CLASS NOTES ON

ELECTRICAL MEASUREMENTS & INSTRUMENTATION

FOR

4th SEMESTER OF

ELECTRICAL ENGINEERING

(B.TECH PROGRAMME)

UNIT-1

SYLLABUS

ELECTRICAL MEASUREMENTS & INSTRUMENTATION (2-0-0)

- Introduction: Objective, scope and outcome of the course.
- **Measuring Instruments: Moving coil, moving iron, electrodynamic and induction instruments-construction, operation, torque equation and errors. Applications of instruments for measurement of current, voltage, single-phase power and single-phase energy. Errors in wattmeter and energy meter and their compensation and adjustment. Testing and calibration of single-phase energy meter by phantom loading.**
- Polyphase Metering: Blondel's Theorem for n-phase, p-wire system. Measurement of power and reactive kVA in 3-phase balanced and unbalanced systems: One-wattmeter, two- wattmeter and three-wattmeter methods. 3-phase induction type energy meter. Instrument Transformers: Construction and operation of current and potential transformers. Ratio and phase angle errors and their minimization. Effect of variation of power factor, secondary burden and frequency on errors. Testing of CTs and PTs. Applications of CTs and PTs for the measurement of current, voltage, power and energy.
- Potentiometers: Construction, operation and standardization of DC potentiometers– slide wire and Crompton potentiometers. Use of potentiometer for measurement of resistance and voltmeter and ammeter calibrations. Volt ratio boxes. Construction, operation and standardization of AC potentiometer in-phase and quadrature potentiometers. Applications of AC potentiometers.
- Measurement of Resistances: Classification of resistance. Measurement of medium resistances – ammeter and voltmeter method, substitution method, Wheatstone bridge method. Measurement of low resistances – Potentiometer method and Kelvin's double bridge method. Measurement of high resistance: Price's Guardwire method. Measurement of earth resistance.
- AC Bridges: Generalized treatment of four-arm AC bridges. Sources and detectors. Maxwell's bridge, Hay's bridge and Anderson bridge for self inductance measurement. Heaviside's bridge for mutual inductance measurement. De Sauty Bridge for capacitance measurement. Wien's bridge for capacitance and frequency measurements. Sources of error in bridge measurements and precautions. Screening of bridge components. Wagner earth device.

TEXT BOOKS

[1]. A Course in Elec. & Electronics Measurements & Instrumentation: A K.

Sawhney [2]. Modern Electronic Instrumentation and Measurement Techniques:

Helfrick & Cooper [3]. Electrical Measurement and Measuring Instruments -

Golding & Waddis

Course Outcome For Electronic Measurement & Instrumentation

CO1 Acquire detailed knowledge of different-different instruments.
CO2 Develop the ability to select measuring instruments for a given application.
CO3 Design the different AC and DC bridges and the application of different bridges for measurements

MEASURING INSTRUMENTS

1.1 Definition of instruments

An instrument is a device in which we can determine the magnitude or value of the quantity to be measured. The measuring quantity can be voltage, current, power and energy etc. Generally instruments are classified in to two categories.

Instrument

Absolute Instrument | **Secondary Instrument**

1.2 Absolute instrument

An absolute instrument determines the magnitude of the quantity to be measured in terms of the instrument parameter. This instrument is really used, because each time the value of the measuring quantities varies. So we have to calculate the magnitude of the measuring quantity, analytically which is time consuming. These types of instruments are suitable for laboratory use. Example: Tangent galvanometer.

1.3 Secondary instrument

This instrument determines the value of the quantity to be measured directly. Generally these instruments are calibrated by comparing with another standard secondary instrument.

Examples of such instruments are voltmeter, ammeter and wattmeter etc. Practically secondary instruments are suitable for measurement.

Secondary instruments

Indicating instruments | **Recording** | **Integrating** | **Electromechanically Indicating instruments**

1.3.1 Indicating instrument

This instrument uses a dial and pointer to determine the value of measuring quantity. The pointer indication gives the magnitude of measuring quantity.

1.3.2 Recording instrument

This type of instruments records the magnitude of the quantity to be measured continuously over a specified period of time.

1.3.3 Integrating instrument

This type of instrument gives the total amount of the quantity to be measured over a specified period of time.

1.3.4 Electromechanical indicating instrument

For satisfactory operation electromechanical indicating instrument, three forces are necessary. They are

(a) Deflecting force

(b) Controlling force

(c)Damping force

1.4 Deflecting force

When there is no input signal to the instrument, the pointer will be at its zero position. To deflect the pointer from its zero position, a force is necessary which is known as deflecting force. A system which produces the deflecting force is known as a deflecting system. Generally a deflecting system converts an electrical signal to a mechanical force.

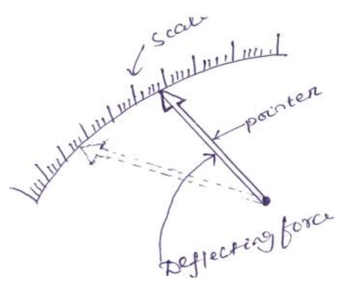


Fig. 1.1 Pointer scale

1.4.1 Magnitude effect

When a current passes through the coil (Fig.1.2), it produces a imaginary bar magnet. When a soft-iron piece is brought near this coil it is magnetized. Depending upon the current direction the poles are produced in such a way that there will be a force of attraction between the coil and the soft iron piece. This principle is used in moving iron attraction type instrument.

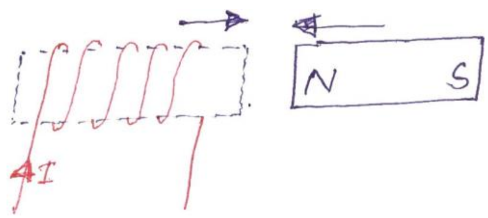


Fig. 1.2

If two soft iron pieces are place near a current carrying coil there will be a force of repulsion between the two soft iron pieces. This principle is utilized in the moving iron repulsion type instrument.

1.4.2 Force between a permanent magnet and a current carrying coil

When a current carrying coil is placed under the influence of magnetic field produced by a permanent magnet and a force is produced between them. This principle is utilized in the moving coil type instrument.

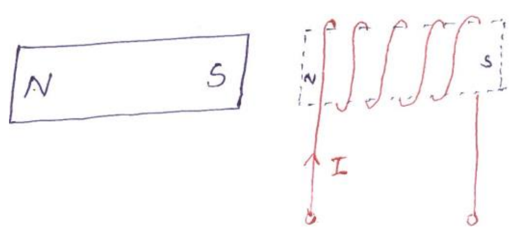


Fig. 1.3

1.4.3 Force between two current carrying coil

When two current carrying coils are placed closer to each other there will be a force of repulsion between them. If one coil is movable and other is fixed, the movable coil will move away from the fixed one. This principle is utilized in electrodynamometer type instrument.

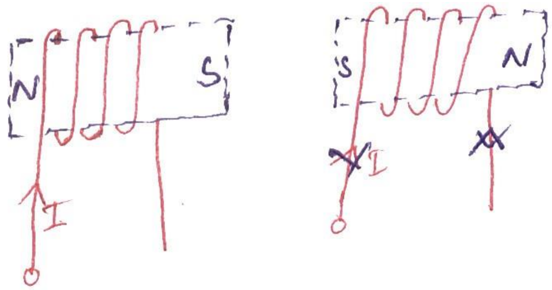


Fig. 1.4

1.5 Controlling force

To make the measurement indicated by the pointer definite (constant) a force is necessary which will be acting in the opposite direction to the deflecting force. This force is known as controlling force. A system which produces this force is known as a controlled system. When the external signal to be measured by the instrument is removed, the pointer should return back to the zero position. This is possibly due to the controlling force and the pointer will be indicating a steady value when the deflecting torque is equal to controlling torque.

$$T_d = T_C \qquad (1.1)$$

1.5.1 Spring control

Two springs are attached on either end of spindle (Fig. 1.5).The spindle is placed in jewelled bearing, so that the frictional force between the pivot and spindle will be minimum. Two springs are provided in opposite direction to compensate the temperature error. The spring is made of phosphorous bronze.

When a current is supply, the pointer deflects due to rotation of the spindle. While spindle is rotate, the spring attached with the spindle will oppose the movements of the pointer. The torque produced by the spring is directly proportional to the pointer deflection θ .

$$T_C \propto \theta \qquad (1.2)$$

The deflecting torque produced T_d proportional to ‘I’. When $T_C = T_d$, the pointer will come to a steady position. Therefore

□ □ (1.3)

I

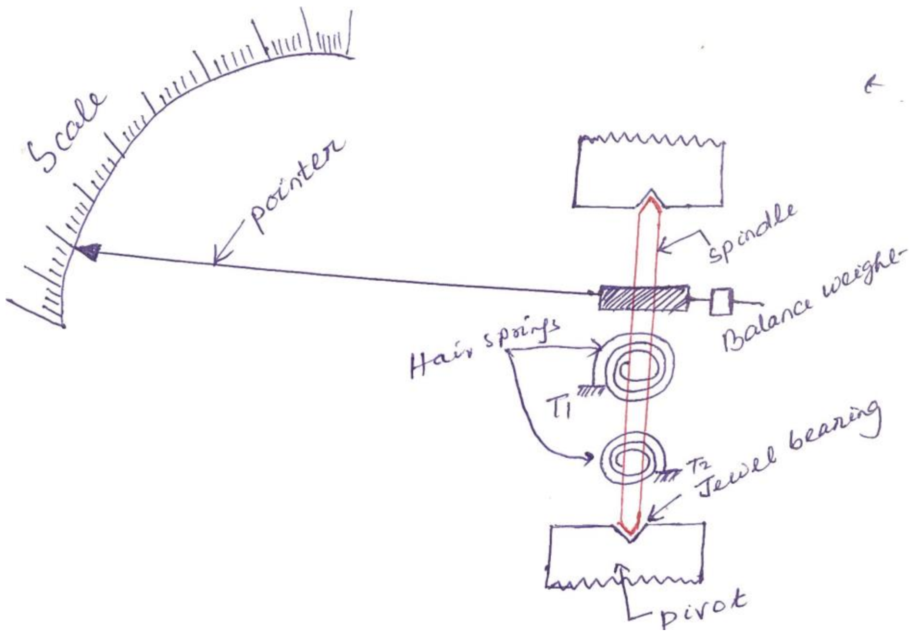


Fig. 1.5

Since, □ and I are directly proportional to the scale of such instrument which uses spring controlled is uniform.

1.6 Damping force

The deflection torque and controlling torque produced by systems are electro mechanical. Due to inertia produced by this system, the pointer oscillates about it final steady position before coming to rest. The time required to take the measurement is more. To damp out the oscillation is quickly, a damping force is necessary. This force is produced by different systems.

(a) Air friction damping
(b) Fluid friction damping
(c) Eddy current damping

1.6.1 Air friction damping

The piston is mechanically connected to a spindle through the connecting rod (Fig. 1.6). The pointer is fixed to the spindle moves over a calibrated dial. When the pointer oscillates in clockwise direction, the piston goes inside and the cylinder gets compressed. The air pushes the piston upwards and the pointer tends to move in anticlockwise direction.

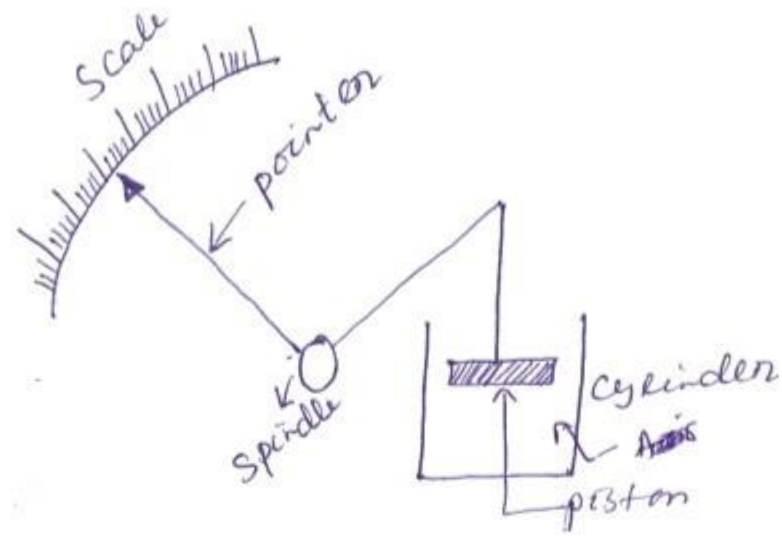


Fig. 1.6

If the pointer oscillates in anticlockwise direction the piston moves away and the pressure of the air inside cylinder gets reduced. The external pressure is more than that of the internal pressure. Therefore the piston moves down wards. The pointer tends to move in clock wise direction.

1.6.2 Eddy current damping

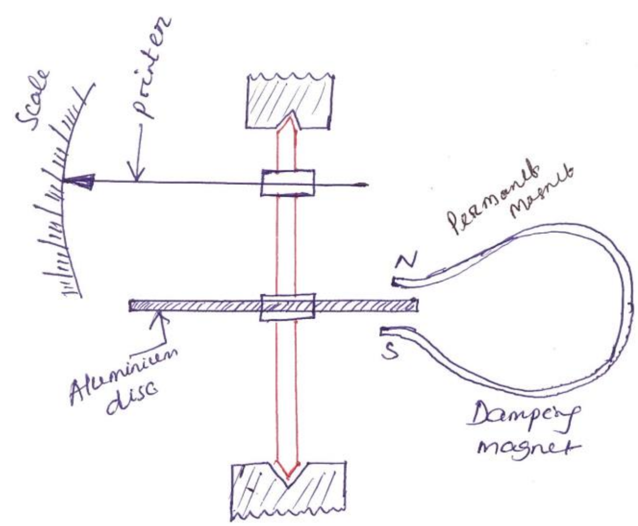


Fig. 1.6 Disc type

An aluminum circular disc is fixed to the spindle (Fig. 1.6). This disc is made to move in the magnetic field produced by a permanent magnet.

When the disc oscillates it cuts the magnetic flux produced by damping magnet. An emf is induced in the circular disc by faradays law. Eddy currents are established in the disc since it has several closed paths. By Lenz's law, the current carrying disc produced a force in a direction opposite to oscillating force. The damping force can be varied by varying the projection of the magnet over the circular disc.

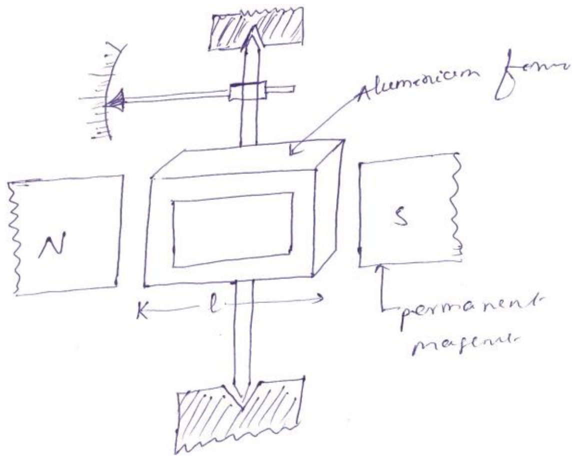


Fig. 1.6 Rectangular type

1.7 Permanent Magnet Moving Coil (PMMC) instrument

One of the most accurate type of instrument used for D.C. measurements is PMMC instrument.

Construction: A permanent magnet is used in this type instrument. Aluminum former is provided in the cylindrical in between two poles of the permanent magnet (Fig. 1.7). Coils are wound on the aluminum former which is connected with the spindle. This spindle is supported with jeweled bearing. Two springs are attached on either end of the spindle. The terminals of the moving coils are connected to the spring. Therefore the current flows through spring 1, moving coil and spring 2.

Damping: Eddy current damping is used. This is produced by aluminum former.

Control: Spring control is used.

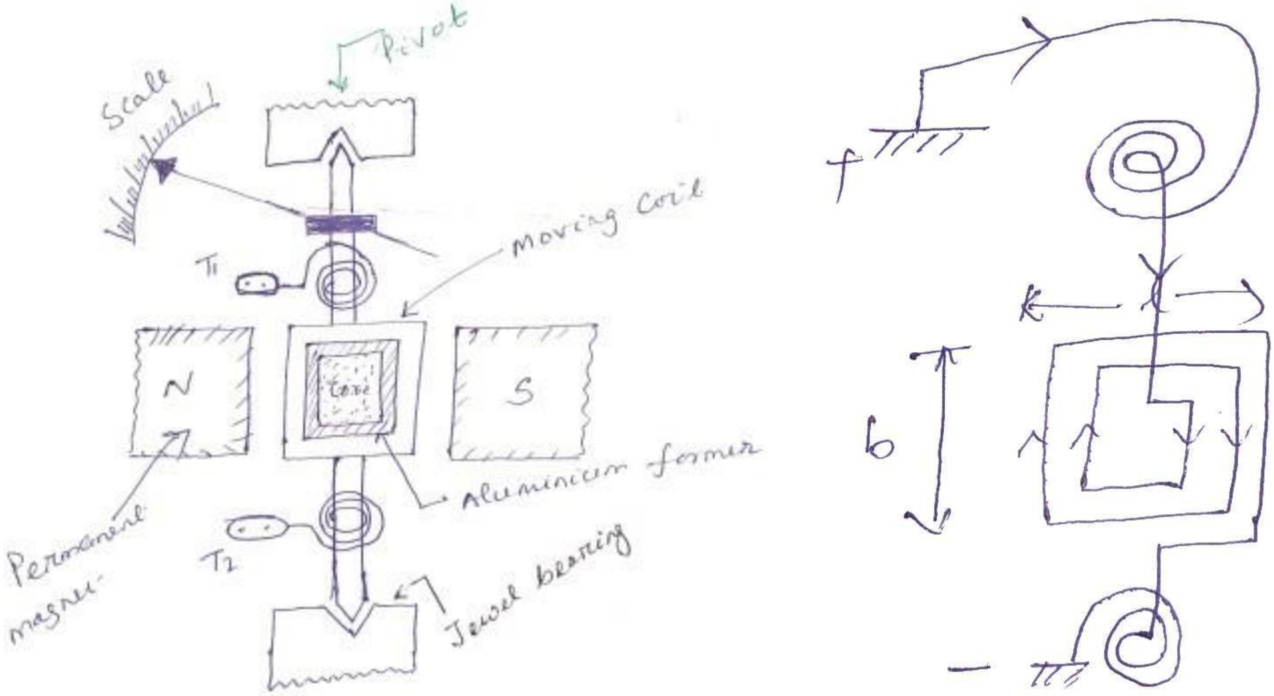


Fig. 1.7

Principle of operation

When D.C. supply is given to the moving coil, D.C. current flows through it. When the current carrying coil is kept in the magnetic field, it experiences a force. This force produces a torque and the former rotates. The pointer is attached with the spindle. When the former rotates, the pointer moves over the calibrated scale. When the polarity is reversed a torque is produced in the opposite direction. The mechanical stopper does not allow the deflection in the opposite direction. Therefore the polarity should be maintained with PMMC instrument.

If A.C. is supplied, a reversing torque is produced. This cannot produce a continuous deflection. Therefore this instrument cannot be used in A.C.

Torque developed by PMMC

Let T_d =deflecting torque

T_C = controlling torque

□ = angle of deflection K=spring constant b=width of the coil l=height of the coil or length of coil

N=No. of turns

I=current

B=Flux density

A=area of the coil

The force produced in the coil is given by

$F = BIL \sin \theta$ (1.4)

When $\theta = 90^\circ$

For N turns, $F = NBIL$ (1.5)

Torque produced $T_d = F \times$ distance $= F \times r$ (1.6)

$T_d = NBIL \times b = BINA$ (1.7)

$T_d = BANI$ (1.8)

$T_d \propto I$ (1.9)

Advantages

- ✓ Torque/weight is high
- ✓ Power consumption is less
- ✓ Scale is uniform
- ✓ Damping is very effective
- ✓ Since operating field is very strong, the effect of stray field is negligible
- ✓ Range of instrument can be extended

Disadvantages

- ✓ Use only for D.C.
- ✓ Cost is high
- ✓ Error is produced due to ageing effect of PMMC
- ✓ Friction and temperature error are present

1.7.1 Extension of range of PMMC instrument

Case-I: Shunt

A low shunt resistance connected in parrel with the ammeter to extent the range of current. Large current can be measured using low current rated ammeter by using a shunt.

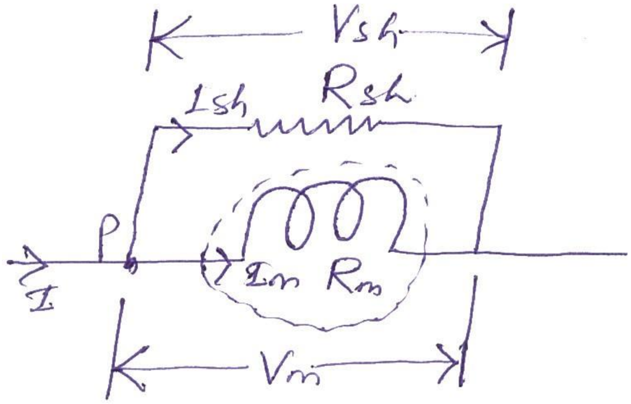


Fig. 1.8

Let R_m =Resistance of meter

R_{sh} =Resistance of shunt

I_m = Current through meter

I_{sh} =current through shunt

I= current to be measure

$\therefore V_m = V_{sh}$ (1.10)

$I_m R_m = I_{sh} R_{sh}$

$\frac{I_m}{I_{sh}} = \frac{R_{sh}}{R_m}$ (1.11)

Apply KCL at 'P' $I = I_m + I_{sh}$ (1.12)

Eq^n (1.12) ÷ by I_m

$$\frac{I}{I_m} = 1 - \frac{I_{sh}}{I_m} \qquad (1.13)$$

$$\frac{I}{I_m} = 1 + \frac{R_m}{R_{sh}} \qquad (1.14)$$

$$\therefore I = I_m\left(1 + \frac{R_m}{R_{sh}}\right) \qquad (1.15)$$

$\left(1 + \frac{R_m}{R_{sh}}\right)$ is called multiplication factor

Shunt resistance is made of manganin. This has least thermoelectric emf. The change is resistance, due to change in temperature is negligible.

Case (II): Multiplier

A large resistance is connected in series with voltmeter is called multiplier (Fig. 1.9). A large voltage can be measured using a voltmeter of small rating with a multiplier.

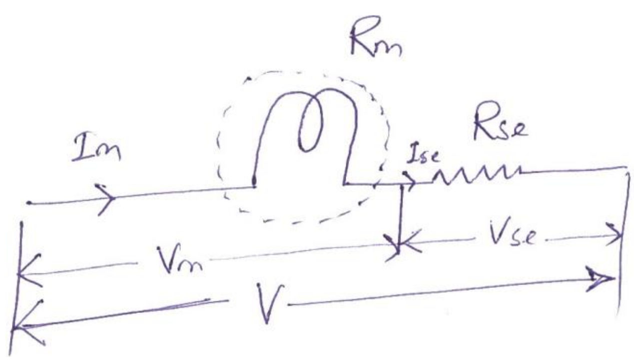


Fig. 1.9

Let

R_m =resistance of meter

R_{se} =resistance of multiplier

V_m =Voltage across meter

V_{se} = Voltage across series resistance

V= voltage to be measured

$$I_m = I_{se} \qquad (1.16)$$

$$\frac{V_m}{V_{se}} = \frac{R_m}{R_m + R_{se}} \tag{1.17}$$

$$V_{se} = V_m \left(1 + \frac{R_{se}}{R_m}\right) \tag{1.18}$$

Apply KVL, $V = V_m + V_{se}$ (1.19)

Eq^n (1.19) $\div V_m$

$$\frac{V}{V_m} = 1 + \frac{V_{se}}{V_m} = \left(1 + \frac{R_{se}}{R_m}\right) \quad (1.20)$$

$$\therefore V = V_m \left(1 + \frac{R_{se}}{R_m}\right) \quad (1.21)$$

$\left(1 + \frac{R_{se}}{R_m}\right) =$ Multiplication factor

1.8 Moving Iron (MI) instruments

One of the most accurate instrument used for both AC and DC measurement is moving iron instrument. There are two types of moving iron instrument.

- Attraction type
- Repulsion type

1.8.1 Attraction type M.I. instrument

Construction: The moving iron fixed to the spindle is kept near the hollow fixed coil (Fig. 1.10). The pointer and balance weight are attached to the spindle, which is supported with jeweled bearing. Here air friction damping is used.

Principle of operation

The current to be measured is passed through the fixed coil. As the current is flow through the fixed coil, a magnetic field is produced. By magnetic induction the moving iron gets magnetized. The north pole of moving coil is attracted by the south pole of fixed coil. Thus the deflecting force is produced due to force of attraction. Since the moving iron is attached with the spindle, the spindle rotates and the pointer moves over the calibrated scale. But the force of attraction depends on the current flowing through the coil.

Torque developed by M.I

Let '□ ' be the deflection corresponding to a current of 'i' amp

Let the current increases by di, the corresponding deflection is '□ □ *d*□ '

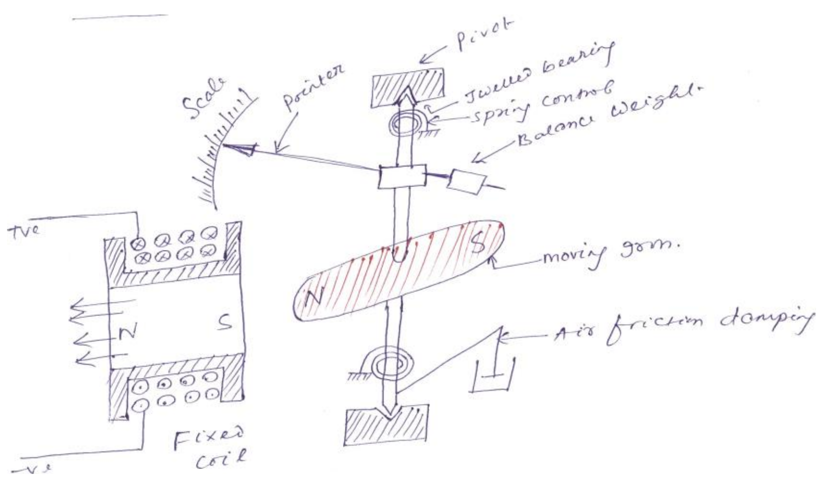


Fig. 1.10

There is change in inductance since the position of moving iron change w.r.t the fixed electromagnets.

Let the new inductance value be ‘L+dL’. The current change by ‘di’ is dt seconds.

Let the emf induced in the coil be ‘e’ volt.

$$e = \frac{d}{dt}(Li) = L\frac{di}{dt} + i\frac{dL}{dt} \tag{1.22}$$

Multiplying by ‘idt’ in equation (1.22)

$$e \times idt = L\frac{di}{dt} \times idt + i\frac{dL}{dt} \times idt \tag{1.23}$$

$$e \times idt = Lidi + i^2 dL \tag{1.24}$$

Eq^n (1.24) gives the energy is used in to two forms. Part of energy is stored in the inductance. Remaining energy is converted in to mechanical energy which produces deflection.

Fig. 1.11

Change in energy stored=Final energy-initial energy stored

$$= \frac{1}{2}(L + dL)(i + di)^2 - \frac{1}{2}Li^2$$

$$= \frac{1}{2}\{(L + dL)(i^2 + di^2 + 2idi) - Li^2\}$$

$$= \frac{1}{2}\{(L + dL)(i^2 + 2idi) - Li^2\}$$

$$= \frac{1}{2}\{Li^2 + 2Lidi + i^2dL + 2ididL - Li^2\}$$

$$= \frac{1}{2}\{2Lidi + i^2dL\} \qquad (1.25)$$

$$= Lidi + \frac{1}{2}i^2dL \qquad (1.26)$$

Mechanical work to move the pointer by $d\theta$

$$= T_d \, d\theta$$

By law of conservation of energy,

Electrical energy supplied=Increase in stored energy+ mechanical work done. (1.27)

Input energy= Energy stored + Mechanical energy

$$Lidi + i^2dL = Lidi + \frac{1}{2}i^2dL + T_d \, d\theta \qquad (1.28)$$

$$\frac{1}{2}i^2dL = T_d \, d\theta$$

$$T_d = \frac{1}{2}i^2\frac{dL}{d\theta} \qquad (1.29)$$

At steady state condition $T_d = T_C$

$$\frac{1}{2}i^2\frac{dL}{d\theta} = K\theta \qquad (1.30)$$

$$\theta = \frac{1}{2K}i^2\frac{dL}{d\theta} \qquad (1.31)$$

□

□ □ i^2 (1.32)

When the instruments measure AC, □ □ i^2_{rms}

Scale of the instrument is non uniform.

Advantages

- ✓ MI can be used in AC and DC
- ✓ It is cheap
- ✓ Supply is given to a fixed coil, not in moving coil.
- ✓ Simple construction
- ✓ Less friction error.

Disadvantages

- ✓ It suffers from eddy current and hysteresis error
- ✓ Scale is not uniform
- ✓ It consumed more power
- ✓ Calibration is different for AC and DC operation

1.8.2 Repulsion type moving iron instrument

Construction: The repulsion type instrument has a hollow fixed iron attached to it (Fig. 1.12). The moving iron is connected to the spindle. The pointer is also attached to the spindle in supported with jeweled bearing.

Principle of operation: When the current flows through the coil, a magnetic field is produced by it. So both fixed iron and moving iron are magnetized with the same polarity, since they are kept in the same magnetic field. Similar poles of fixed and moving iron get repelled. Thus the deflecting torque is produced due to magnetic repulsion. Since moving iron is attached to spindle, the spindle will move. So that pointer moves over the calibrated scale.

Damping: Air friction damping is used to reduce the oscillation.

Control: Spring control is used.

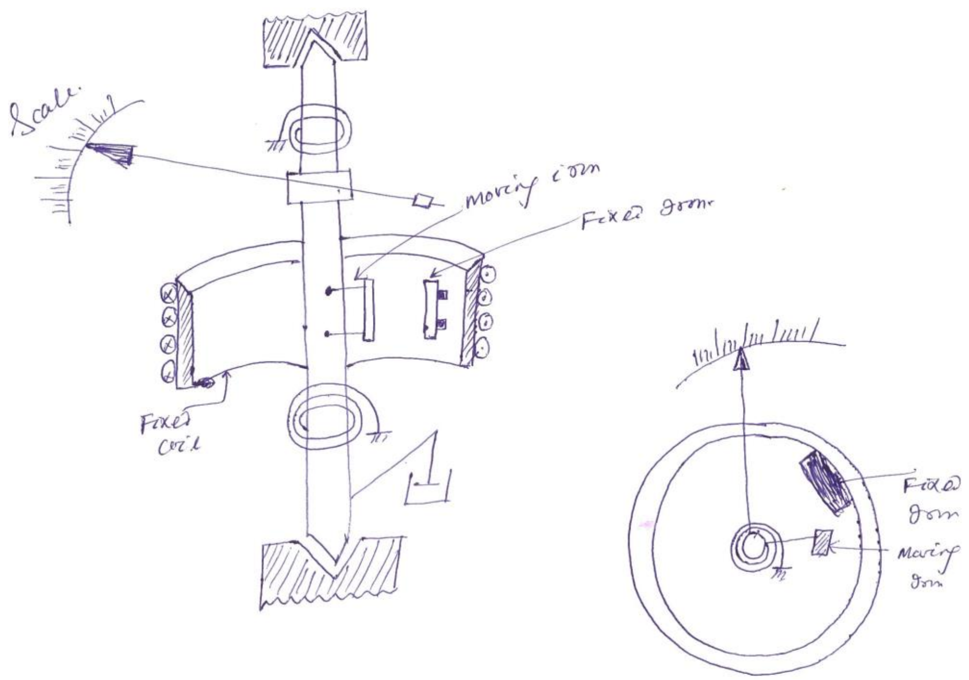


Fig. 1.12

1.9 Dynamometer (or) Electromagnetic moving coil instrument (EMMC)

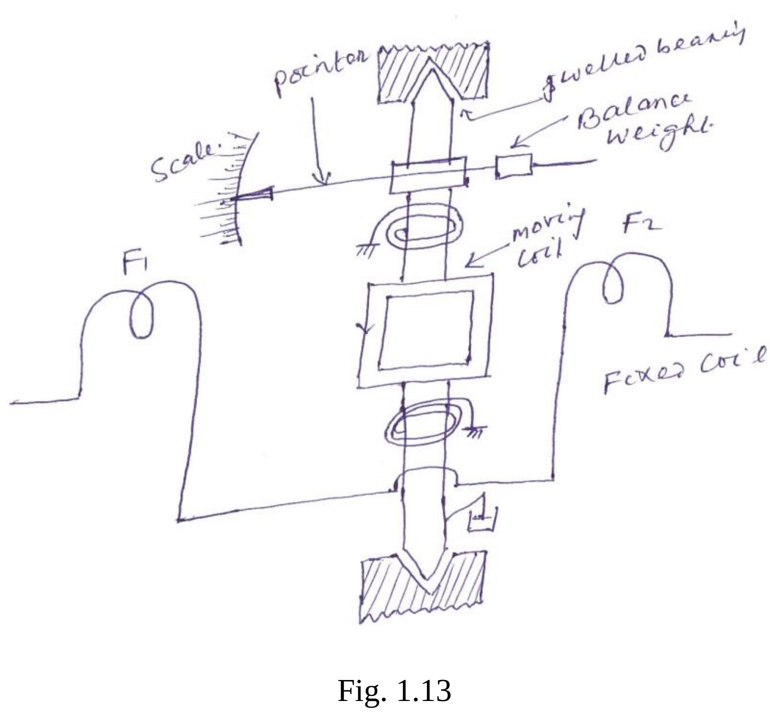


Fig. 1.13

This instrument can be used for the measurement of voltage, current and power. The difference between the PMMC and dynamometer type instrument is that the permanent magnet is replaced by an electromagnet.

<u>Construction</u>:A fixed coil is divided in to two equal half. The moving coil is placed between the two half of the fixed coil. Both the fixed and moving coils are air cored. So that the hysteresis effect will be zero. The pointer is attached with the spindle. In a non metallic former the moving coil is wounded.

Control: Spring control is used.

Damping: Air friction damping is used.

<u>Principle of operation</u>:

When the current flows through the fixed coil, it produced a magnetic field, whose flux density is proportional to the current through the fixed coil. The moving coil is kept in between the fixed coil. When the current passes through the moving coil, a magnetic field is produced by this coil.

The magnetic poles are produced in such a way that the torque produced on the moving coil deflects the pointer over the calibrated scale. This instrument works on AC and DC. When AC voltage is applied, alternating current flows through the fixed coil and moving coil. When the current in the fixed coil reverses, the current in the moving coil also reverses. Torque remains in the same direction. Since the current i_1 and i_2 reverse simultaneously. This is because the fixed and moving coils are either connected in series or parallel.

<u>Torque developed by EMMC</u>

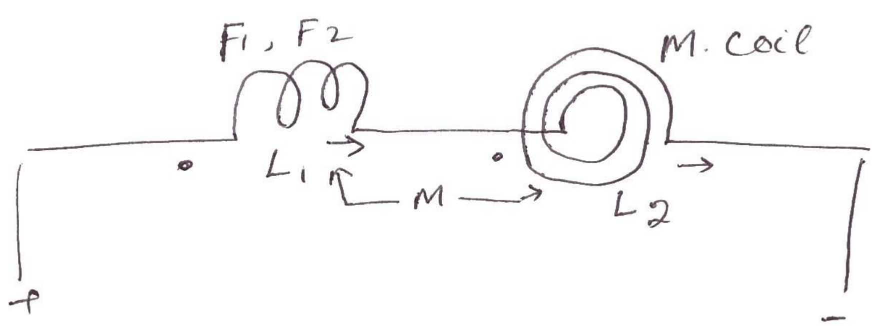


Fig. 1.14

Let

L_1=Self inductance of fixed coil

L_2= Self inductance of moving coil

M=mutual inductance between fixed coil and moving coil

i_1=current through fixed coil

i_2=current through moving coil

Total inductance of system,

$$L_{total} = L_1 + L_2 + 2M \quad (1.33)$$

But we know that in case of M.I

$$T_d = \frac{1}{2} i^2 \frac{d(L)}{d\theta} \quad (1.34)$$

$$T_d = \frac{1}{2} i^2 \frac{d}{d\theta}(L_1 + L_2 + 2M) \quad (1.35)$$

The value of L_1 and L_2 are independent of 'θ' but 'M' varies with θ

$$T_d = \frac{1}{2} i^2 \times 2 \frac{dM}{d\theta} \quad (1.36)$$

$$T_d = i^2 \frac{dM}{d\theta} \quad (1.37)$$

If the coils are not connected in series $i_1 \neq i_2$

$$\therefore T_d = i_1 i_2 \frac{dM}{d\theta} \quad (1.38)$$

$$T_C = T_d \quad (1.39)$$

$$\therefore \theta = \frac{i_1 i_2}{K} \frac{dM}{d\theta} \quad (1.40)$$

Hence the deflection of pointer is proportional to the current passing through fixed coil and moving coil.

1.9.1 Extension of EMMC instrument

Case-I Ammeter connection

Fixed coil and moving coil are connected in parallel for ammeter connection. The coils are designed such that the resistance of each branch is same.

Therefore

$I_1 = I_2 = I$

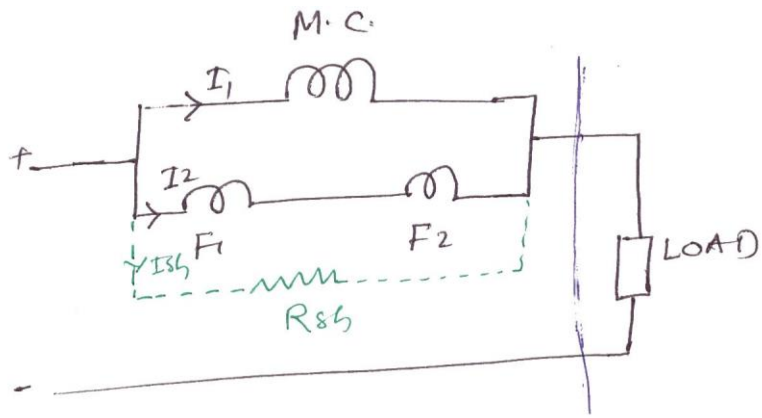


Fig. 1.15

To extend the range of current a shunt may be connected in parallel with the meter. The value R_{sh} is designed such that equal current flows through moving coil and fixed coil.

$$\therefore T_d = I_1 I_2 \frac{dM}{d\theta} \quad (1.41)$$

$$\text{Or } \therefore T_d = I^2 \frac{dM}{d\theta} \quad (1.42)$$

$$T_C = K\theta \quad (1.43)$$

$$\therefore \theta = \frac{I^2}{K} \frac{dM}{d\theta} \quad (1.44)$$

$$\therefore \theta \propto I^2 \text{ (Scale is not uniform)} \quad (1.45)$$

Case-II Voltmeter connection

Fixed coil and moving coil are connected in series for voltmeter connection. A multiplier may be connected in series to extent the range of voltmeter.

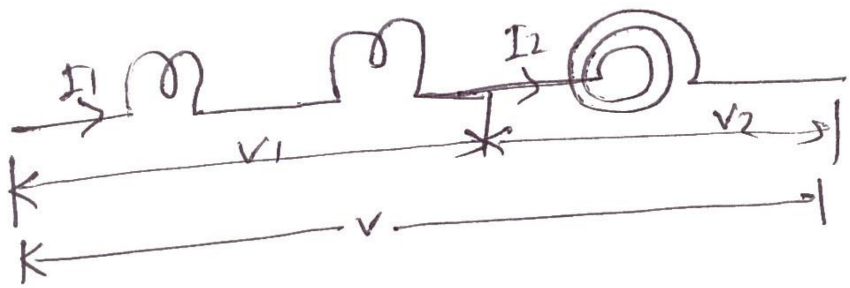


Fig.1.16

Fig. 1.16

$$I_1 = \frac{V_1}{Z_1}, I_2 = \frac{V_2}{Z_2} \tag{1.46}$$

$$T_d = \frac{V_1}{Z_1} \times \frac{V_2}{Z_2} \times \frac{dM}{d\theta} \tag{1.47}$$

$$T_d = \frac{K_1 V}{Z_1} \times \frac{K_2 V}{Z_2} \times \frac{dM}{d\theta} \tag{1.48}$$

$$T_d = \frac{K V^2}{Z_1 Z_2} \times \frac{dM}{d\theta} \tag{1.49}$$

$$T_d \propto V^2 \tag{1.50}$$

$$\therefore \theta \propto V^2 \quad \text{(Scale in not uniform)} \tag{1.51}$$

Case-III As w**attmeter**

When the two coils are connected to parallel, the instrument can be used as a wattmeter. Fixed coil is connected in series with the load. Moving coil is connected in parallel with the load. The moving coil is known as voltage coil or pressure coil and fixed coil is known as current coil.

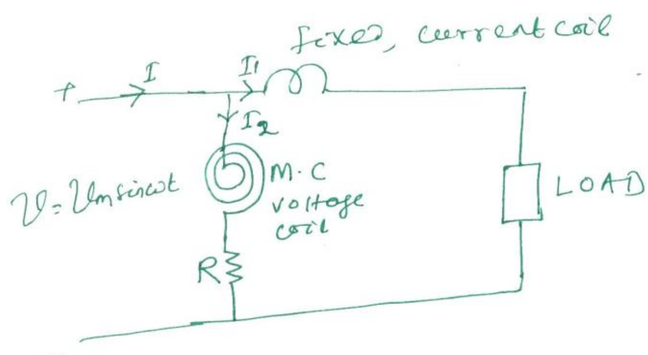


Fig. 1.17

Assume that the supply voltage is sinusoidal. If the impedance of the coil is neglected in comparison with the resistance ‘R’. The current,

$$I_2 = \frac{v_m \sin wt}{R} \tag{1.52}$$

Let the phase difference between the currents I_1 and I_2 is ϕ

$$I_1 = I_m \sin(wt - \phi) \tag{1.53}$$

$$T_d = I_1 I_2 \frac{dM}{d\theta} \tag{1.54}$$

$$T_d = I_m \sin(wt - \phi) \times \frac{V_m \sin wt}{R} \frac{dM}{d\theta} \tag{1.55}$$

$$T_d = \frac{1}{R}(I_m V_m \sin wt \sin(wt - \phi)) \frac{dM}{d\theta} \tag{1.56}$$

$$T_d = \frac{1}{R} I_m V_m \sin wt . \sin(wt - \phi) \frac{dM}{d\theta} \tag{1.57}$$

The average deflecting torque

$$(T_d)_{avg} = \frac{1}{2\Pi} \int_0^{2\Pi} T_d \times d(wt) \tag{1.58}$$

$$(T_d)_{avg} = \frac{1}{2\Pi} \int_0^{2\Pi} \frac{1}{R} \times I_m V_m \sin wt . \sin(wt - \phi) \frac{dM}{d\theta} \times d(wt) \tag{1.59}$$

$$(T_d)_{avg} = \frac{V_m I_m}{2 \times 2\Pi} \times \frac{1}{R} \times \frac{dM}{d\theta} \left[\int \{\cos\phi - \cos(2wt - \phi)\} dwt \right] \tag{1.60}$$

$$(T_d)_{avg} = \frac{V_m I_m}{4\Pi R} \times \frac{dM}{d\theta} \left[\int_0^{2\Pi} \cos\phi . dwt - \int_0^{2\Pi} \cos(2wt - \phi) . dwt \right] \tag{1.61}$$

$$(T_d)_{avg} = \frac{V_m I_m}{4\Pi R} \times \frac{dM}{d\theta} \left[\cos\phi [wt]_0^{2\Pi} \right] \tag{1.62}$$

$$(T_d)_{avg} = \frac{V_m I_m}{4\Pi R} \times \frac{dM}{d\theta} [\cos\phi (2\Pi - 0)] \tag{1.63}$$

$$(T_d)_{avg} = \frac{V_m I_m}{2} \times \frac{1}{R} \times \frac{dM}{d\theta} \times \cos\phi \tag{1.64}$$

$$(T_d)_{avg} = V_{rms} \times I_{rms} \times \cos\phi \times \frac{1}{R} \times \frac{dM}{d\theta} \tag{1.65}$$

$$(T_d)_{avg} \square\ KVI \cos\square \qquad (1.66)$$

$$T_C \square\ \square \qquad (1.67)$$

$$\square\ \square\ KVI \cos \square \qquad (1.68)$$

$$\square\ \square\ VI \cos\square \qquad (1.69)$$

<u>Advantages</u>

- ✓ It can be used for voltmeter, ammeter and wattmeter
- ✓ Hysteresis error is nill
- ✓ Eddy current error is nill
- ✓ Damping is effective
- ✓ It can be measure correctively and accurately the rms value of the voltage

<u>Disadvantages</u>

- ✓ Scale is not uniform
- ✓ Power consumption is high(because of high resistance)
- ✓ Cost is more
- ✓ Error is produced due to frequency, temperature and stray field.
- ✓ Torque/weight is low.(Because field strength is very low)

Errors in PMMC

- ✓ The permanent magnet produced error due to ageing effect. By heat treatment, this error can be eliminated.
- ✓ The spring produces error due to ageing effect. By heat treating the spring the error can be eliminated.
- ✓ When the temperature changes, the resistance of the coil vary and the spring also produces error in deflection. This error can be minimized by using a spring whose temperature co-efficient is very low.

1.10 Difference between attraction and repulsion type instrument

An attraction type instrument will usually have a lower inductance, compare to repulsion type instrument. But in other hand, repulsion type instruments are more suitable for economical production in manufacture and nearly uniform scale is more easily obtained. They are therefore much more common than attraction type.

INDUCTION TYPE INSTRUMENTS

11.1 Working Principle of Induction Type Instruments

Consider an aluminum disc placed the between the pole of an electromagnet, as shown in fig. 11.1. Let the flux produced by flow of current of I Amperes through the coil be F and this flux will lag behind I, by a small angle β as shown in vector diagram.

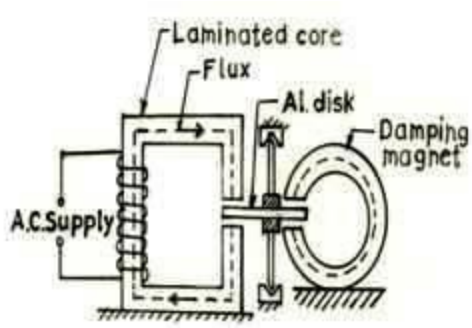


Fig. 11.1 Working principle of induction type instruments

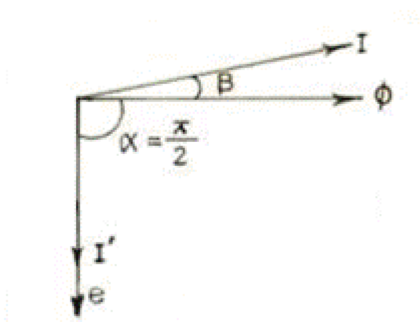


Fig. 11.2 Vector diagram

Since the aluminum disc act as a short circuited secondary of the transformer, therefore, an e.m.f., (say e volts) lagging behind the flux F by $\frac{\pi}{2}$�radians will be induced in it. As a result of this induced e.m.f., the eddy current (I�) starts flowing in the disc. Since the disk is purely resistive therefore the eddy current will be in phase with induced e.m.f. (e) will lag behind the main flux F by $\frac{\pi}{2}$� radians. As the component of eddy current (I�) along flux F is zero, therefore torque produced is zero. It can be proved as follows.

Let the instantaneous values of flux and eddy current be given by F = F_{max} Sin θ and i = I_{max} Sin (θ � α). Where α is the phase angle between the induced eddy current and flux (F).

Instantaneous torque α F i

����������� Mean, torue, $\alpha \frac{1}{\pi}\int_0^{\pi} \Phi i \, d\theta$

����������� $\alpha \frac{1}{\pi}\int_0^{\pi} \Phi max\ Imax\ Sin\ (\theta - \alpha)\ d\theta$

����������� $\alpha \frac{1}{\pi}\int_0^{\pi} \frac{\Phi max\ Imax}{2}\ [Cos\ \alpha - Cos(2\theta - \alpha)d\theta]$

����������� $\alpha \frac{1}{\pi} \times \frac{\Phi max\ Imax}{\sqrt{2}\sqrt{2}} \times \pi\ Cos\ \alpha$

����������� α Fi Cos α

Where F and i are r.m.s. values.

Since in single phase induction type instruments the angle α between main flux F and eddy current I� is $\frac{\pi}{2}$�and Cos $\frac{\pi}{2}$�is zero, therefore torque produced is zero. Hence to obtain the resultant torque it is necessary to produce an eddy current which is either appreciable less than or appreciable more than $\frac{\pi}{2}$ �radians, out of phase with the flux which it reacts. Several arrangements are possible but here we will discuss about the descriptions of the two of these.

11.2 Pole Shaded Method

As shown in Fig. 11.3, in this method, the working current is passed through the coil of an electromagnet which has an air gap in one limb. Permanent magnet is used for providing damping torque. The aluminum disc is mounted on pivots and jewel bearings.

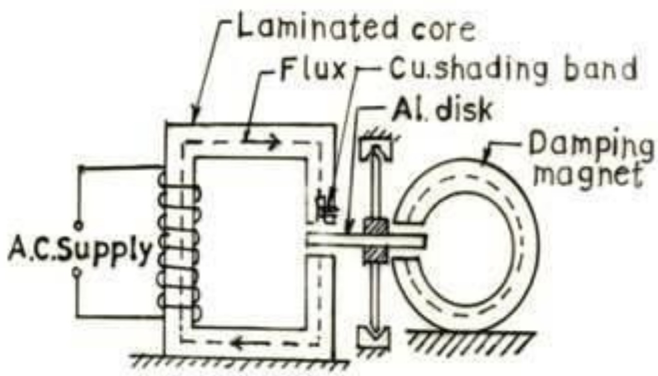


Fig. 11.3 Pole shaded method

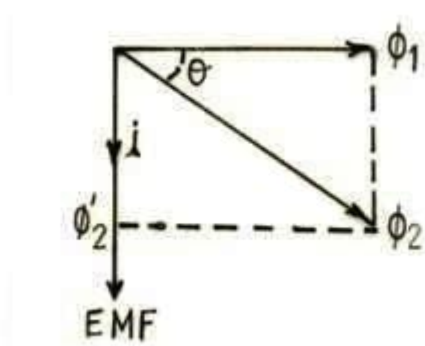


Fig. 11.4 Vector diagram

Two spiral springs are employed to provide controlling torque, wounded in direction opposite to each other if the instrument is used as Voltmeter, Ammeter and Wattmeter etc. One half of the pole face is surrounded by a copper band in order to split the working flux into two different paths. The copper shading band acts as a single turn short circuited secondary winding of the transformer. The spiral springs, pointer and scale etc. have been omitted for simplicity.

11.2.1 Theory

Let the total flux produced in the magnetic core be F Weber. Due to shading of pole, this flux will split up into two fluxes i.e. flux through un-shaded portion and other through the shaded portion. Suppose the flux F_1 be the flux of the shaded portion of the pole. This flux F_1 will induce an e.m.f. in the copper ring, which will lag the flux F_1 by 90�, as shown in Fig. 11.4. The induced e.m.f. will force a current say i to flow in the copper ring which will be lagging behind the flux F_1 by 90^0. The current flowing in the copper ring will produce its own magnetic field say F�$_2$ in phase with current i. The flux given by the shaded portion of the pole will be the vector sum of F_1 and F�$_2$ which is equal to F_2 lagging behind flux F_1 by an angle θ and its value should be 40^0 to 60^0 for producing effective deflecting torque.

Let the flux F_1 and F_2 are the fluxes passing through the shaded and un-shaded portions of the pole respectively induce e.m.fs. e_1 and e_2 in the disc, each of which is 90^0 in phase behind the fluxes responsible for inducing it. These induced e.m.fs; will induce eddy currents (say i_1 and i_2) in the disc lagging by a small angle (say α) behind its voltage due to the inductance of the path in the disc.

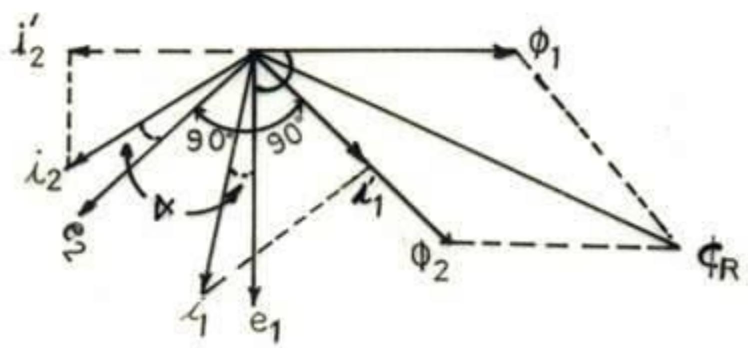


Fig. 11.5 Vector diagram

From Fig. 11.5, it is obvious that each of the current i_1 and i_2 has a component in phase with the other flux such i_1' and i_2'. Hence two torques are acting in a directions having angle θ are produced in the instrument. Resultant of these two torques, provides an operating or deflecting torque.

11.3 Two Pole Method

This method is also known as split phase method. In this method, two laminated magnets A and B are placed near to each other with aluminum (Al) disc in between and a non inductive resistance R is connected in series with the magnetizing coil of magnet A and an inductive coil L is connected in series with the magnetizing coil of magnet B, as shown in Fig. 11.6.

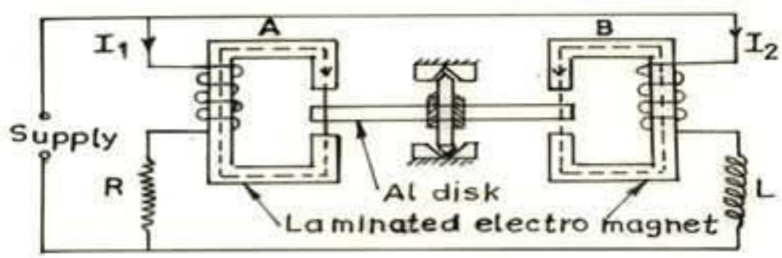


Fig. 11.6 Two pole method (split phase)

Hence there will be two fluxes having phase difference of less than 90� with each other, acting on the disc which will produce a resultant torque in the aluminium disc.

Let the flux produced by the magnet A and B is F_1 and F_2 respectively. F_2 is lagging F_1 by an angle θ as shown in Fig. 11.5. Hence an operating or deflecting torque will be produced as explained above in case of shaded pole method.

INDUCTION TYPE VOLTMETER AND AMMETER

12.1 Shaded Pole Type Voltmeter

A volt meter is an instrument used to measure the potential difference between the two points in an electric circuit. In analog voltmeters, the pointer moves over a calibrated scale in proportion to potential difference across the points where as in case of digital voltmeters, it displays numerical values with the help of analog to digital converter. The induction type voltmeter operates on the either shaded pole method or on two pole method�s working principle as explained in Lesson 11.

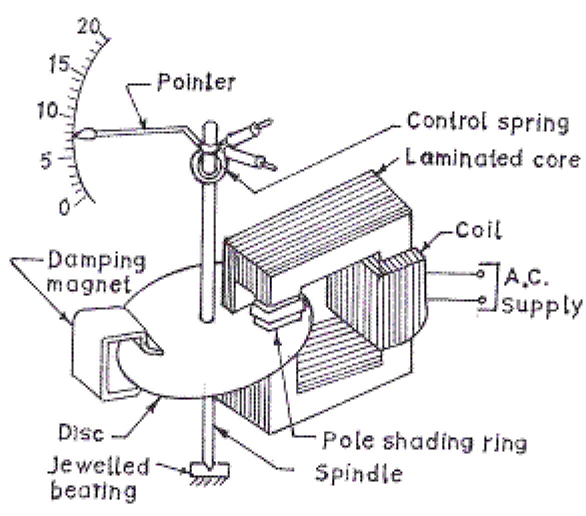


Fig. 12.1 Shaded pole type voltmeter

A non inductive high resistance is also inserted in series with the shunt coil and is connected across the supply, whose potential difference has to be measured. Since the voltmeters are connected across the supply, so the current flowing through coil is very small of the order of 5 to 10 mA. The spindle of aluminum disc is provided with a pointer moving over a calibrated scale in terms of voltage. Spiral springs are provided on both the ends of spindle for providing controlling torque. Permanent magnet (C-magnet) is used to provide damping torque on the spindle. As the instrument is provided with spiral springs, to provide controlling torque, the scale of the instrument is uniform because in such instrument this torque is directly proportional to angle of deflection of the pointer. Spiral springs, pointer and damping magnets are omitted for clear understanding of the figure. For detail working of the instrument, please refer to working principle of induction type instruments described in Lesson 11.

12.2 Split Phase Ammeter

An ammeter is always connected in series with load current directly or through CT (Current Transformer). As shown in Fig. 12.2, both the windings on the two laminated electromagnets A and B are connected in series but winding is shunted by a resistance R with the result of which, the current in this winding lags with respect to the total current (I). Hence the necessary phase angle (α) required between two fluxes is produced by the laminated electromagnets A and B.

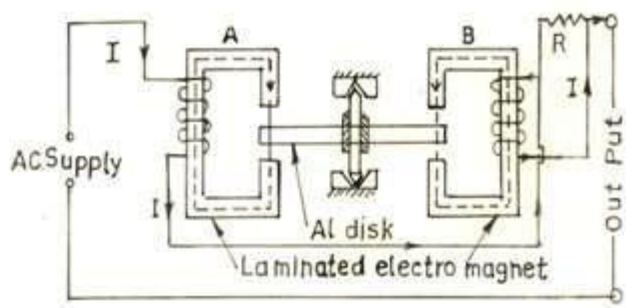


Fig. 12.2 Split phase induction type ammeter

The operating principle of the induction type instrument is based on the two pole method as discussed in Lesson 11. Two fluxes produced by laminated magnet A and B are focused upon the aluminum disc, having a phase angle between them required for producing a resultant torque in the spindle of the moving system. Being a spring control based controlling torque, the scale is uniform and the deflecting torque is directly proportional to square the load current. Eddy current damping is used to provide necessary damping torque by a permanent magnet. Spiral springs, pointer and damping magnets are omitted for clear understanding of the Fig. 12.2.

12.3 Advantages and Disadvantages of Induction Type Instruments

Advantages

(a) Damping is very much effective and efficient.

(b) Full scale deflection more than 200� can be obtained.

Disadvantages

(a) Power consumption is large and hence not recommended where continuous monitoring of ac quantities is required.

(b) Variation in temperature and frequency may cause serious errors if necessary compensations are not provided.

(c) As these instruments are based on principle of induction, they can be used on AC supply only.

12.4 Compensation for Frequency and Temperature Errors

12.4.1 Compensation for variation in frequency

Variation in frequency causes serious errors because deflecting torque is directly proportional to frequency and also the value of impedance (Z) and Cos α depends upon the supply frequency. The error is compensated by use of non inductive shunt in case of an Ammeter, when the frequency increases, the increase in impedance of the winding cause a greater proportion of the total current to flow in the non inductive shunt (whose impedance remains constant for all frequency) and lesser proportion of the total current in flow in the winding and to an extent thus compensate the increase in torque (since T α. f).

In case of voltmeter, the impedance of the winding increases with the increase in frequency, hence smaller current is drawn by the winding, which tends to compensate the increase in torque due to increase in frequency.

12.4.2 Compensation for variation in temperature

Variation in temperature changes the resistance of the eddy current paths, therefore, may result in serious errors. The error is compensated in case of an ammeter, employing a shunt of material having a high temperature coefficient of resistance than the material of the disc. This shunt may be the same one as used for frequency compensation. When the temperature increases, the resistance of the shunt increases, hence the greater portion of the current flows through the coil and decreases in torque due to smaller eddy current in the disc owing to increase in resistance at high temperature is compensated. The combination of shunt and swapping resistance in series with the instrument is often employed to compensate the temperature error in case of voltmeters. Since the frequency errors in induction type instruments are so serious that cannot be compensated satisfactorily. Hence these instruments are used for only constant frequency supplies or where the fluctuation in frequency is very small.

INDUCTION TYPE WATTMETER, WATT-HOUR METER, AND DYNAMOMETER TYPE POWER FACTOR METER

13.1 Induction Type Wattmeter

These types of watt-meters operate on the same working principle on which the induction type ammeter and voltmeter operates. These instruments can only be used on ac supply while dynamo-meter type watt meters can be used on either ac or dc supply system. Induction type watt-meters are useful only when the supply and frequency remains constant. Since both the coils i.e. current coil and pressure coils are necessary in such instrument, it is not essential to use shaded pole principle. Because for producing a deflecting torque, two fluxes are essential with suitable phase angle and it would be available from these two coils.

13.1.1 Construction

A watt-meter has two laminated electromagnet, one of which is excited by load current or definite fraction of it, and is connected in series with the circuit, known as series magnet and the other is excited by the current proportional to the applied voltage or fraction of it and is always connected across the supply, known as shunt magnet. An aluminum disc is so mounted so that it cuts the fluxes produced by both the magnets. As a result of which, two e.m.f�s are produced which induces two eddy currents in the disc. C - Magnet is used to provide necessary damping torque to the pointer, to damp out the oscillations. Deflecting torque is produced due to interaction of these eddy currents and the inducing flux. Copper shading bands are provided either on central limb or on the outer limb of the shunt magnet, and can be so adjusted as to make the resultant flux in the shunt magnet lag behind the applied voltage by 90�. Both the watt-meters are provided with spiral springs A and B, for producing controlling torque to counter balance the deflecting torque. In Fig. 13.2 the spiral spring and damping magnet is omitted for simplicity. The scale of such type instruments is quite uniform and extends over an angle of 300�. Currents up to 100 A can be handled by these watt-meters directly where as beyond this current transformers are used. Two types of induction type watt meters are available. Line diagrams of both of the types are detailed in Fig. 13.1 and 13.2.

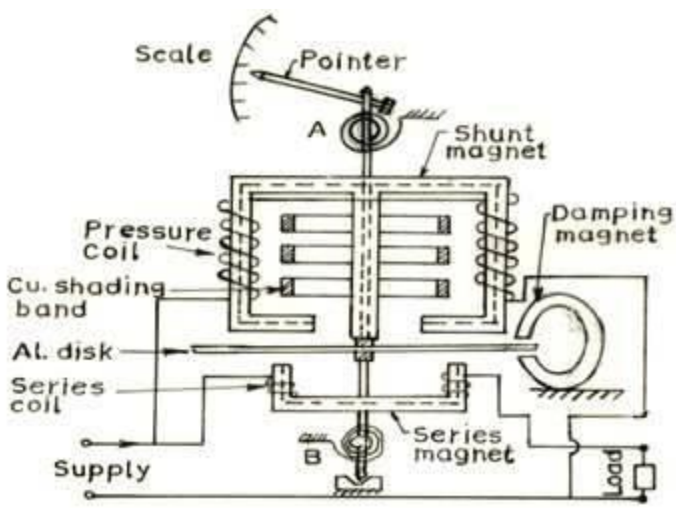


Fig. 13.1 Induction type wattmeter

In the form of the instrument shown in Fig. 13.1, two pressure coils are connected in series in such a way that both of them send flux through the central limb. The series magnet also carries two small current coils connected in series and wound so that they magnetized their respective cores in the same direction. Correct phase displacement between the fluxes produced by series and shunt magnet is obtained by the adjustment of copper shading band on the central limb.

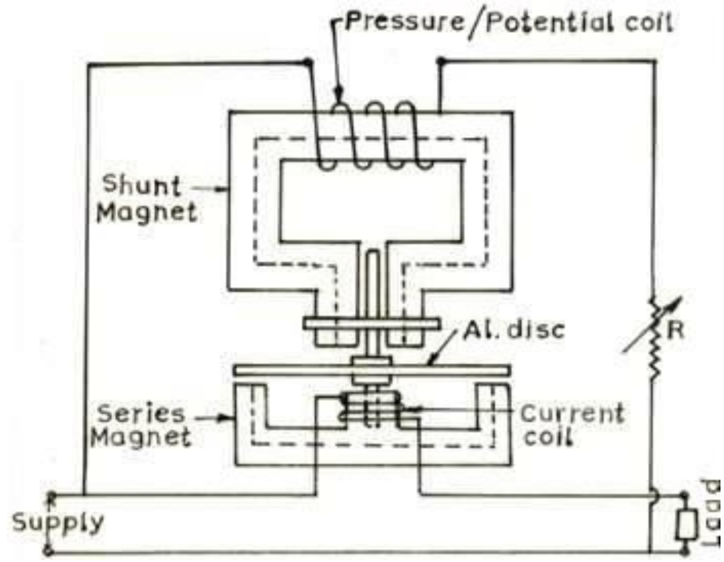


Fig. 13.2 Induction type wattmeter

In Fig. 13.2, there is only one pressure and one current coil. Two projecting poles of shunt magnet are surrounded by a copper shading band whose position can be adjusted for correcting the phase of the flux of this magnet with the applied voltage. The pressure coil circuit of induction type instrument is made as inductive as possible so that the flux of the shunt magnet may lag nearly by 90 degree behind the applied voltage.

13.1.2 Advantages

The advantages of induction watt meters are the same as those of induction ammeters long scale, freedom from effects of stray field, and have effective damping torque.

13.1.3 Disadvantages

Following are the disadvantage of the induction type instruments:

a) Change in temperature causes variation in the resistance of the moving element, affects the eddy currents therein, and so the operating torque. The error due to this is in part offset by a balancing effect due to change in temperature of the windings.

b) Change in frequency from that of the calibration value causes variations in both the reactance of the voltage coil circuit, which is highly inductive, and also in the amount of compensation from the phase compensating circuit. Within the limits of frequency variation met within practice on the mains, this last error in not important.

13.2 Induction Type Single Phase Watt Hour Meter

A watt hour meter is used to sum up the total energy consumed by a consumer during a period so that it can be charged for the actual energy consumed. The working principle, theory and advantage / disadvantages are almost similar to single phase watt meter. The construction of single phase watt hour meter is also almost similar to single phase induction type watt meter as discussed above. The pointer and spiral springs are replaced by wheel-train mechanism for summing up of total energy consumed where as the damping magnet is replaced by braking magnet. The construction of this type of watt hour meter is shown in Fig.

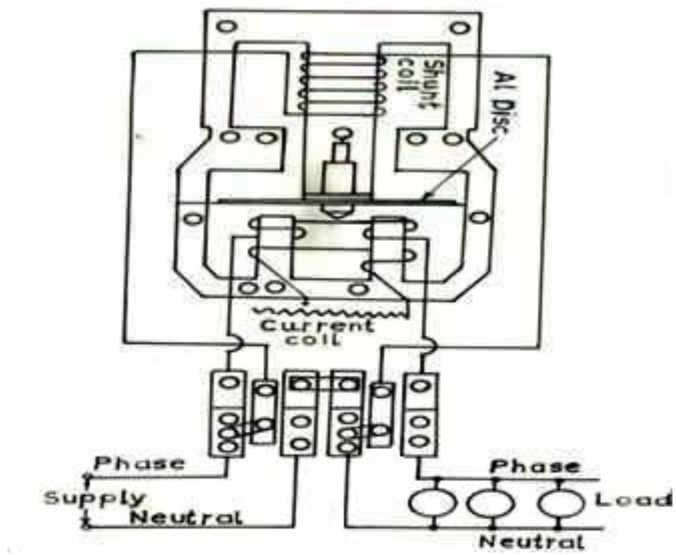


Fig. Induction type energy meter

The brake magnet and recording wheel-train being omitted for clear understanding of the diagram. The description of registering mechanism and braking system is detailed below.

13.2.1 Registering or counting system

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

13.2.2 Braking system

Braking of the disk is provided by a small permanent magnet, located diametrically opposite to the alternating current magnets. The disk moves between the magnets gaps. The movement of rotating disc through the magnetic field crossing the air gap sets up eddy currents in the disc that reacts with the magnetic field and exerts a braking torque. By changing the position of the brake magnet or diverting some of the flux therefore, the speed of the rotating disc can be controlled. Creep error can be rectified by drilling a small hole in the aluminum disc passing through the magnetic flux of braking magnet.

13.3 Errors and Adjustment in Induction Type Instruments

13.3.1 Phase and speed error

It is necessary that the energy meter should give correct reading on all power factors, which is only possible when the field set up by shunt magnet flux lags behind the applied voltage by 90 degree.

Ordinarily the flux set up by shunt magnet does not lag behind the applied voltage exactly by 90 degree because of winding resistance and iron losses. The flux due to shunt magnet is made to lag behind applied voltage by 90 degree with the help of copper shading band provided on the central limb. An error due to incorrect adjustment of shading band will be evident when the meter is tested on a load of power factor less than unity.

An error on the fast side under these conditions can be eliminated by bringing the shading band nearer to the disc and vice versa. An error in the speed of the meter when tested on non inductive load can be eliminated by adjustment of the position of the brake magnet. Movement of the brake magnet in the direction of the spindle will reduce the braking torque and vice versa. Speed of disc is directly proportional to the distance between the disc and brake magnet.

13.3.2 Friction compensation

The two shading bands embrace the flux contained in the two outer limbs of the shunt electromagnet, and thus eddy current are induced in them which cause a phase displacement between the enclosed flux and main gap flux. As a result, a small driving torque is exerted on the disc, this torque being adjusted, by variation of the position of these bands, to compensate for frictional torque in the instrument.

In some energy meter, it is observed that the disc continue to rotate even when the load on the energy meter is zero and potential coil is in excited condition. This defect is known as creeping and is prevented by cutting two holes or slots in the disc on opposite sides of the spindle. The disc tends to remain stationary when one of the holes comes under one of pole of the shunt magnet. In some cases, a small piece of iron wire is attached to the edge of the disc. The force of attraction of the brake magnet upon this wire is sufficient to prevent continuous rotation of the disc under no load condition.

13.3.3 Temperature and frequency errors

The error due to variation in temperature is very small. Since the various effects due to change in temperature tends to neutralize each other on unity power factor if not on low power factor (lagging). Since the meters are used normally on fixed frequency and hence these can be adjusted to have a minimum error at declared supply frequency which is normally 50 cycles / second.

13.4 Single Phase Dynamo-meter Type Power Factor Meter

The power factor meter is used to indicate the instantaneous power factor of the consumer. It consist of two fixed coils CC connected in series carrying the load current (or a definite fraction of it) and two identical moving coils P_1 & P_2 wound with a fine copper wire, fixed at right angle to each other and pivoted on the same spindle. The pressure coils P_1 and P_2 move together and carry a pointer, which indicates the power factor of the circuit directly on the scale.

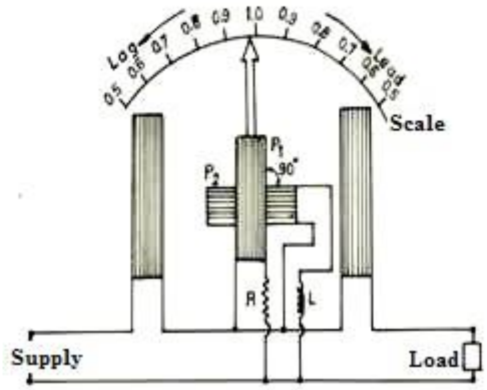


Fig. Dynamometer type power factor meter

The pressure coil P_1 is connected across the supply through a non inductive resistance R and pressure P_2 is connected across the supply through a highly inductive choke coil of inductance L. The value of non inductive resistance R and inductance L are so chosen that for the normal frequency, the current in the two pressure coil P_1 and P_2 is same. Thus these coils P_1 and P_2 produce equally strong magnetic field displaced by 90^0 in space as well as in the phase. For measurement of power factor on high voltage system, the current and pressure coils of the instrument may be connected to the main circuit through current and potential transformer respectively.

13.4.1 Theory

While measuring power factor of an installation, there may be three possibilities of installations power factor, which are described here:

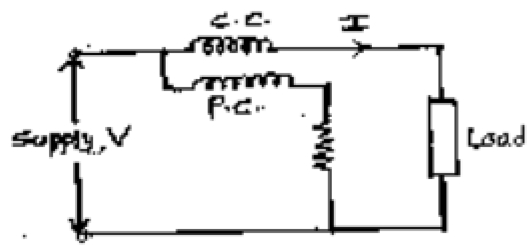
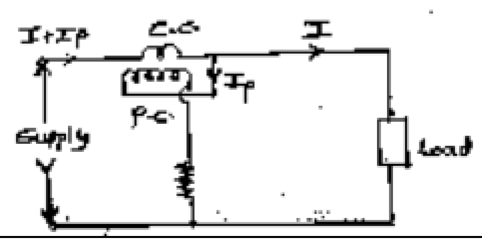
(a) **Power Factor is Unity:** When the circuit is switched on, the current in the potential coil P_1 will be in phase with current in coils CC, where as the current in pressure coil P_2 will lag 90^0 behind the voltage or behind the current in the circuit coli CC. Thus pressure coil P_1 will experience a turning moment so its plane will come in a position parallel to a plane of a current coil CC. The average torque on coil P_2 will be zero but being mechanically coupled to coil P_1, it will follow the rotation of coil P_1. Hence the pointer will in the centre of the calibrated scale and it will show the power factor as unity. The position of coil P_1 is shown in Fig. and it will maintain the reading till the load current is in phase with the voltage.

(b) **When Power Factor is Zero (lagging):** In this situation, the current flowing in the pressure coil P_2 will be in phase with load current flowing in the fixed current coil CC, both lagging behind the applied circuit voltage by 90^0 and current in pressure coil P_1 will lead the load current in current coil CC by 90^0. Thus only pressure coil P_2 will experience a turning moment so its plane will come in a position parallel to the plane of current coils CC. At this instant, the pointer will indicate zero power factor lagging.

(c) **When Power Factor Zero (leading):** When the current flowing in fixed coils CC leads the applied voltage by 90 degree and, therefore, the field of pressure coils P_1 by 90 degree and that of coil P_2 by 180 degree. Hence the polarity of field in current coils is the reverse of that considered above. At this instant, the pointer will indicates the power factor as zero leading on the other half of the scale.

For an intermediate power factor, the moving system takes up intermediate position and the pointer makes an angle of (90 degree - F) with the axis of the fixed coils where F the phase angle between load current is and applied voltage of the load circuit.

Errors in wattmeter and energy meter and their compensation and adjustment

Errors in Wattmeter	Compensation method
  Error due to connection method	To overcome this error, wattmeter's are provided with additional compensating winding which is connected in series with pressure coil but positioned in such a manner that it produces a field in opposition to that produced by current in current coil.
Error due to pressure coil inductance	A suitable value capacitor connected in parallel with pressure coil.
Error due to Pressure Coil Capacitance	This error can be reduced by designing pressure coil circuit such that inductive reactance of the circuit matches exactly with the capacitance reactance of the circuit i.e. XL=XC.
Error due to mutual inductance effect	This error can be reduced by proper design of pressure coil and current coil system so that they always remain in a zero position of mutual inductance.
Error due to stray magnetic fields	To avoid this error, magnetic shield is placed over CC & PC.
Error due to eddy currents	These are minimized by avoiding solid metal parts and using laminated core.
Temperature error	Using zero temperature coefficient materials for coils and components, this can be minimized.
Error due to vibration of moving system	It is avoided by designing the moving system such that its natural freq is greater than 2 times the freq of deflecting torque of the wattmeter.
Error due to friction	The weight of moving system be reduced to minimum possible.

Phantom Loading

Definition: Phantom loading is the phenomena in which the **appliances consume electricity even when they turn off**. The disc of the energy meter rotates which increases the reading of the meter, but the devices do not consume power**.** This type of loading is also known as the **vampire** or **virtual loading**. The phantom loading mainly occurs in the "electronic" appliances.

The phantom loading is used for examining the current rating ability of the energy meter. The actual loading arrangement will waste a lot of power. The phantom loading consumes very less power as compared to real loading, and because of this reason, it is used for testing the meter.

In phantom loading, the pressure coil and the current coil are separately excited by the supply source. The pressure coil is energised from the small supply voltage, and the current energises the current coil at very small voltages.

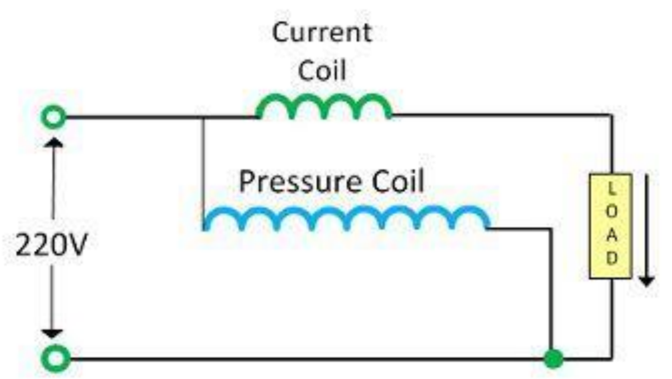
The pressure and current coil circuit have low impedance (less obstruction of movement of the electron) because of which highly rated current is passed through it. The total current supplied for the phantom loading is the sum of the pressure coil current which is supplied at normal voltage and the current of the current coil supply at low voltages.

Example of Phantom Loading

Consider the DC energy meter having rating voltage 220V and current 9 Ampere. The resistance of the pressure coil and the current coil is 4400Ω and 0.1Ω respectively. The power consumption of the load by direct and indirect phantom is explained below.

Direct Loading Arrangement

The circuit for direct loading is shown in the figure



Direct Loading Arrangement

Circuit Globe

below.

The power consumption of the pressure coil circuit is calculated as

$$\textbf{Power} = (220)^2 / 4400 = 48400/4400 = 11\text{watt}$$

The power consumption of the current circuit is expressed as

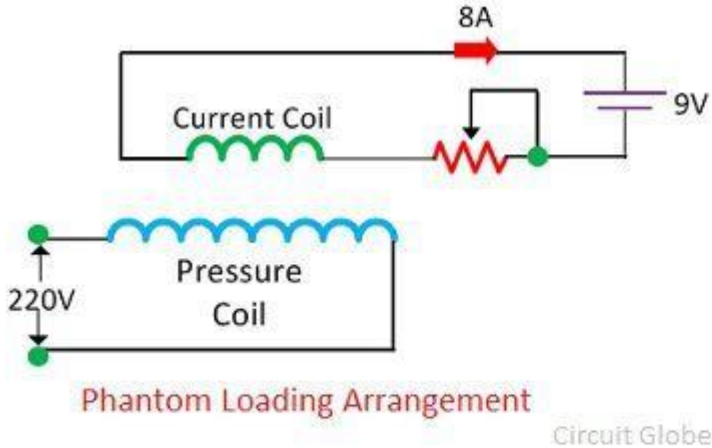
$$\textbf{Power} = 220 \times 9 = 1980\text{watt}$$

The total power consumed by the pressure and current circuit

Power = 11watt + 1980watt = 1991watt

Phantom Loading Arrangement

The circuit of the phantom loading is shown in the figure below.



The power consumption of the pressure coil is given below.

$$P = (220)^2/4400 = 11\text{watt}$$

The current coil of the phantom loading arrangement is separately excited by the battery of the 9V. The power of the current coil is measured as

Power = 9 X 9 = 81watt

The total power consumed by the phantom loading is expressed as

Total Power = 11watt + 81watt = 92watt

The above example shows that in phantom loading the pressure and the current coil is separately excited by the meter. Hence the power loss is less in phantom loading as compared to direct loading.