DepartmentofElectricalandElectronicsEngineering

Electrical Measurements and Sensors (25EE305)

UNIT – III
MEASURMENT OF POWER & ENERGY

Dynamometer type wattmeter works on very simple principle and this principle can be stated as when any current carrying conductor is placed inside a magnetic field, it experiences a mechanical force anddue to this mechanical force deflection of conductor takes place.

Construction and Working Principle of Electrodynamometer Type Wattmeter Now let us look at constructional details of electrodynamometer. It consists of following parts. Moving Coil Moving coil moves the pointer with the help of spring control instrument. Limited of current flows through the moving coil so as to avoid heating. So in order to limit the current we have connected the high value resistor in series with the moving coil. The moving is air cored and is mounted on a pivoted spindle and can move freely. In **electrodynamometer type wattmeter**, moving coil works as pressurecoil. Hence moving coil is connected across the voltage and thus the current flowing through this coilis always proportional to the voltage

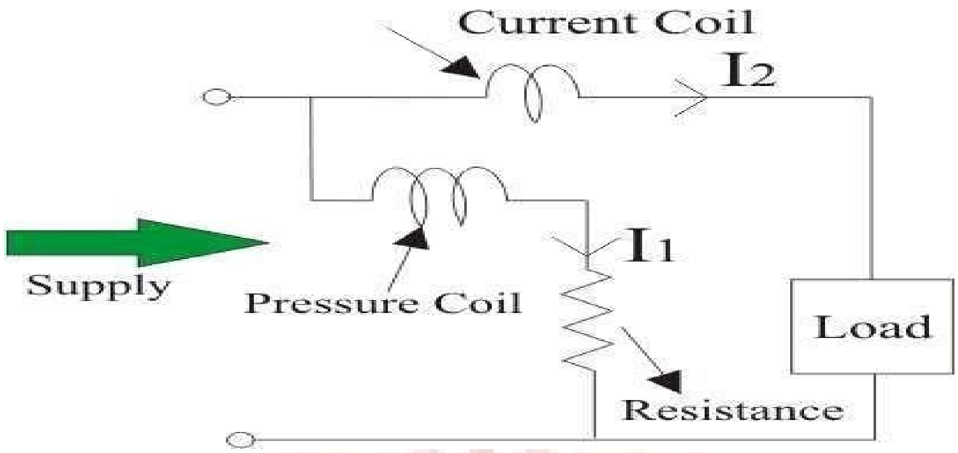
Fixed Coil

The fixed coil is divided into two equal parts and these are connected in series with the load, therefore the load current will flow through these coils. Now the reason is very obvious of using two fixed coils instead of one, so that it can be constructed to carry considerable amount of electric current. These coils are called the current coils of **electrodynamometer type wattmeter**. Earlier these fixed coils are designed to carry the current of about 100 amperes but now the modern wattmeter are designed to carry current of about 20 amperes in order to save power.

Control System Out of two controlling systems i.e.

1. Gravity control
2. Spring control, only spring controlled systems are used in these types of wattmeter. Gravity controlled system cannot be employed because they will be appreciable amount of errors.

Damping System Air friction damping is used, as eddy current damping will distort the weak operating magnetic field and thus it may leads to error. **Scale** There is uniform scale which is used in these types of instrument as moving coil moves linearly over a range of 40 degrees to 50 degrees on either side. Now let us derive the expressions for the controlling torque and deflecting torques. In order to derive these expressions let us consider the circuit diagram given below:



We know that instantaneous torque in electro dynamic type instruments is directly proportional to product of instantaneous values of currents flowing through both the coils and the rate of change of flux linked with the circuit. Let I_1 and I_2 be the instantaneous values of currents in pressure and current coils respectively. So the expression for the torque can be written as:

$$T = I_1 \times I_2 \times \frac{dM}{dx}$$

Where, x is the angle. Now letthe applied value of voltage across the pressure coil be $v = \sqrt{2}V sin\omega t$Assuming the electrical resistance to the pressure coil be veryhigh hence we can neglect reactance with respect to its resistance. In this the impedance is equal to its electrical resistance therefore it is purely resistive. The expression for instantaneous current can be written as $I_2 = v / R_p$ where R_p is the resistance of pressure coil

$$I_2 = \sqrt{2} \times \frac{V sin\omega t}{R_p}$$

If there is phase difference between voltage and electric current, then expressionfor instantaneous current through current coil can be writtenas

$$I_1 = I(t) = \sqrt{2} I sin(\omega t - \phi)$$

As current through the pressure coil is very very small compared to the current through current coil hence current through the current coil can be considered as equal to total load current. Hence the instantaneous value of torque can be written as

$$\sqrt{2} \times \frac{V sin\omega t}{R_p} \times \sqrt{2} \times I \times sin(\omega t - \phi) \times \frac{dM}{dx}$$

Average value of deflecting torque can be obtained by integrating the instantaneous torque from limit 0 to T, where T is the time period of the cycle.

$$T_d = deflecting\ torque = \frac{VI}{R_p} cos\phi \times \frac{dM}{dx}$$

Controlling torque is given by $T_c = K_x$ where K is spring constant and x is finalsteady state value of deflection.

Advantages of Electrodynamometer Type Wattmeter

Following are the **advantages of electrodynamometer type wattmeter** and theyare written as follows:

1. Scale is uniform upto a certain limit.
2. They can be used for both to measure ac as well dc quantities as scale is calibrated for both.

Errors in Electrodynamometer Type Wattmeter

Following are the errors in the electrodynamometer type watt meters:

1. Errors in the pressure coil inductance.
2. Errors may be due to pressure coil capacitance.
3. Errors may be due to mutual inductance effects.

4. Errors may be due connections.(i.e. pressure coil is connected after current coil)
5. Error due to Eddy currents.
6. Errors caused by vibration of moving system.
7. Temperature error.
8. Errors due to stray magnetic field.

What is Low Power Factor Wattmeter?

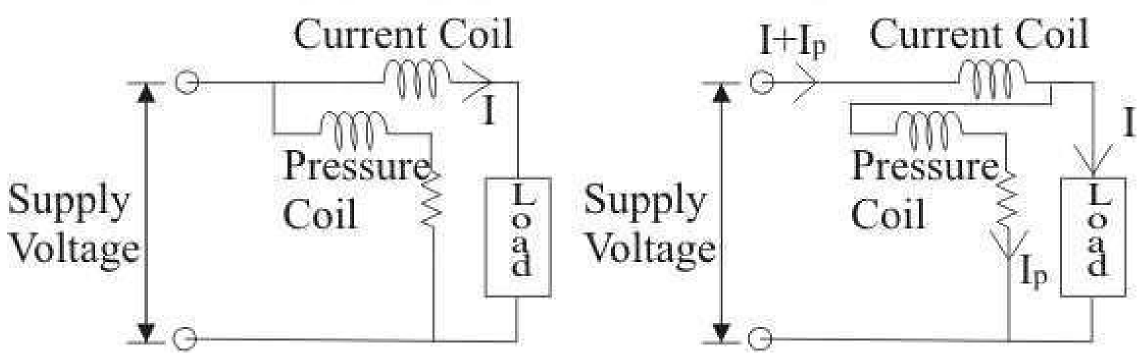
As the name suggests the low power factor meter are the instruments that measureslower values of power factor accurately.

There are two main reasons that would suggests us that we should not use ordinary wattmeter in measuring the low value of power factor.

1. The value of deflecting torque is very low even though we fully excite thecurrent and pressure coils.
2. Errors due pressure coil inductance.

some modification or adding some new features we can use modified electro dynamic wattmeter or low power factor to measure the low power factor accurately.

(1) The electrical resistance of the ordinary wattmeter's pressure coil is reduced to low value such that current in the pressure coil circuit is increased, thus it leads to. In this category two cases diagrams arises and these are shown below:



both the ends of the pressure coil is connected to supply side (i.e. current coil is in series with the load). The supply voltage is equal to the voltage across the pressure coil. Thus in this case we

have power shown by the first wattmeter is equal to the power loss in the load plus power loss in the current coil.

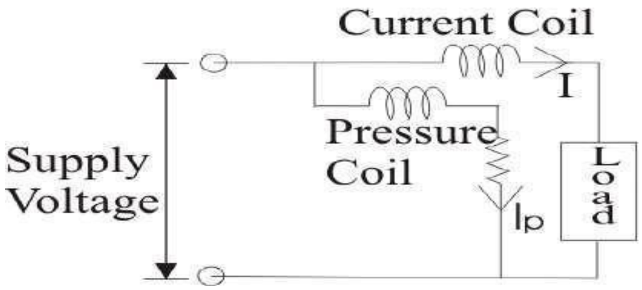
$$Mathematically\ P_1 = power\ consumed\ by\ load + I^2R_1$$

In the second category, the current coil is not in series with the load and the voltage across the pressure coil is not equal to the applied voltage. The voltage across pressure coil is equal to the voltage across the load. In this power shown by the second watt meter is equal to the power loss in the load plus the power loss in the pressure coil.

$$Mathematically\ P_2 = power\ consumed\ by\ load + I^2R_2$$

From the above discussion we conclude that in both cases we have some amount of errors hence there is need to do some modification in above circuits to have minimum error.

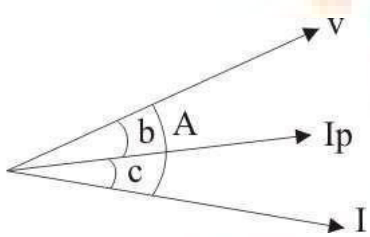
The modified circuit is shown below: We have used here a special coil called compensating coil, it carries current equal to the sum of two currents i.e load current plus pressure coil current. The pressure coil is placed such that the field produced by the compensating coil is opposed by the field produced by pressure coil as shown in the above circuit diagram.



Thus the net field is due to the current I only. Hence by this way error caused by pressure coil can be neutralised.

(2) We require compensating coil in the circuit in order to make the low power factor meter. It is the second modification that we have discussed in detail above.

(3) Now the third point deals with the compensation of the inductance of pressure coil, which can be achieved by doing modification in above circuit.



Now let us derive an expression for the correction factor for pressure coil inductance. And from this correction factor we are going to derive an an expression for error due to inductance of pressure coil. If we consider the inductance of pressure coil we don't have voltage across pressure in phase with theapplied voltage. Hence it that case it lag by anangle

$$b = tan^{-1}\frac{W_l}{R + r_p}$$

Where, R is electrical resistance in series with pressure coil, r_p is pressure coil resistance, here we also conclude that the current in the current coil is also laggingby some angle with the current in pressure coil. And this angle is given by C = A -

b. At this time reading of the voltmeter is given by

$$\frac{VIcos(C)\frac{dM}{dx}}{K+R_p}\cdots\cdots\cdots(1)$$

Where, R_p is (r_p+R) and x is angle. If we ignore the effect of inductance of pressure i.e putting b = 0 we have expression for true power as

$$\frac{VIcos(A)\frac{dM}{dx}}{K\cdot R_p}\cdots\cdots\cdots(2)$$

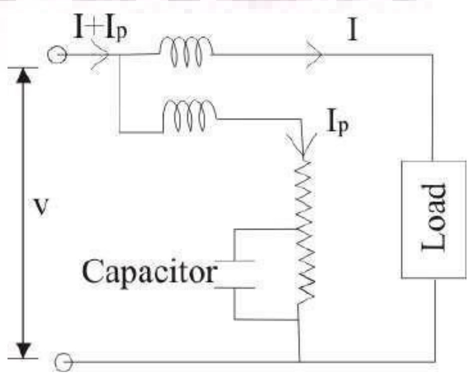
On taking ratio of equations (2) and (1) we have expression for correction factor aswritten below:

$$\frac{cos(A)}{cos(b)cos(A-b)}$$

And from this correction factor error can be calculated as

$$Error=\{1-(correction\ factor)\}\times(actual\ reading\ of\ the\ voltmeter)$$

On substituting the value of correction factor and taking suitable approximation we have expression for error as VIsin(A)*tan(b).



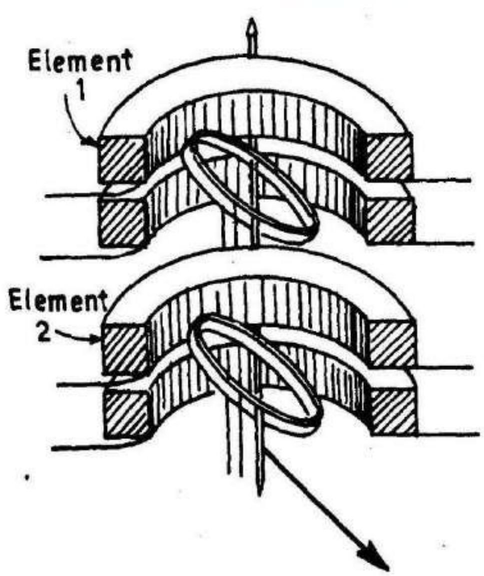
Now we know that the error caused by pressure coil inductance is given by the expression e = VIsin(A) tan(b), if power factoris low (i.e in our case the value of φ is large hence we have large error). Thus in order to avoid this situation we have connect the variable series resistance with a capacitor as shown in the above figure. This final modified circuit so obtained is called **low power factor meter**. Amodern low power factor meter is designed such that it gives high accuracy while measuring power factors even lower than 0.1.

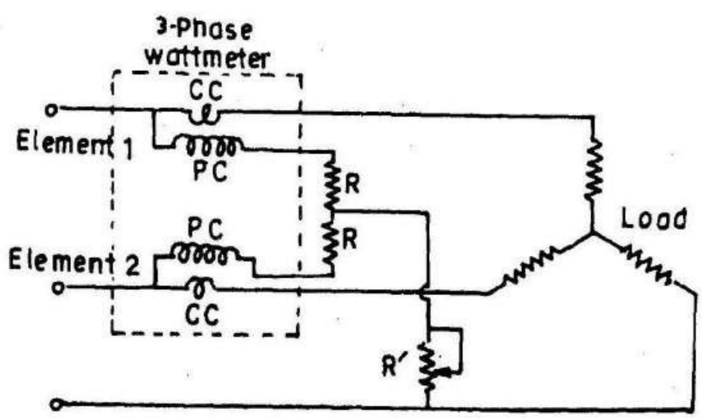
TWO-ELEMENT WATTMETER FOR THREE-PHASE SYSTEM

Two single-phase wattmeters were used to measure the power in a three-phase, three-wire sys- tem. The two single-phase wattmeters can be combined into a single instrument

The scale of this instrument indicates the sum or difference of the power values indicated by the separate meters. To make the single wattmeter, two sets of potential coils are mounted on a single shaft. Also, two sets of field coils are mounted on the instrument frame so that they have the proper relationship to the armature coils. In this way, each of two power measuring mechanisms develops a torque that is proportional to the power in the circuit to which it is connected. These torque values are added to obtain the total power in the three-phase, three- wire circuit. If the power factor of the system is less than 0.5, the torque of one mechanism opposes that of the second mechanism. The difference between the torque values is the power indication.

A wattmeter containing two dynamometer mechanisms is called a *two-element wattmeter*.





Now the pressure coil is split into two parts one is purely inductive another is purely resistive as shown in the diagram by resistorand inductor. At present the reference plane is making an angle A with coil 1. And the angle between both the

WATT HOUR METER

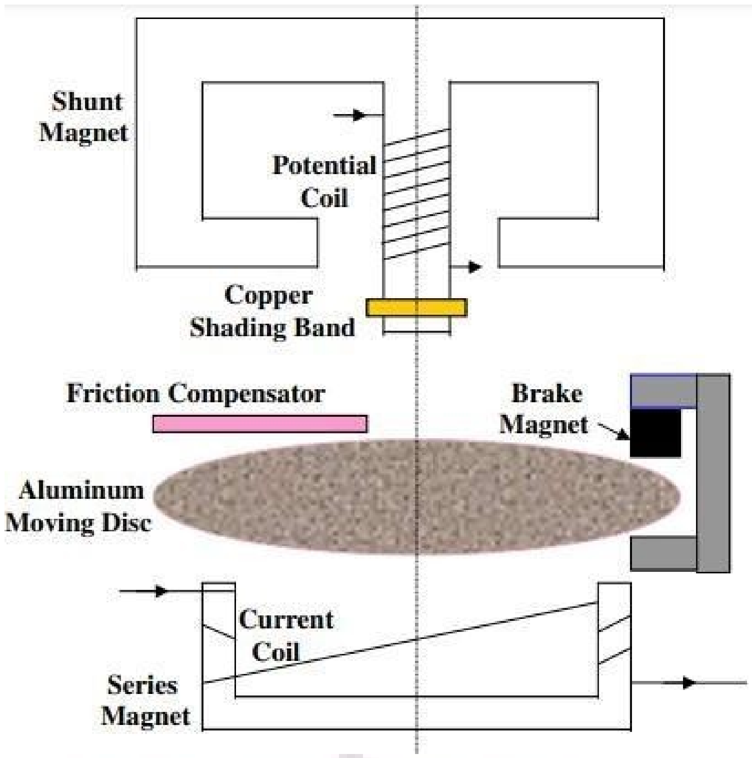
Watt-hour meter is in fact a measuring device which can evaluate and records the electrical power passing through a circuit in a certain time. By implementing the Watt-hour meter, we can know how much amount of electrical energy is used by a consumer or a residence or an electrically powered device or a business.

Electrical utilities install these meters at their consumer's place to evaluate the electrical usage for the purpose of billing. The reading is taken in each one billingperiod. Usually, the billing unit is Kilowatt-hour (kWh). This is equal to the total usage of electrical energy by a consumer of one kilowatt during a period of one hour and it is also equal to 3600000 joules. The Watt-Hour Meter is often referred as energy meter or electric meter or electricity meter or electrical meter. Mainly the watt-hour meter comprises of a tiny motor and a counter. The motor will operate by diverting exact fraction of currentwhich is flowing in the circuit tobe measured.

Electromechanical Type Induction Meter

In this type of meter, a non-magnetic and electrically conductive aluminium metal disc is made to revolve in a magnetic field. The rotation is made possible with the power passing through it. The rotation speed is proportional to the power flow through the meter. Gear trains and counter mechanisms are incorporated to integrate this power. This meter works by counting the total number of revolutions and it is relative to the usage of energy.

A series magnet is connected in series with the line and that comprises of a coil of few turns with thick wire. A shunt magnet is connected in shunt with the supply and comprises of a coil of large number of turns with thin wire. A braking magnet which is a permanent magnet is included for stopping the disc at the time of powerfailure and to place the disc in position. This is done by applying a force opposite to the rotation of the disc.



A flux is produced by the series magnet that is directly proportional to the current flow and another flux is produced by the shunt magnet corresponding to the voltage. Because of the inductive nature, these two fluxes lag each other by 90°. An eddy current is developed in the disc which is the interface of the two fields. This current is produced by a force that is corresponding to the product of instantaneous current, voltage and the phase angle among them. A break torque is

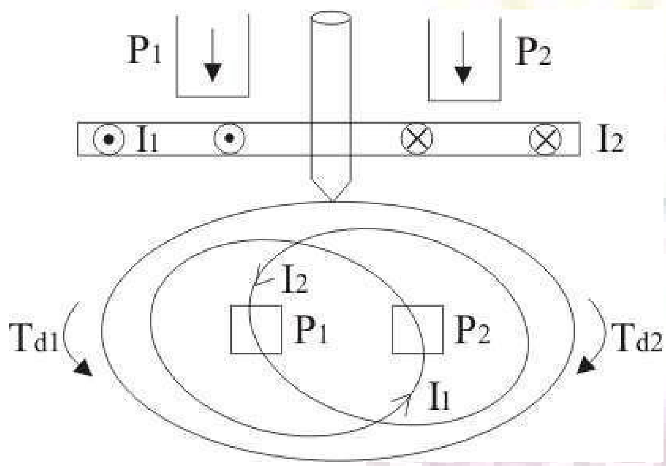
developed on the disc by the braking magnet positioned over one side of the disc. The speed of the disc becomes constant when the following condition is achieved,

Braking torque = Driving torque. The gear arrangement linked with the shaft of the disc is implemented for recording the number of revolution. This is for single phase AC measurement. Additional number of coils can be implemented for different phase configuration.

$$Power = \frac{3600.Kh}{time\ in\ sec\ for\ one\ revolution\ of\ the\ disc}$$

INDUCTION TYPE METERS

The principle of working and construction of ***induction type meter*** is very simple and easy to understand that's why these are widely used in measuring energy in domestic as well as industrial world. In all induction meters we have two fluxes which are produced by two different alternating currents on a metallic disc. Due to alternating fluxes there is an induced emf, the emf produced at one point (as shown in the figure given below) interacts with the alternating current of the other side resulting in the production of torque



Similarly, the emf produced at the point two interacts with the alternating current at point one, resulting in the production of torque again but in opposite direction. Hence due to these two torques which are in different directions, the metallic disc moves. This is basic principle of working of an **induction type meters**. Now let us derive the mathematical expression for deflecting torque. Let us take flux produced at point one be equal to F_1 and the flux and at point two be equal to F_2. Now the instantaneous values of these two flux can written as:

$$F_1 = F_{m1} sin\omega t, \quad F_2 = F_{m2} sin(\omega t - B)$$

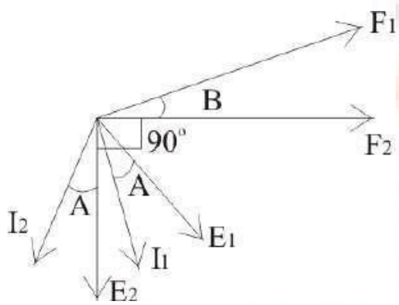
Where, F_{m1} and F_{m2} are respectively the maximum values of fluxes F_1 and F_2, B is phase difference between two fluxes. We can also write the expression for inducedemf's

$$E_1 = -\frac{d(F_1)}{dt} \quad and \quad E_2 = -\frac{d(F_2)}{dt}$$

Thus we have the expression for eddy currents at point one is

$$I_1 = \frac{E_1}{Z} = K \times f \times F_1$$

Where, K is some constant and f is frequency. Let us draw phasor diagram clearly showing F_1, F_2, E_1, E_2, I_1 and I_2. From phasor diagram, it clear that I_1 and I_2 are respectively lagging behind E_1 and E_2 by angle A



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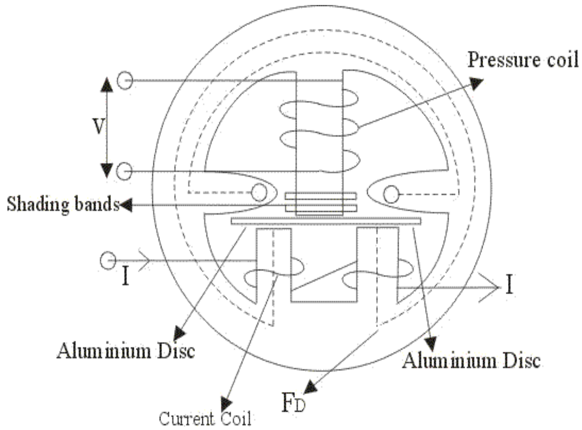
The angle between F_1 and F_2 is B. From the phasor diagram the angle between F_2 and I_1 is (90- B+A) and the angle between F_1 and I_2 is (90 + B + A). Thus we write the expression for deflecting torque as

$$T_{d1} = K \times F_2 \times I_1 \times cos(90 - B + A) = K \times F_1 \times F_2 \times \frac{f}{Z} cos(90 - B + A),$$

Similarly the expression for T_{d2} is

$$T_{d2} = K \times F_1 \times F_2 \times \frac{f}{Z} cos(90 + A + B)$$

,



The total torque is T_{d1} - T_{d2}, on substituting the value of T_{d1} and T_{d2} and simplifying the expression we get

$$T_{d1} - T_{d2} = K \times F_1 \times F_2 \times \frac{f}{Z} sin(B)cos(A),$$

Which is known as the general expression for the deflecting torque in the **induction type meters**. Now there are two types of induction meters and they arewritten as follows:

- Single phase type
- Three phase type induction meters.

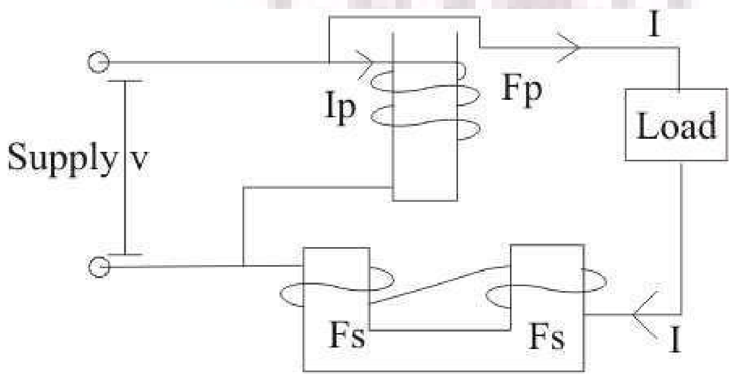
Here we are going to discuss about the single phase induction type in detail. Givenbelow is the picture of single phase induction type meter.

Single phase induction type energy meter consists of four important systems whichare written as follows:

Driving System: Driving system consists of two electromagnets on which pressure coil and current coils are wounded, as shown above in the diagram. The coil which consisted of load current is called current coil while coil which is in parallel with the supply voltage (i.e. voltage across the coil is same as the supply voltage) is called pressure coil. Shading bands are wounded on as shown above in the diagram so as to make angle between the flux and and applied voltage equal to 90 degrees. Moving System: In order to reduce friction to greater extent floating shaft energy meter is used, the friction is reduced to greater extinct because the rotating disc which is made up of very light material like alumini umis not in contact with any of the surface. It floats in the air. One question must be arise in our mind is that how the aluminium disc float in the air? To answer this question we need to see the constructional details of this special disc, actually it consists of small magnets on both upper and lower surfaces. The upper magnet is attracted to an electromagnet in upper bearing while the lower surface magnet also attracts towards the lower bearing magnet, hence due to these opposite forces the light rotating aluminium disc floats.

Braking System: A permanent magnet is used to produce breaking torque in single phase induction energy meters which are positioned near the corner of the aluminium disc.

Counting System: Numbers marked on the meter are proportion to the revolutionsmade by the aluminium disc, the main function of this system is to record the number of revolutions made by the aluminium disc. Now let us look at the working operation of the single phase induction meter. In order to understand the working of this meter let us consider the diagram given below:



Here we have assumed that the pressure coil is highly inductive in nature and consists of very large number of turns. The current flowin in the pressure coil is I_p which lags behind voltage by an angle of 90 degrees. This current produces flux F. F is divided into two parts F_g and F_p.

1. F_g which moves on the small reluctance part across the side gaps.
2. F_p: It is responsible for the production of driving torque in the aluminium disc. It moves from high reluctance path and is in phase with the current in the pressure coil. F_p is alternating in nature and thus emf E_p and current I_p. The load current which is shown in the above diagram is flowing through the current coil produces flux in the aluminium disc, and due this alternating flux there on the metallic disc, an eddy current is produced which interacts with the flux F_p which results in production of torque. As we have two poles, thus two torques are produced which are opposite to each other. Hence from the theory of induction meter that we have discussed already above the net torque is the difference of the two torques.

Advantages of Induction Type Meters

Following are the advantages of induction type meters:

1. They are inexpensive as compared to moving iron type instruments.
2. They have high torque is to weight ratio as compared to other instruments.
3. They retain their accuracy over wide range of temperature as well as loads.

THREE PHASE ENERGY METER

Introduction

It is well established that for measurement of total power or energy in a n-conductor system, it is required to use a meter with (n-1) elements. The principle of single phase energy meter can as well be extended to obtain a poly-phase energy meter, in particular a three phase energy meter. Usually, a three phase energy meter is available as a 2-element meter or 3-element meter, each element being similar in construction to the single phase meter and all elements mounted on a common shaft. The torque developed by each element is summed up mechanically and the total number of revolutions made by the shaft is proportional to the total three phaseenergy consumption.

Construction, Operation and Testing

In a two-element, three phase energy meter the two discs are mounted on a common spindle and each disc has its own brake magnet. The moving system drives a single gear train. Each unit is provided with its own copper shading ring, shading band, friction compensator, etc., for adjustments to be made to obtain the correct reading.

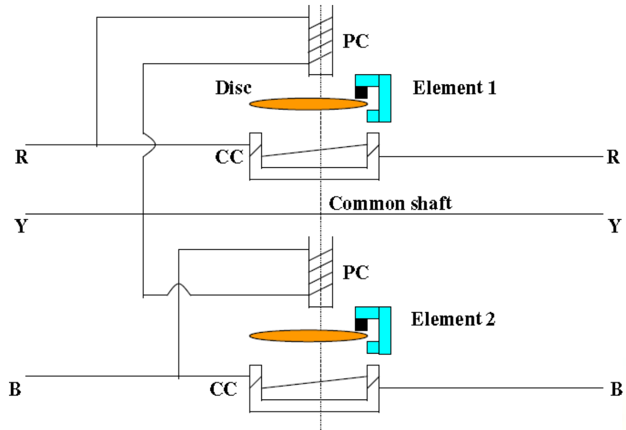


Figure 8.7 Three Phase Energy Meter

A two element energy meter used for three phase energy measurements in three phase three wire systems, is schematically shown in figure 8.7. It is needful that forthe same power/ energy, the driving torque should be equal in the two elements. This is checked by torque adjustment. For torque adjustment, the two current coils are connected in series opposition and the two potential coils are connected in parallel. Full load current is allowed to pass through the current coil. This set up causes the two torques to be in opposition and so, if the torques are equal, then the disc should not move. If there is any slight motion indicating inequality of the two torques, then the magnetic shunt is adjusted until the disc stalls. Thus the torque balancing is obtained beforetesting the meter. The friction compensator and brake magnet positions are adjusted to each of the two/three elements separately, treating each of them as a single phase element on single phase AC supply. The calibrationof three phase meter can also be performed in a similar manner, as that described earlier, for single phase energymeters.

ERRORS IN ENERGY METERS

The energy measurements by energy meters involve errors owing to manysources and reasons as follows:

1. **Errors in driving system** include errors due to incorrect magnitude of fluxvalues, phase angles, etc. and lack of symmetry in magnetic circuit.

2 **Errors in braking system** such as changes in the strength of brake magnet, changes in disc resistance, self braking effect of series magnet flux and abnormal friction of the moving parts. 3 Errors in registering system are also expected to be present since they involve mechanical parts. They are taken care of by calibration of the meter.

4 errors caused due to friction, overloads, phase angle variations, temperature effects, creeping of the meter, etc. These errors are avoided by correct adjustments made usingthe various compensator facility provided on the meter.

Adjustments

Full Load UPF Adjustment: The potential coil is connected across rated supply voltage and rated full load current at unity power factor is passed through the current coil. The brake magnet position is adjusted to vary the braking torque so that the moving system moves at correct speed.

Lag or LPF adjustment: It is clear from equation (8.10) that the energy meter will register correct value only if the angle between the shunt magnet flux, f P and the supply voltage, V is 900 (D = 900). Hence the pressure coil should be designed to be highly inductive. Also, various lag adjustment devices are made useof for this purpose. For LPF adjustments, the pressure coil is connected across the rated supply voltage and rated full load current at 0.5 lagging power factor is passed through the current coil. The lag device is adjusted until the meter runs at true speed.

Light Load UPF Adjustment: Firstly, full load UPF and LPF adjustments are made on the meter until it runs at correct speed. Then rated supply voltage is applied across the pressure coil and a very low current of 5-10 % of full load valueis passed through the meter at unity power factor. The light load adjustment is doneso that the meter runs at proper speed.

Creep Adjustment: Firstly, full load UPF and light load adjustments are made forcorrect speeds at both the loads and the performance is rechecked at0.5 power factor. Then, as a final check on all the above adjustments, the pressure coil is excited by 110 % of the rated voltage with zero load current. If the light load adjustment is proper, the meter should not creep under these conditions. If the error still persists, then all the above adjustments are carried out once again

Phantom Loading

In the energy meter testing, the actual registration of energy (by the meter) is verified against known standard values at various loads and power factors. The energy meter testing helps in providing suitable adjustments in the meter so as to reduce errors. The actual registration is verified under the following test conditions.

At rated voltage, 5% of rated current and unity power factor.

At rated voltage, 125% of rated current and unity power

factor. At rated voltage, rated current, and 0.5 lagging power

factor. At rated voltage, 50% of rated current and unity power

factor.

At rated voltage, 0.5% of rated current and unity power factor. This test is called starting test. Since, at this small load also, the disc should start rotating, Of course, accuracy is not the criteria in this test.

At 110% of rated voltage and open-circuited current coil. This test is called as creep test. The disc should not creep (or rotate) under this test conditions.

In order to test high capacity energy meters for the above conditions, tremendous loss of power will occur. Hence, to reduce wastage of power, phantom loading is used for testing the energy meter.

Phantom Loading :

Phantom loading is a fictitious loading that resembles the actual full-load conditions. The main advantage of testing a meter under phantom loading conditions over direct loading one is that the power or energy consumption is comparatively too small.

Phantom Loading in Energy Meter

As shown in the figure above, the pressure coil (or the shunt winding) is energized with its rated voltage and the current coil (or the series winding) is energized by a low voltage supply. The impedance of the current coil circuit is quite small. So for the rated amount of current also, the power consumption will be small. Although the impedance of the pressure coil is high, the current through it is very small.

Hence, the power consumed in the pressure coil will also be small. Therefore, the overall power or energy dissipation during the testing period will be small. For this reason, phantom loading is considered to be the most economical one for testing purposes.

Trivector meter

Trivector meter is an energy meter which accurately measures all the parameters of supply such as voltage, current, power factor, active load, reactive load, apparent load etc., now a days static electronic meters are used for commercial and industrial applications. These electronic meters use micro controllers with their own programming language.

Trivector meter gets the input supply to be measured using CT/PTs. That is current input from Current Transformers and voltage input from Potential Transformers connected in the circuit. It is a true four quadrant measuring instrument. LCD display with annunciators for showing various critical events is used.

Principle of Operation:

The principle of operation of trivector energy meter is explained with the help of block diagram.

It mainly consists of the following units.

- Energy measuring unit: voltage sampling, current sampling, measuring integrated circuit

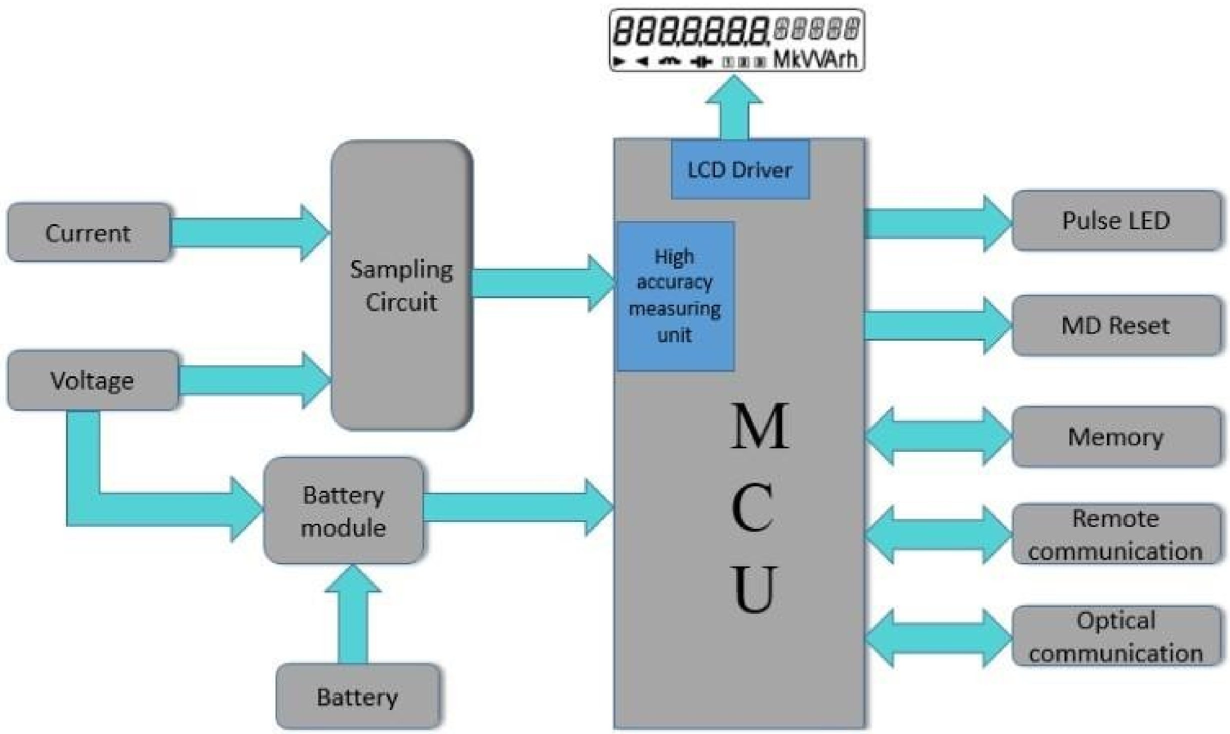
An analogue to digital converter is used to sample voltage and current relative to incoming waveform. For getting accurate results the sampling rate should be high.

- **Data processing unit:** Micro Controller Unit [MCU], Memory storage cards

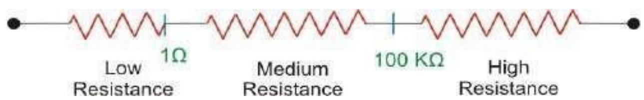
Very highly reliable Read Only Memory [ROM] is used to retain the data for so many years even if there is no power.

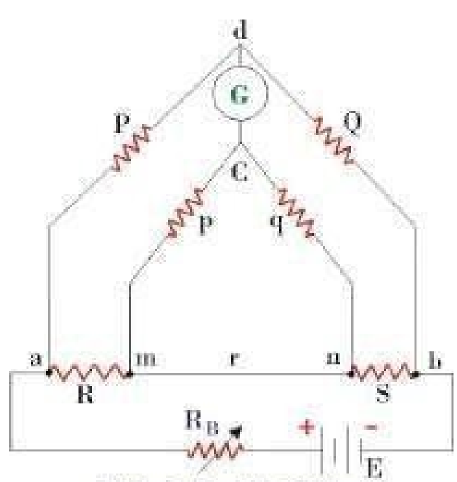
- **Power supply unit:** AC power supply, battery
- **Input/output unit:** LCD display, Optical communication, RJ11 port for Remote communication

Data from ROM can either be displayed on the meter LCD or communicated via an optical communication port/RJ11 port on to a hand-held Meter Reading Instrument [MRI].



Block Diagram of Trivector Meter





Kelvin Double Bridge