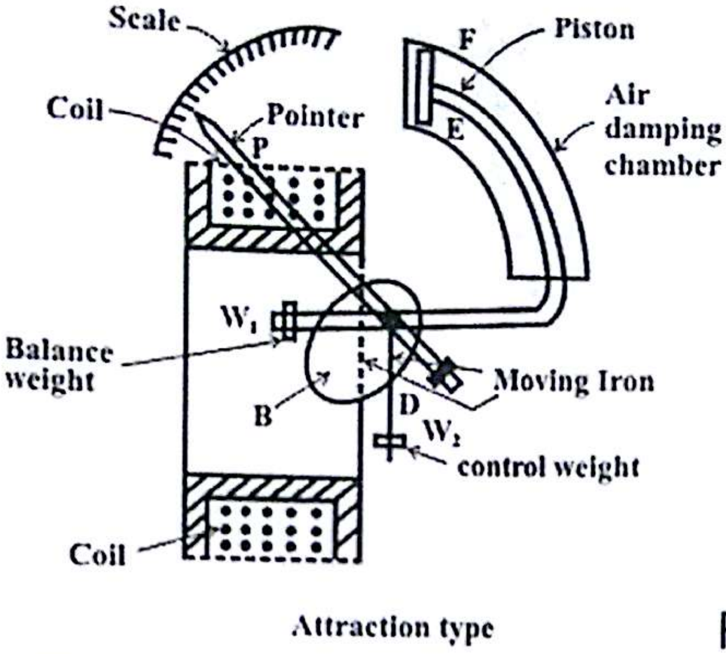


Figure 2 – Attraction moving iron instrument

Measurement of Electric Voltage and Current

- Moving iron instruments are used as Voltmeter and Ammeter only.
- Both can work on AC as well as on DC.

Ammeter

- Instrument used to measure current in the circuit.
- Always connected in series with the circuit and carries the current to be measured.
- This current flowing through the coil produces the desired deflecting torque.
- It should have low resistance as it is to be connected in series.

Voltmeter

- Instrument used to measure voltage between two points in a circuit.
- Always connected in parallel.
- Current flowing through the operating coil of the meter produces deflecting torque.
- It should have high resistance. Thus a high resistance of order of kilo ohms is connected in series with the coil of the instrument.

4. Dynamometer

The electrodynamometer type instrument is a transfer instrument. A transfer instrument is one which is calibrated with a d.c. source and used without any modifications for a.c. measurements. Such a transfer instrument has same accuracy for a.c. and d.c. measurements. The electrodynamometer type instruments are often used in accurate a.c. voltmeters and ammeters, not only at the power line frequency but also in the lower audiofrequency range. With some little modifications, it can be used as a wattmeter for the power measurements.

Why PMMC Instruments can not be used for a.c. measurements ?

The PMMC instrument cannot be sued on a.c. currents or voltages. If a.c. supply is given to these instruments, an alternating torque will be developed. Due to moment of inertia of moving system, the pointer will not follow rapidly changing alternating torque and will fail to show any reading. In order that the instrument should be able to read a.c. quantities, the magnetic field in the air gap must change along with the change in current. This principle is used in the electrodynamometer type instrument. Instead of a permanent magnet, the electrodynamometer type instrument uses the current under measurement to produce the necessary field flux.

The Fig. 1 shows the construction of electrodynamometer type instrument.

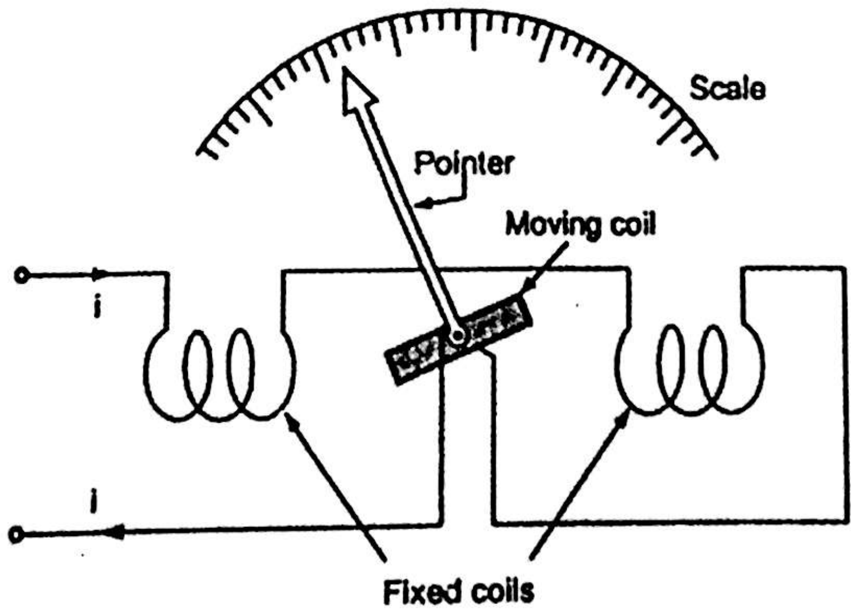


Fig. 1 electrodynamometer type instrument

1.1 Construction

The various type of the electrodynamometer type instrument are:

Fixed Coils : The necessary field required for the operation of the instrument is produced by the fixed coils. A uniform field is obtained near the center of coil due to division of coil in two sections. These coils are air cored. Fixed coils are wound with fine wire for using as voltmeter, while for ammeters and wattmeters it is wound with heavy wire. The coils are usually varnished. They are clamped in place against the coil supports. This makes the construction`rigid.

Ceramic is usually used for mounting supports. If metal parts would have been used then it would weaken the field of the fixed coil.

Moving Coil : The moving coil is wound either as a self-sustaining coil or else on a non-metallic former. If metallic former is used, then it would induce eddy currents in it. The construction of moving coil is made light as well as rigid. It is air cored.

Controlling : The controlling torque is provided by springs. These springs act as leads to the moving coil.

Moving System : The moving coil is mounted on an aluminium spindle. It consists of counter weights and pointer. Sometimes a suspension may be used, in case a high accuracy is desired.

Damping : The damping torque is provided by air friction, by a pair of aluminium vanes which are attached to the spindle at the bottom. They move in sector shaped chambers. As operating field would be distorted by eddy current damping, it is not employed.

Shielding : The field produced by these instruments is very weak. Even earth's magnetic field considerably affects the reading. So shielding is done to protect it from stray magnetic fields. It is done by enclosing in a casing high permeability alloy.

Cases and Scales : Laboratory standard instruments are usually contained in polished wooden or metal cases which are rigid. The case is supported by adjustable levelling screws.

A spirit level may be provided to ensure proper levelling.

For using electrodynamometer instrument as ammeter, fixed and moving coils are connected in series and carry the same current. A suitable shunt is connected to these coils to limit current through them upto desired limit.

The electrodynamometer instruments can be used as a voltmeter by connecting the fixed and moving coils in series with a high noninductive resistance. It is most accurate type of voltmeter.

For using electrodynamometer instrument as a wattmeter to measure the power, the fixed coils acts as a current coil and must be connected in series with the load. The moving coils acts as a voltage coil or pressure oil and must be connected across the supply terminals. The wattmeter indicates the supply power. When current passes through the fixed and moving coils, both coils produce the magnetic fields. The field produced by fixed coil is proportional to the load current while the field produced by the moving coil is proportional to the voltage. As the deflecting torque is produced due to the interaction of these two fields, the deflection is proportional to the power supplied to the load.

5. Digital Voltmeters

Digital voltmeters are instruments that measure voltage or voltage drop in a circuit. They use solid-state components and display values digitally. Typically, digital voltmeters (digital volt meters) can be used to locate excessive resistance that may indicate an open circuit or ground. They are also used to identify low voltage or voltage drops that may indicate a poor connection. The positive lead is connected to the circuits positive side and the negative lead is connected to the circuits ground. The digital voltmeters internal resistance is the impedance, which is usually expressed in ohms per volt. This amount is relatively high in order to prevent the device from drawing significant current and disturbing the operation of the circuit being tested. The sensitivity of the voltmeter determines the range of voltages that digital voltmeters can measure.

Measurement

Digital voltmeters can measure a range of alternating current (AC) voltages, direct current (DC) voltages, or both AC and DC voltages. Devices typically display between three and seven digits. Some digital voltmeters can capture minimum and maximum voltages called spike readings. Others measure the root mean square (RMS), a range of frequencies, or the signal power in decibels. Digital voltmeters are also used to monitor resistance temperature
detectors (RTDs), thermocouples, transistors,

and diodes. Benchtop, rack mounted, and handheld devices are commonly available. Battery powered units do not require plug-in power. Digital voltmeters with audibility continuity beep when the probes touch. Devices with analog bar graph capabilities display status readings such as battery power, signal level, and continuity.

How does the Digital voltmeter display the measured voltage?

DVMs display the measured voltage using LCDs (Liquid Crystal Display) or LEDs (Light Emitting Diode) to display the result in a floating point format. DVMs have some characteristics such that they usually have scales that are 0-0.3v, 0-3v, 0-30v, 0-300v, etc. It is not clear why those ranges were chosen but they are commonplace.

How is the circuit designed in the Digital Voltmeter?

The **Digital voltmeter** is ideal to use for measuring the output voltage of the DC (Direct current) power supply. It includes a 3.5-digit LED display with a negative voltage indicator. It measures DC voltages from 0 to 199.9v with a resolution of 0.1v. The voltmeter is based on single ICL7107 chip and may be fitted on a small 3cm * 7cm printed circuit board. The circuit should be supplied with a 5V voltage supply and consumes only around 25mA (milli ampere).

6. Ammeters

Digital ammeters are instruments that measure current flow in amperes and display current levels on a digital display. These devices provide information about current draw and current continuity in order to help users troubleshoot erratic loads and trends. They have both positive and negative leads and feature extremely low internal resistance.

Digital ammeters are connected in series with a circuit (and never parallel) so that current flow passes through the meter. High current flow may indicate a short circuit, unintentional ground, or defective component. Low current flow may indicate high resistance or poor current flow within the circuit.

Measurement Type

Digital ammeters can measure levels of alternating current (AC) and direct current (DC). Some devices that measure AC current also measure root mean square (RMS) power, which is the square root of the time average of the square of the instantaneous power. Many digital ammeters include a current sensor built into the meter or that clamps around the wire. Different types of digital ammeters can measure different ranges of AC current, DC current, and AC current frequency.

Form Factor

Some devices are handheld and portable, while others are designed for benchtop or shop floor use. Battery-powered digital ammeters can be operated without plug-in power and are often suitable for outdoor use.

Features

Many digital ammeters provide special measurement types or advanced options or features.

- **Adjustable sampling rate** - The sampling rate is manually adjustable.
- **Alarm LED** - Alarm light-emitting diodes (LEDs) light when the RMS value or peak value is greater than the range. Typically, alarm LEDs light only when the range has been greatly exceeded.
- **Application software** - The device has embedded application software.
- **Auto-Ranging** - Auto-ranging devices are self-adjusting to offer the best measurement scenario.
- **Battery powered** - Devices are battery-powered.
- **Data acquisition** - Devices with data acquisition capabilities have a computer interface and software for uploading data.
- **Data storage / logging** - Data storage or data logging devices have internal memory for storing data.

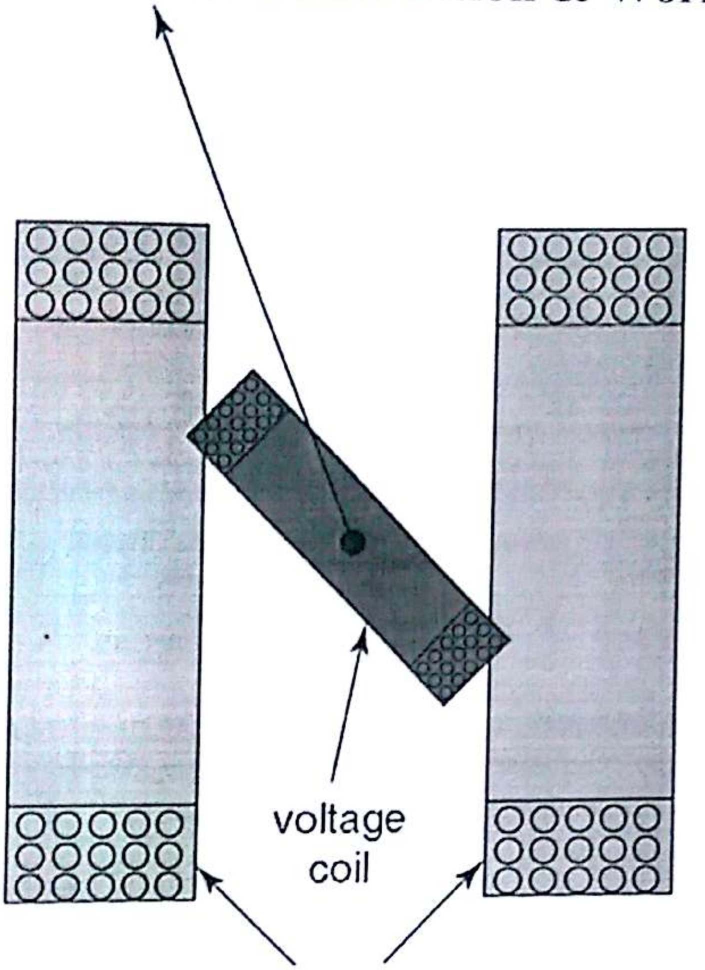
- **Temperature compensated** - Temperature-compensated devices are designed to counteract known errors caused by temperature changes.
  Triggering - Devices with triggering have an interface for external triggering.

7.

Wattmeter

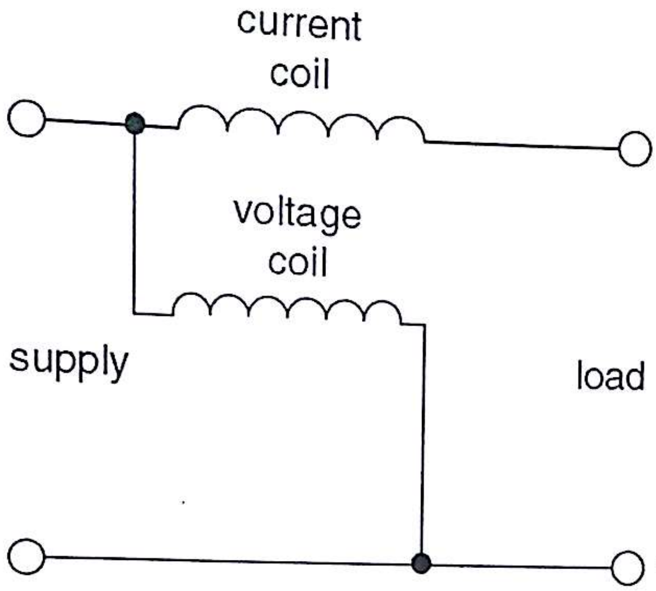
The **wattmeter** is an instrument for measuring the electric power (or the supply rate of electrical energy) in watts of any given circuit. Electromagnetic wattmeters are used for measurement of utility frequency and audio frequency power; other types are required for radio frequency measurements.

Wattmeter Construction & Working Principle:



- The dynamometer wattmeter works on the motor principle.
- As shown in the above figure, the wattmeter has two sets of coils.
- One coil is fixed and is made in two identical parts. It is made upon heavy gauge copper wire. So it has low resistance. This is named as current coil.
- The other coil which is known as voltage coil, is wound from fine gauge wire. So it has relatively high resistance. The voltage

coil is mounted on a circular manner. It is placed between the two parts of the current coil.



- The manner of connecting the wattmeter into a circuit is given in the 2nd figure.
- As shown, The current coil is connected in series with the load so that the circuit current flows through it.
- Similar to the voltmeter circuit, the voltage coil is connected in parallel with the load.
- Both voltage and current coils will produce magnetic fields.
- These fields interact to each other and produce a deflecting torque on the voltage coil.
- The interacting fields are proportional to the circuit
voltage(V) and current(I) respectively.
- So the produced deflecting torque is proportional to the product of circuit voltage

and current. ie, VI which is nothing but circuit power.

- Restoring torque is provided by contrawound spiral springs, as in the moving coil meter.
- The voltage coil may be connected either on the supply side or the load side of the current coil. The choice of connection depends on other factors concerning the load.

A dynamometer wattmeter reads both ac and dc powers.

8. Watthour Meter

Energy meter or watt-hour meter or is an electrical instrument that measures the amount of electrical energy used by the consumers. Utilities is one of the electrical departments, which install these instruments at every place like homes, industries, organizations, commercial buildings to charge for the electricity consumption by loads such as lights, fans, refrigerator and other home appliances.

Basic unit of power is watts and it is measured by using a watt meter. One thousand watts make one kilowatt. If one uses one kilowatt in one hour duration, one unit of energy gets consumed. So energy meters measure the rapid voltage and currents, calculate their product and give instantaneous power. This power is integrated over a time interval, which gives the energy utilized over that time period.

look on logging initially
① Grid current ② Gen. current ③ load output voltage & P.F.

Transient 940 ms

Transient I 304 ms.

Left side slope - (Rising) .CSV - 43

Zoom 30 msec. t_1 = 334.8 ms t_2 = 987 ms t_3 = 1.29 sec (steady state)

freq. load. .CSV - 85

Right side slope (Log)

14 Nov 2016 - Load Perturbations 5:40 pm.

Two Basic Types of Watt-Hour Meter

The energy meters are classified into two basic categories, such as:

- Electromechanical Type Induction Meter
- Electronic Energy Meter

Watt hour meters are classified into two types by taking the following factors into considerations:

- Types of displays analog or digital electric meter.
- Types of metering points: secondary transmission, grid, local and primary distribution.
- End applications like commercial, industrial and domestic purpose
- Technical aspects like single phases, three phases, High Tension (HT), Low Tension (LT) and accuracy class materials.

The electricity supply connection may be either single phase or three phase depending on the supply utilized by the domestic or commercial installations.