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Measurement of Energy and Industrial Metering.

Energy is the total power delivered / consumed over a time interval, that is

energy = power × time

Electrical energy developed as work or dissipated as heat may be expressed as

$$W = \int_0^t v \cdot i \cdot dt$$

If v is expressed as V, i in A, t in sec, the unit of energy is joule or watt-sec which is 1 Watt over an interval of one second. If the unit of time is taken as hour, then energy is then expressed as watt hours.

Energy Meters for AC circuits

Induction type of energy meters are universally used for measurement of energy in domestic and industrial ac circuits.

Induction type of meters possess lower friction & higher torque / weight ratio.

Induction type meters are inexpensive, accurate and retain their accuracy over a wide range of loads and temperature conditions.

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Single Phase Induction Type Watt-hour Meter

Operating mechanism has four main parts

- driving system
- Moving System
- Braking System
- Registering system

a) Driving System

The driving system of the meter consists of two electromagnets. The core of these electromagnets is made up of silicon steel laminations. The coil of one of the electromagnets is excited by the load current. This coil is called current coil.

The coil of second electromagnet is connected across the supply, and, therefore carries a current proportional to the supply voltage. This coil is called pressure coil. consequently the two electromagnets are called series and shunt magnets, resp.

Copper shading bands are provided on the central limb. The position of these bands is adjustable. The function of these bands is to bring the flux produced by the shunt magnet exactly in quadrature with the applied voltage.

b) Moving System

This consists of an aluminium disc mounted on a light alloy shaft. This disc is positioned

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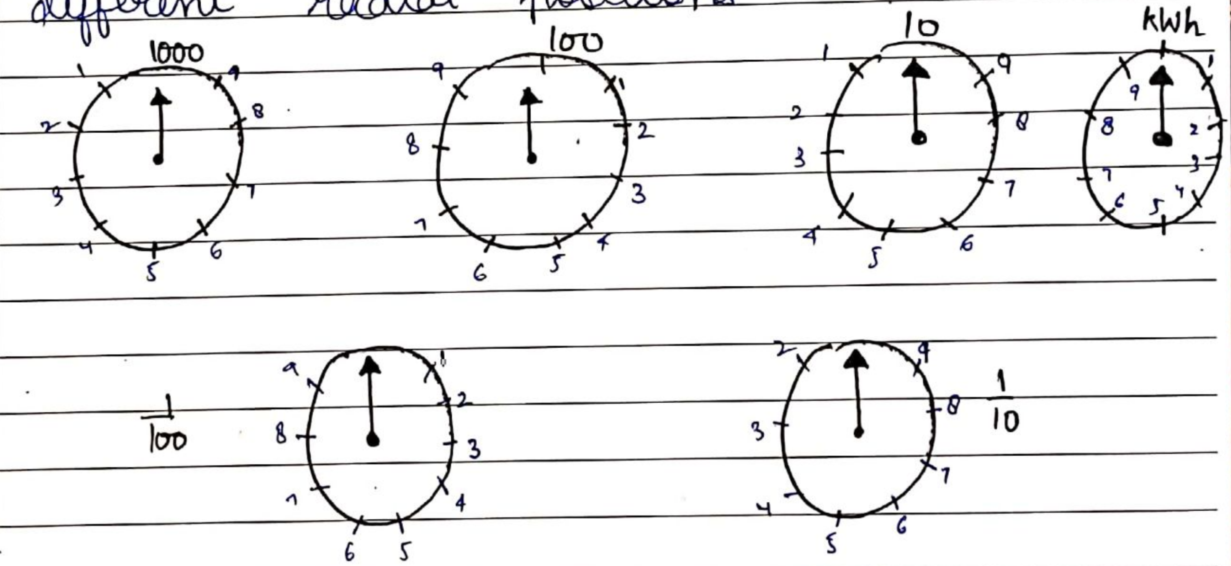
in the air gap between series and shunt magnet.
The upper bearing of the rotor (moving system) is a steel pin located in a hole in the bearing cap fixed to the top of the shaft. The rotor runs on a hardened steel pivot, screwed to the foot of the shaft. The pivot is supported by a jewel bearing. A pinion engages the shaft with the counting / registering mechanism.

c) Braking System
A permanent magnet positioned near the edge of the aluminium disc forms the braking system. The aluminium disc moves in the field of this magnet and thus provides a braking torque. The position of the permanent magnet is adjustable, and, therefore braking torque can be adjusted by shifting the position of the permanent magnet to different radial positions.



Pointer type of register

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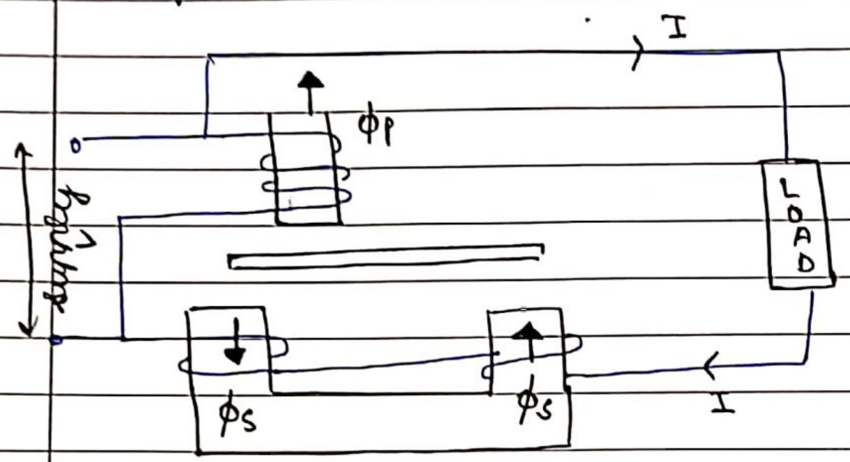
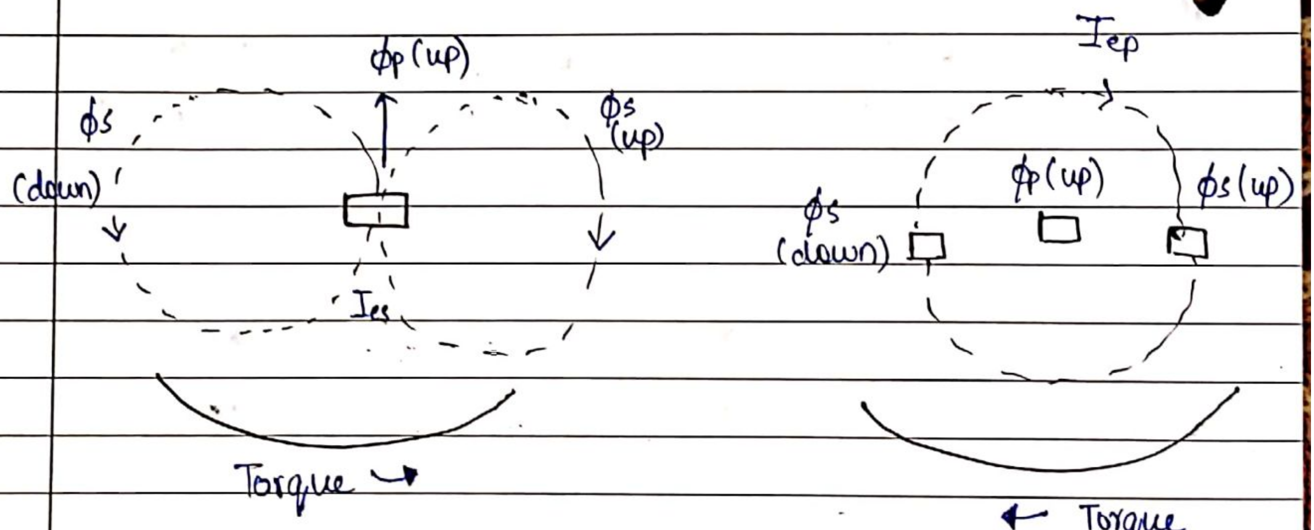
d) Registering (Counting Mechanism) The function of registering / counting mechanism is to record continously a number which is proportional to the revolutions made by the moving system. By a suitable system, a train of reduction gears, the pinion on the rotor shaft drives a series of five / six pointers.
These rotate on round dials which are marked with ten equal divisions.

Theory and Operation





Working of a single phase induction type energy meter.

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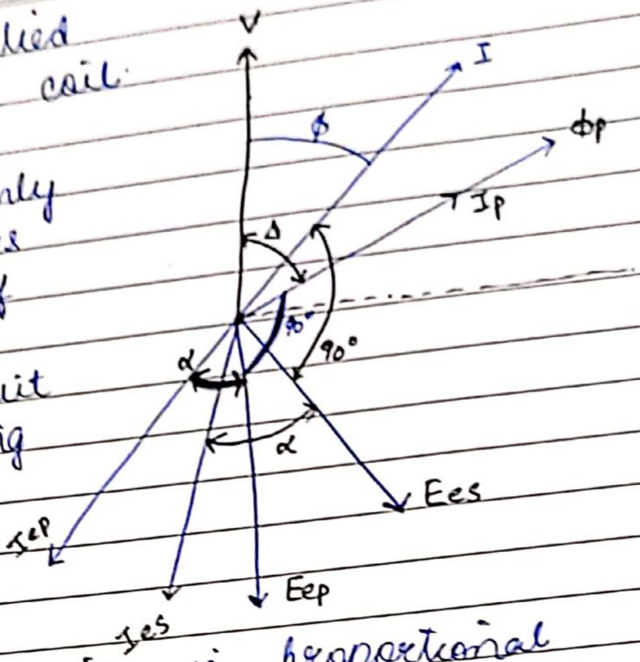
- Supply voltage is applied across the pressure coil.



- Pressure coil is highly inductive as it has very large number of turns & reluctance of its magnetic circuit is very small owing to presence of air gaps of very small length.

- I_p through pressure coil is proportional to the supply voltage and lags it by a few degrees less than 90°. This is because the winding has small resistance and there are iron losses in the magnetic circuit.

- Current I_p produces a flux ϕ_{pt}. This flux divides itself into two parts — ϕ_g and ϕ_p. The major portion ϕ_g flows across the side gaps as reluctance of this path is small.

- The reluctance of the path of flux ϕ_p is large and hence magnitude is small. This flux ϕ_p goes across aluminium disc and hence is responsible for production of driving torque.

- Flux ϕ_p is in phase with current I_p &

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is proportional to it. ∴ $\phi_p \propto$ voltage V and lags it by an angle a few degrees less than 90°.

- Since ϕ_p is alternating in nature, it induces an eddy emf in disc which in turn produces eddy current, I_{ep}.

- The load current I flows through the current coil and produces a flux ϕ_s.

- This flux is proportional to load current & is in phase with it. This flux produces eddy current I_{es} in the disc.

- Now eddy current I_{es} interacts with flux ϕ_p to produce a torque & eddy current I_{ep} interacts with ϕ_s to produce another torque.

- These torques are in the opposite direction and net torque is the difference of these.

let V = applied voltage.
I = load current.
ϕ = phase angle of load.
I_p = pressure coil current
Z = impedance of eddy current path
Δ = phase angle b/w supply voltage and pressure coil flux.
f = frequency

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E_{ep} = eddy emf induced by flux ϕ_p.
I_{ep} = eddy current due to flux ϕ_p.

E_{es} : eddy emf induced by flux ϕ_s.
I_{es} : eddy current due to flux ϕ_s.
α = phase angle of eddy current path

Net driving torque

$$T_d \propto \phi_1 \phi_2 \frac{f}{Z} \sin\beta \cos\alpha$$

$$= K_1 \phi_1 \phi_2 \frac{f}{Z} \sin\beta \cos\alpha$$

K_1 = constant.
β = phase angle b/w fluxes ϕ_1 and ϕ_2

In our case, ϕ are ϕ_p, ϕ_s.

$\therefore$ β = phase angle between ϕ_p and ϕ_s
$= \Delta - \phi$

$\therefore$ Driving torque, $T_d = K_1 \phi_p \phi_s \frac{f}{Z} \sin(\Delta - \phi) \cos\alpha$

But $\phi_p \propto V$. $\phi_s \propto I$

$\therefore$ $T_d = K_2 V I \frac{f}{Z} \sin(\Delta - \phi) \cos\alpha$

If f, Z and α are constant,

$T_d = K_3 VI \sin(\Delta - \phi)$

If N is the steady speed, braking torque
$T_B = K_4 N$.

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At steady speed, $T_d = T_B$

$\therefore K_4 N = K_3 VI \sin(\Delta - \phi)$.

$N = K \cdot VI \sin(\Delta - \phi)$

If $\Delta = 90^\circ$: $N = KVI \sin(90 - \phi)$

$\therefore N = KVI \cos\phi$

$\therefore N = K \times (\text{power})$

$\therefore$ To make speed of rotation $\propto$ power Δ should be 90°.

$\therefore$ ϕ_p must be made to lag supply voltage by 90°.

Total no' of revolutions $= \int N \cdot dt$

$= K \int VI \sin(\Delta - \phi)\, dt$

If $\Delta = 90^\circ$, Total no' of revolutions

$= K \int (VI\cos\phi)\, dt$

$= K \int (\text{power})\, dt$

$= K \times (\text{energy})$.

$\therefore$ Total no' of revolutions is a measure of the energy consumed directly.

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VArh Metering

i, Measurement of VArh is a means of charging bulk consumers for failing to maintain a high power factor.

ii, Required for measurement of VAh.

iii, Used as a record of operating conditions when there is an exchange of energy b/w two or more interconnected power stations

Total no' of revolutions made in a specified time $= K\int VI \sin(\Delta - \phi)\, dt$.

If $\Delta = 0°$ or $180°$ (by making additional quadrature shift) ~~then~~ ~~$\omega = 90°$~~

No' of revolutions $= K\int VI \sin(0 - \phi)\, dt$

$= K\int VI \sin\phi\, dt = K\int (VArh) \cdot dt$

$\therefore$ Induction type energy meter can be converted into reactive Volt-Ampere hour meter if pressure coil flux is brought in phase with the voltage.

ENERGY METER TESTING.

Testing includes the checking of actual registration of the meter as well as adjustment done to bring the error of the meter within prescribed limits.

AC METER TESTING.

1) At 5 % of marked current with upf.

(2) At 100 or 125 % of marked current with upf.

(3) At one Intermediate load with upf.

(4) At marked current and 0.5 lagging pf.

(5) Creep Test : With applied voltage of 110 % of its marked value of ~~currents~~ & circuit of current open, meter should not revolve through more than one revolution.

(6) Starting Test : At 0.5 % of unmarked value of current and normal voltage, the meter should start and run.

PHANTOM LOADING :

When current rating of a meter under test is high, a test with actual loading involves wastage of power.
To avoid this, phantom / fictious loading is done.

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Phantom loading consists of supplying the pressure circuit from a circuit of reqd normal voltage and the current circuit with a low voltage supply as the impedance of this circuit is very low.

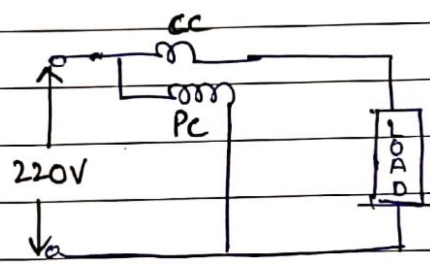
Thus total power supplied for the test is due to = small pressure coil current at normal voltage + circuit current supplied at low voltage.

Thus power supplied is small.

Q. 220V, 5A dc energy meter is tested at its marked ratings. Resistance of pressure circuit is 8800Ω & that of current coil is 0.1Ω. Calculate the power consumed when testing the meter with :

(i) direct loading
(ii) Phantom loading with current circuit excited by a 6V battery.

(i) Direct



Power in pressure ckt $= \frac{(220)^2}{8800}$

$= 5.5W$

Power consumed in current circuit $= 220 \times 5 = 1100W.$

$\therefore$ Total power consumed $= 5.5 + 1100 = 1105.5W.$

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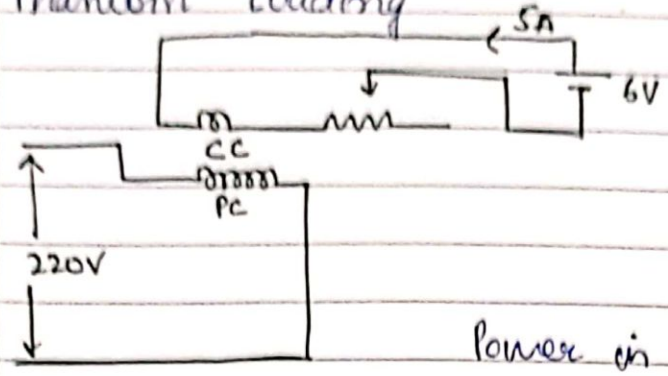
ii, Phantom Loading



Power consumed in pressure circuit

$$= \frac{(220)^2}{8800} = 5.5\,W$$

Power in current circuit $= 6 \times 5$

$= 30W$

Total power consumed $= 5.5 + 30 = 35.5W$.

This power consumption is considerably smaller than the direct loading.

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Power Measurement

D.C. power may be measured by a wattmeter or by an ammeter or voltmeter, the product of whose readings gives the power in the circuit.

In a.c. circuits,

instantaneous power $p = ei$

where e & i are instantaneous values of voltage & current.

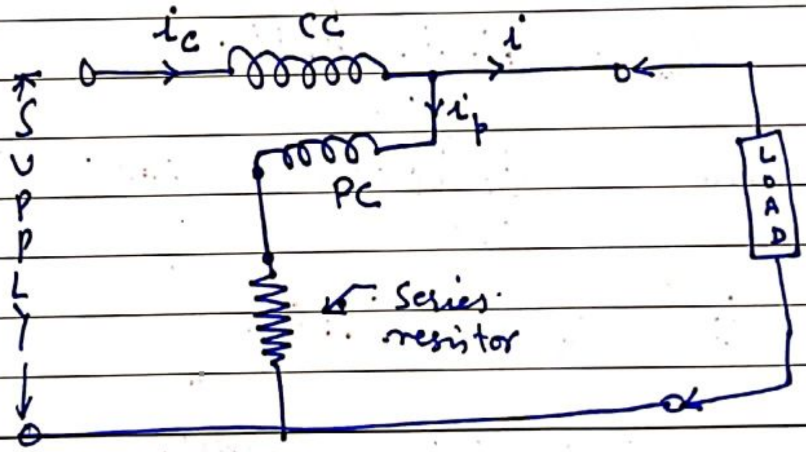
For sinusoidal voltage and current and a phase angle ϕ b/w them, the average power

$$\boxed{P = EI\cos\phi}$$

Where E & I are rms values of voltage & current.

Thus we have to use a wattmeter and use of voltmeter & ammeter only can not compute power in a.c. circuits.

Electrodynamometer type ~~instrument~~ principle is most commonly used wattmeter which has fixed and moving coils which react to the effect of current squared. The coils are connected in the form shown below:—



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The fixed or field coil carries the total line current i_c. The movable coil is located in the magnetic field of the fixed coil. A high resistance is connected in series with movable coil which limits the current i_p through it. The movable coil is also known as voltage or pressure coil. ~~The~~

$$i_p = \frac{e}{R_p}$$ where e = Inst voltage across the load & R_p is the total resistance of the movable coil & its series resistance.

The deflection of movable coil is proportional to the product of two currents i_c & i_p. Thus average deflection:

$$\theta_{av} = K \frac{1}{T} \int_0^T i_c i_p \, dt$$

$$i_c = i_p + i; \qquad ; \quad i_p = \frac{e}{R_p};$$

$$\theta_{av} = K \cdot \frac{1}{T} \int_0^T (i_p + i) \frac{e}{R_p} \cdot dt.$$

Since i_p is very small; $\therefore i_c \approx i$,

$$\theta_{av} = K' \cdot \frac{1}{T} \int_0^T ei\,dt.$$

now $\frac{1}{T}\int_0^T ei\,dt = P_{av} = EI\cos\phi$;

$$\therefore \boxed{\theta_{av} = K' EI\cos\theta}$$

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Deflection $\propto$ Power

Thus an electrodynamometer type inst indicates average power delivered to the load.

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The electrodynamometer wattmeter consumes some power for maintenance of its magnetic field but it is actually so small as compared to load power, that it may be neglected. However if a correct reading of the load power is required, the current coil should exactly carry the load current, and the potential coil should be connected across the load terminals.

Two configurations are possible.

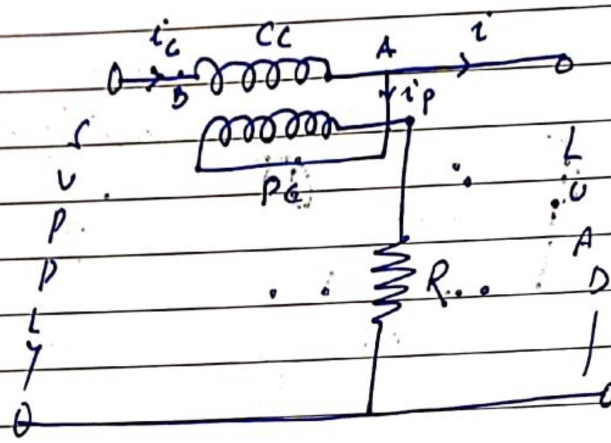

Fig (a)

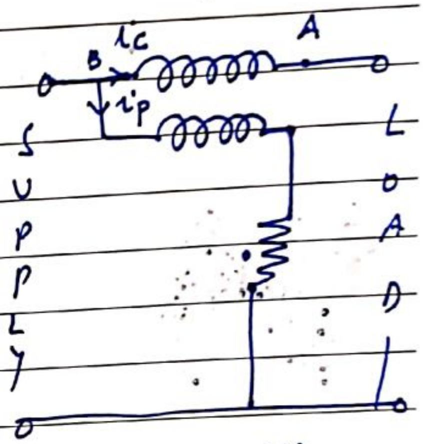

Fig (b).

Fig (a): The voltage is properly metered but the current coil carries ~~an extra~~ current which is higher than load current by i_p. ($i_c = i_p + i$); Thus wattmeter reading is higher by an amount of additional power loss in the voltage circuit.

Fig (b): The current is metered exactly but the voltage across pressure coil is higher than the load voltage by an amount of V.D in the current coil. Thus wattmeter reading is again higher by an amount of power loss in the C.C.

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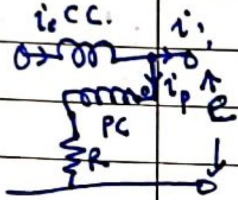
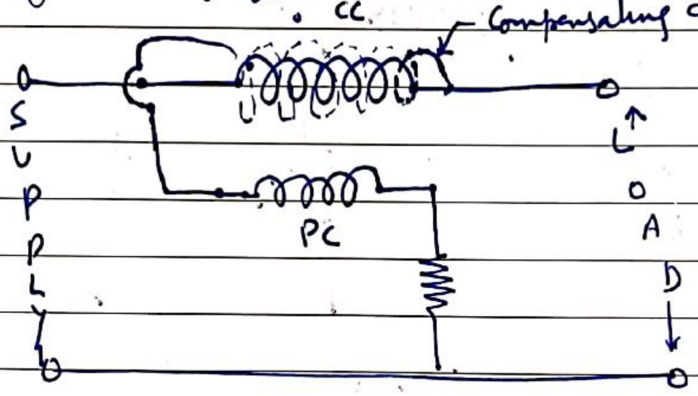
choice of connection depends the situation. Generally fig (a) is preferred for HCLV applications and fig (b) is preffered choice for HVLC applications.

However we can exactly measure load power by providing compensation to this increase reading.

Consider for configuration shown in fig (a).





The compensating coil is in series with the voltage coil ~~circuit~~ but in such a way that it produces magnetic effect that opposes the magnetic effect produced by current coil current. Thus neutralizes the voltage coil component of the current in the current coil.

Under no load, the deflection would be zero.

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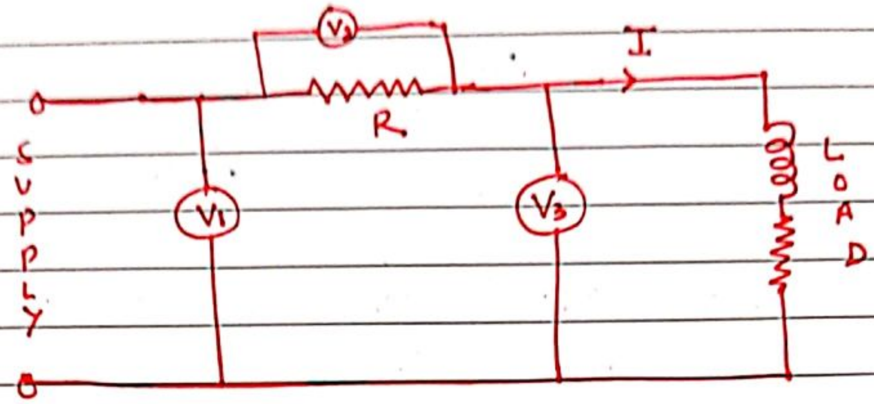
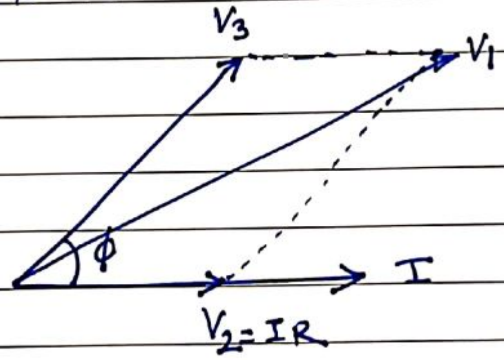
Measurement of power without using a wattmeter

(i) Three - voltmeter method



Three voltmeters V_1, V_2 and V_3 are connected as shown b/w supply & load. R is a non-inductive resistor connected in series with load.

$\vec{V_1} = \vec{V_2} + \vec{V_3}$



$$V_1^2 = V_2^2 + V_3^2 + 2V_2V_3\cos\phi$$

neglecting currents taken by voltmeters V_2 & V_3, R carries the same load current. Thus $V_2 = IR$.

$$\therefore V_1^2 = V_2^2 + V_3^2 + 2IRV_3\cos\phi$$
$$= V_2^2 + V_3^2 + 2R(V_3 I\cos\phi);$$

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Now $V_3 I\cos\phi$ = load power;

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$\therefore$ power in load $V_3 I \cos\phi = \dfrac{V_1^2 - V_2^2 - V_3^2}{2R}$

and power factor is given by

$$\boxed{\cos\phi = \frac{V_1^2 - V_2^2 - V_3^2}{2 V_2 V_3}}$$

Two assumption are made:— R Contains the same current as load current.
& Resistor is entirely non-inductive.

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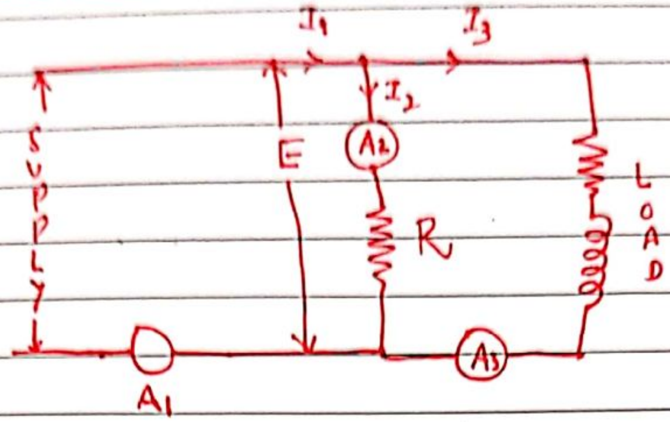
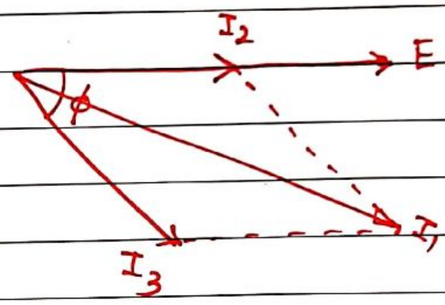
(iii) Three Ammeter method



The reading of Ammeter A_1 is the vector sum of readings of Ammeters A_2 & A_3.



R is a non inductive resistor through current I_2 flows which is in phase with voltage E.

From vector diagram; $I_1^2 = I_2^2 + I_3^2 + 2 I_2 I_3 \cos\phi$

but $I_2 = E/R$;

$$I_1^2 = I_2^2 + I_3^2 + 2 \cdot \frac{E}{R} I_3 \cos\phi;$$

$$= I_2^2 + I_3^2 + \frac{2}{R}(E I_3 \cos\phi);$$

Hence load power is $E I_3 \cos\phi = (I_1^2 - I_2^2 - I_3^2)\frac{R}{2}$

& p.f. $\cos\phi = \dfrac{I_1^2 - I_2^2 - I_3^2}{2 I_2 I_3}$

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Measurement of Power in three phase circuits (3-ϕ).

(A) using 1-ϕ wattmeter

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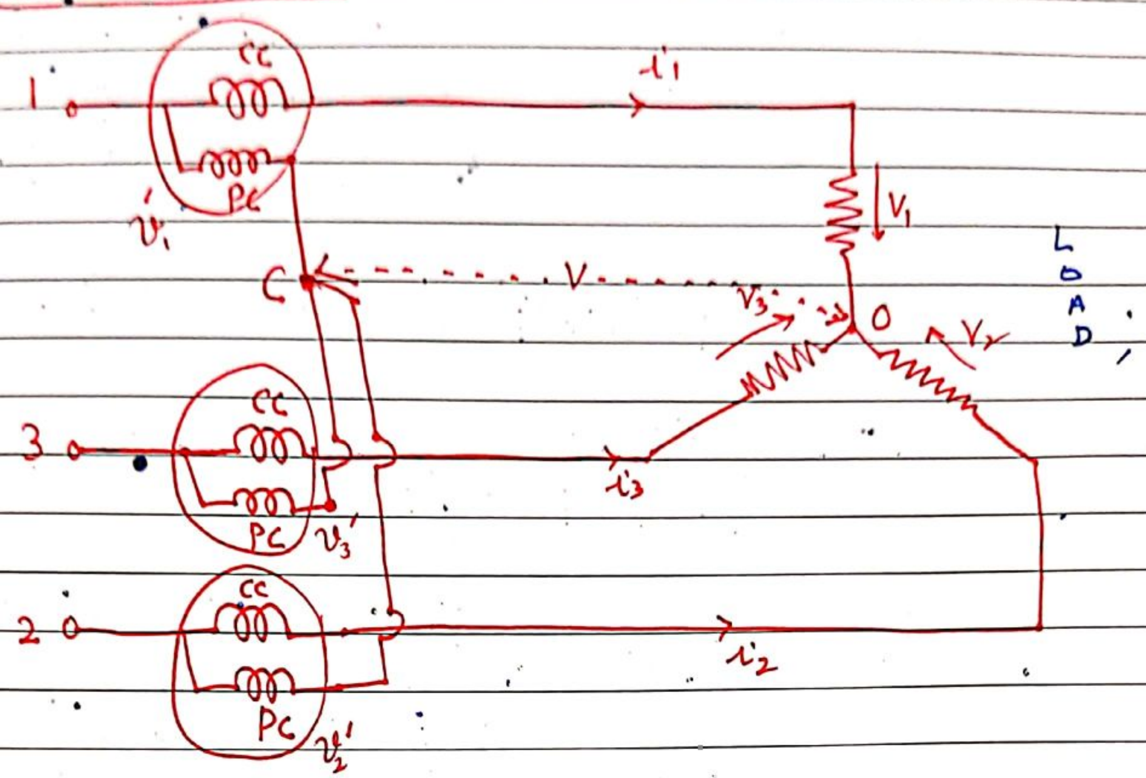

If a network is supplied through n conductors, the total power is measured by summing the readings of n wattmeters so arranged that a current element of a wattmeter is in each line and the corresponding voltage element is connected between that line and a common point. If the common point is located on one of the lines, then the power may be measured by $(n-1)$ wattmeters.

Consider a Y- connected 3-phase load supplied from a 3-ϕ supply with wattmeters connect in each line. The common point of pressure coils is at C which is different from the potential at O by [V].

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Total instantaneous power in the load

$$p = v_1 i_1 + v_2 i_2 + v_3 i_3$$

Now reading of wattmeter 1, $p_1 = v_1' i_1$

" " " 2, $p_2 = v_2' i_2$

" " " 3, $p_3 = v_3' i_3$;

Now $v_1 = v + v_1'$, $v_2 = v + v_2'$. $v_3 = v + v_3'$

Also;

$\therefore p_1 = (v_1 - v) i_1$, $p_2 = (v_2 - v) i_2$; $p_3 = (v_3 - v) i_3$

$\therefore p_1 + p_2 + p_3 = v_1 i_1 - v i + v_2 i_2 - v i_2 + v_3 i_3 - v i_3$

$= v_1 i_1 + v_2 i_2 + v_3 i_3 - v(i_1 + i_2 + i_3)$.

now $v_1 i_1 + v_2 i_2 + v_3 i_3$

Thus sum of three wattmeters is nothing but three phase power.

$p_1 + p_2 + p_3 =$ 3-ϕ power $=$

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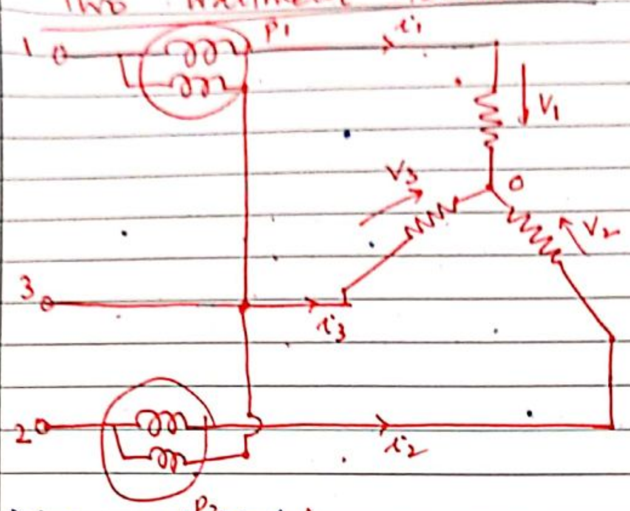
Two wattmeter Method



Y-Connected Load.

Reading of wattmeter 1, $p_1 = i_1(V_1 - V_3)$.

" " 2 $p_2 = i_2(V_2 - V_3)$.

Sum of wattmeter readings $S = p_1 + p_2$

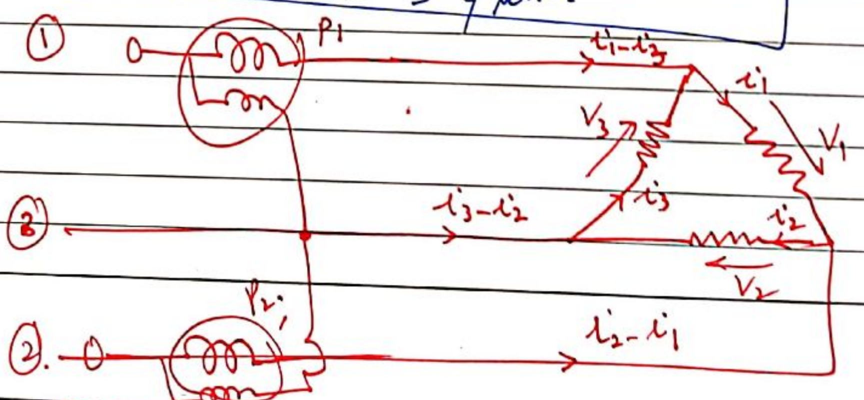
$= i_1V_1 - i_1V_3 + i_2V_2 - i_2V_3$

$= V_1i_1 + V_2i_2 - V_3(i_1 + i_2)$.

KCL at 0 $\rightarrow$ $i_1 + i_2 + i_3 = 0$. $\therefore i_1 + i_2 = -i_3$,

$$\boxed{S = P_1 + P_2 = V_1 i_1 + V_2 i_2 + V_3 i_3 = 3\text{-}\phi \text{ power}}$$

Δ-Connected Load.



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For Δ connected load :

$$P_1 = (i_1 - i_3)(-V_3)$$

$$P_2 = (i_2 - i_1)(V_2)$$

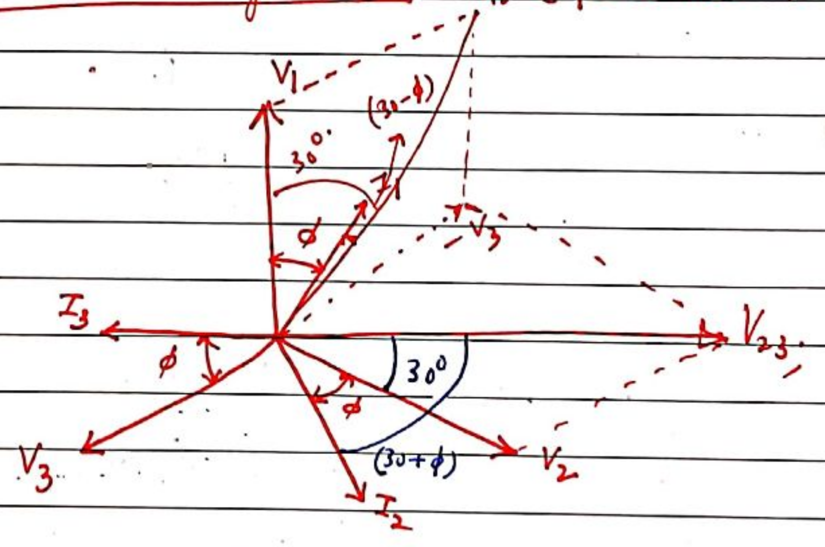
Sum $P_1 + P_2 = -i_1 V_3 + i_3 V_3 + i_2 V_2 - i_1 V_2$

$$= -i_1(V_2 + V_3) + V_2 i_2 + V_3 i_3 ;$$

KVL in loop = $V_1 + V_2 + V_3 = 0 \quad \therefore V_2 + V_3 = -V_1$

$$\therefore \boxed{P_1 + P_2 = V_1 i_1 + V_2 i_2 + V_3 i_3 = \text{3-phase power}}$$

3-phase Balanced System



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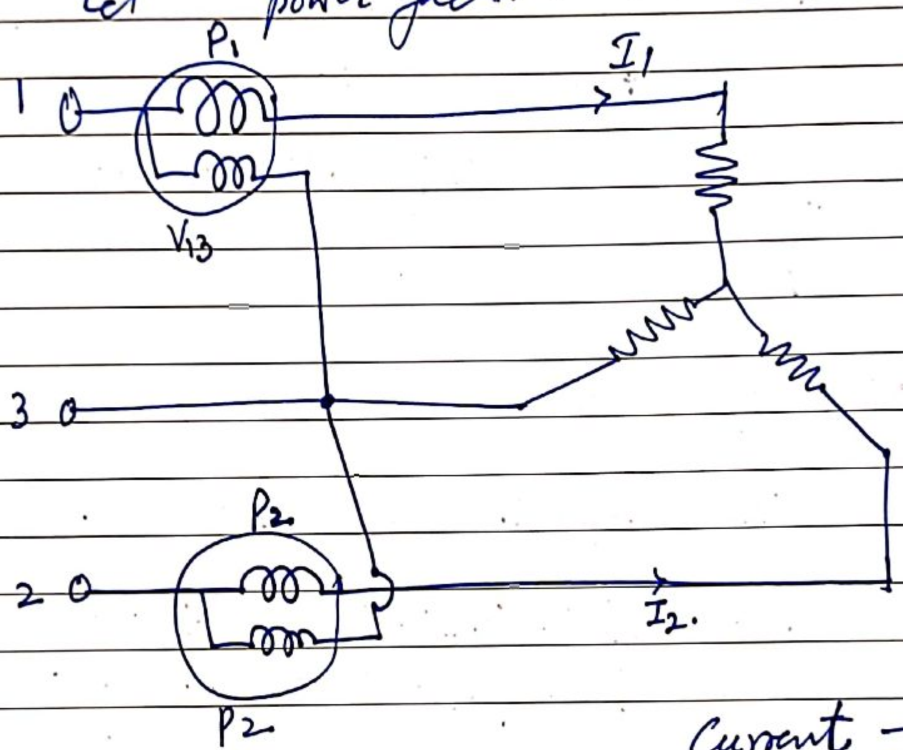
Let $V_1 = V_2 = V_3 = V$ (rms phase voltage).

$I_1 = I_2 = I_3 = I$ (rms phase current).

$V_{13} = V_{23} = V_{12} = \sqrt{3}V$ line voltages.

~~Sp~~ — line current is same as phase current for Y-connection.

Let power factor = $\cos\phi$;



Reading of wattmeter 1 → Current — I_1; voltage — V_{13}. $\angle$ b/w $I_1, V_{13} = 30 - \phi$;

$$P_1 = V_{13} I_1 \cos(30 - \phi)$$

$$P_1 = \sqrt{3} V I \cos(30 - \phi).$$

Reading of wattmeter 2 ⟶ Current — I_2; Voltage — V_{23}; $\angle$ b/w I_2 & V_{23} → $30 - \phi$).

$$P_2 = V_{23} I_2 \cos(30 + \phi)$$

$$= \sqrt{3} V I \cos(30 + \phi).$$

Now $P_1 + P_2 = \sqrt{3}VI\left[\cos(30-\phi) + \cos(30+\phi)\right]$

$= 3VI\cos\phi$; = 3-ϕ power.

Power factor:

Similarly $P_1 - P_2 = \sqrt{3}VI\left[\cos(30-\phi) - \cos(30+\phi)\right]$

$= \sqrt{3}VI\sin\phi$;

$$\therefore \frac{P_1 - P_2}{P_1 + P_2} = \frac{\sqrt{3}VI\sin\phi}{3VI\cos\phi} = \frac{\tan\phi}{\sqrt{3}};$$

$$\therefore \boxed{\phi = \tan^{-1}\sqrt{3}\left(\frac{P_1 - P_2}{P_1 + P_2}\right)}$$

Effect of Power factor upon readings of wattmeter.

(i) with p.f = 1.0, $\cos\phi = 1$; $\phi = 0°$;

$P_1 = \sqrt{3}VI\cos(30+\phi) = \frac{3}{2}VI$

$P_2 = \sqrt{3}VI\cos(30-\phi) = \frac{3}{2}VI$.

Total 3-ϕ power $\boxed{P = 3VI}$; at unity p.f.

(ii) When p.f = 0.5; $\phi = 60°$;

$P_1 = \sqrt{3}VI\cos(30-60) = \frac{3}{2}VI$;

$P_2 = \sqrt{3}VI\cos(30+60°) = $ zero;

Total power $P = \frac{3}{2}VI + \text{zero} = \frac{3}{2}VI$;

now 3-ϕ power $= 3VI\cos\phi = \frac{3}{2}VI$;

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(8) When $p.f = 0$; $\phi = 90°$,

$P_1 = \sqrt{3}\ VI \cos(30+90°) = \frac{\sqrt{3}}{2} VI$;

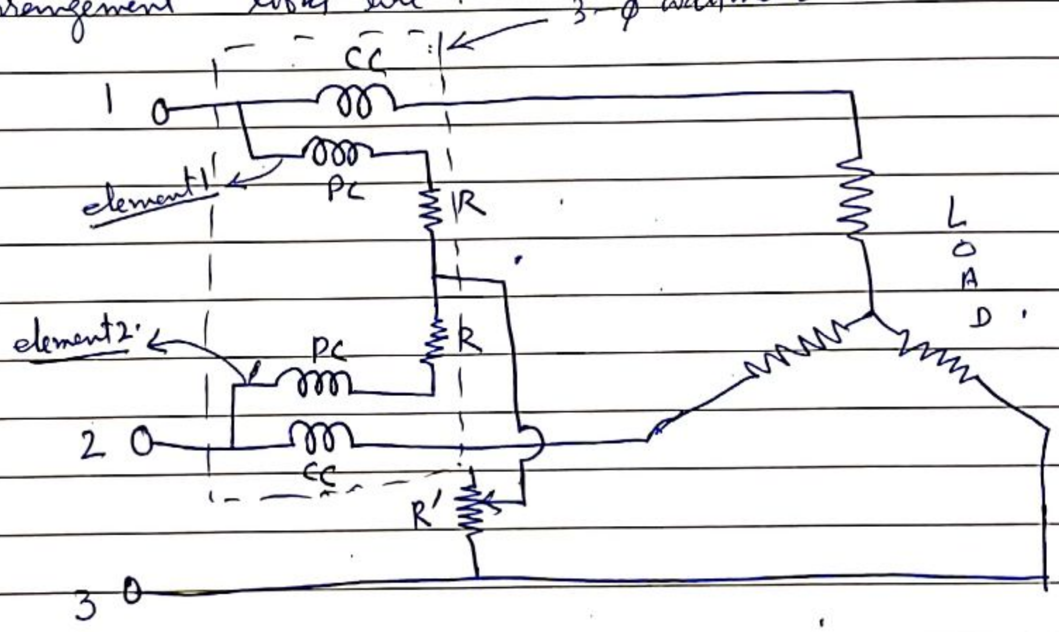
$P_2 = \sqrt{3}\ VI \cos(30-90°) = -\frac{\sqrt{3}}{2} VI$;

Total power $P = P_1 + P_2 =$ zero.

Readings of two wattmeters are same but of opposite sign. Total 3-ϕ power is zero.

Three phase wattmeter

The dynamometer type three phase wattmeter consists of two seperate wattmeter moments mounted together in one case on the same spindle. The arrangement looks like :-



The connections of 2 elements of a 3-ϕ wattmeter are the same as that for two wattmeter method using single phase wattmeter. The torque on each element is proportional to the power being measured by it. The total torque deflecting the moving system is the sum of the deflecting torques of two elements.

Deflecting torque of element 1 $\propto P_1$

" " " " 2 $\propto P_2$

Total deflecting torque $\propto (P_1 + P_2) \propto P$ (3-ϕ power).

In order that a 3-ϕ wattmeter reads correctly, there should not be any mutual interference b/w the two elements. A laminated iron shield may be ~~used~~ placed b/w the elements to eliminate the mutual effect. Compensation for mutual effects may be done by Weston's method. Resistance R' may be adjusted to compensate for errors caused by mutual interference.

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Measurement of Reactive power :-

Reactive power is, $Q = VI \sin\phi$

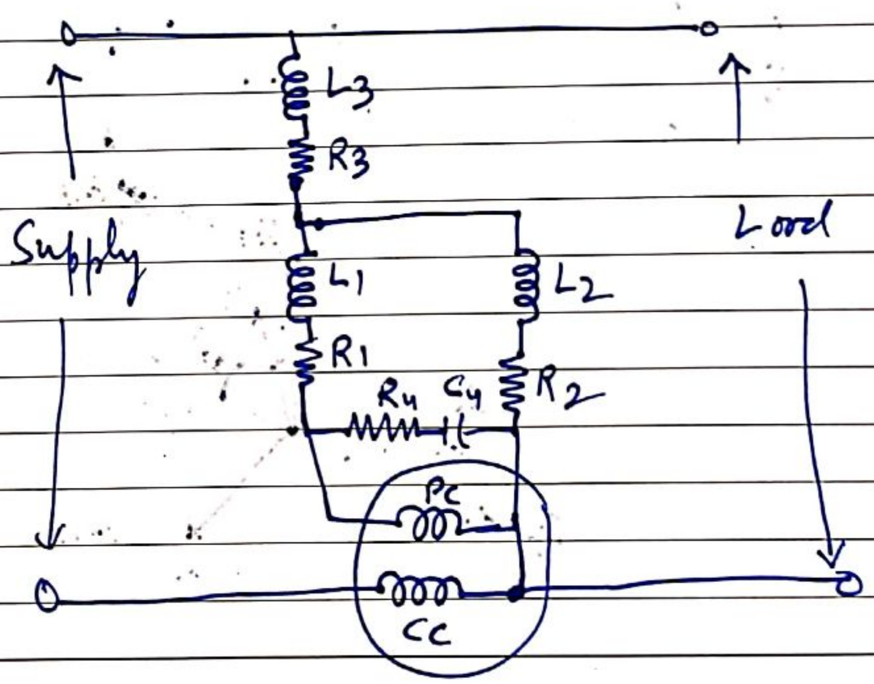
The apparent power is VI which determines the line and generator capacity. The value of apparent power is determined by.

$$VI = \sqrt{P^2 + Q^2}$$

$P = VI\cos\phi$
$Q = VI \sin\theta$.
sq + add.

Single phase VAR Meter

This is the same electrodynamometer wattmeter in whose pressure coil circuit a large inductive reactance is substituted for the series resistance. so that the pressure coil current is in quadrature with the voltage.



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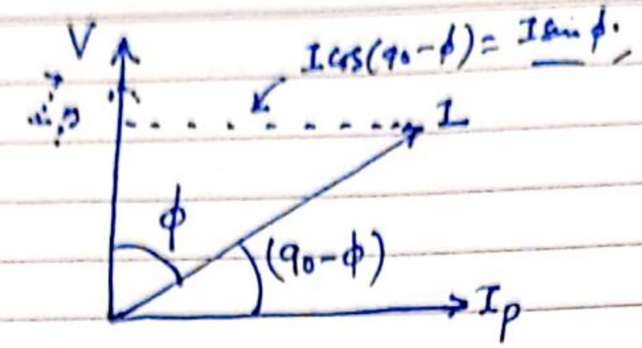
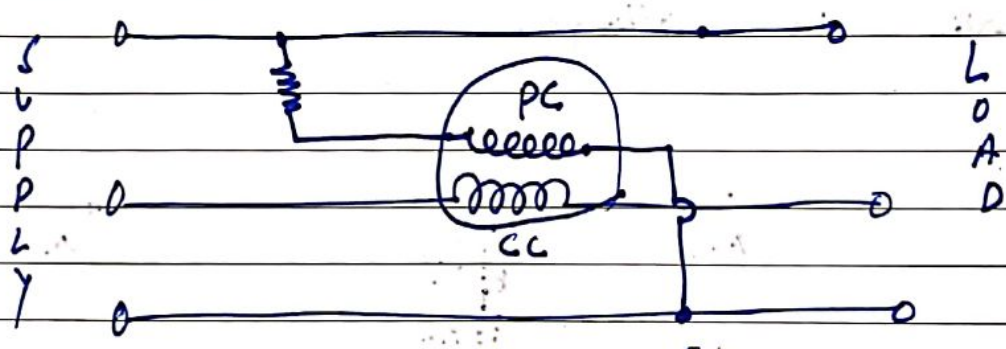
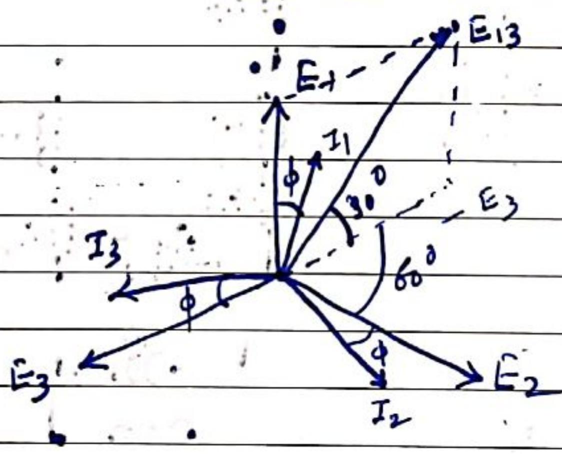


under these conditions the wattmeter again reads $VI\cos(90-\phi) = VI\sin\phi$ = reactive power.

Three phase VAR Meter :-

a) Making use of a wattmeter (1-φ).





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The single phase wattmeter is connected as shown with current coil in line 2 and pressure coil across lines 1 & 3.

Current in the current coil = I_2

voltage across press. coil = $E_{13} = E_1 - E_3$;

angle b/w E_{13} and I_2 = $30+60+\phi = (90+\phi)$

$\therefore$ Wattmeter reading $= I_2 E_{13} \cos(90+\phi)$

$= -\sqrt{3} E I \sin\phi$;

$= -W_r$.

Now 3-phase reactive power $= 3 E I \sin\phi$

$= 3 \times \frac{W_r}{\sqrt{3}}$

$$\boxed{3\text{-}\phi \ VAR = \sqrt{3} W_r}$$

Let W is Total active power (3-ϕ);

$$\boxed{p.f = \tan^{-1} \frac{\sqrt{3} W_r}{W}}$$

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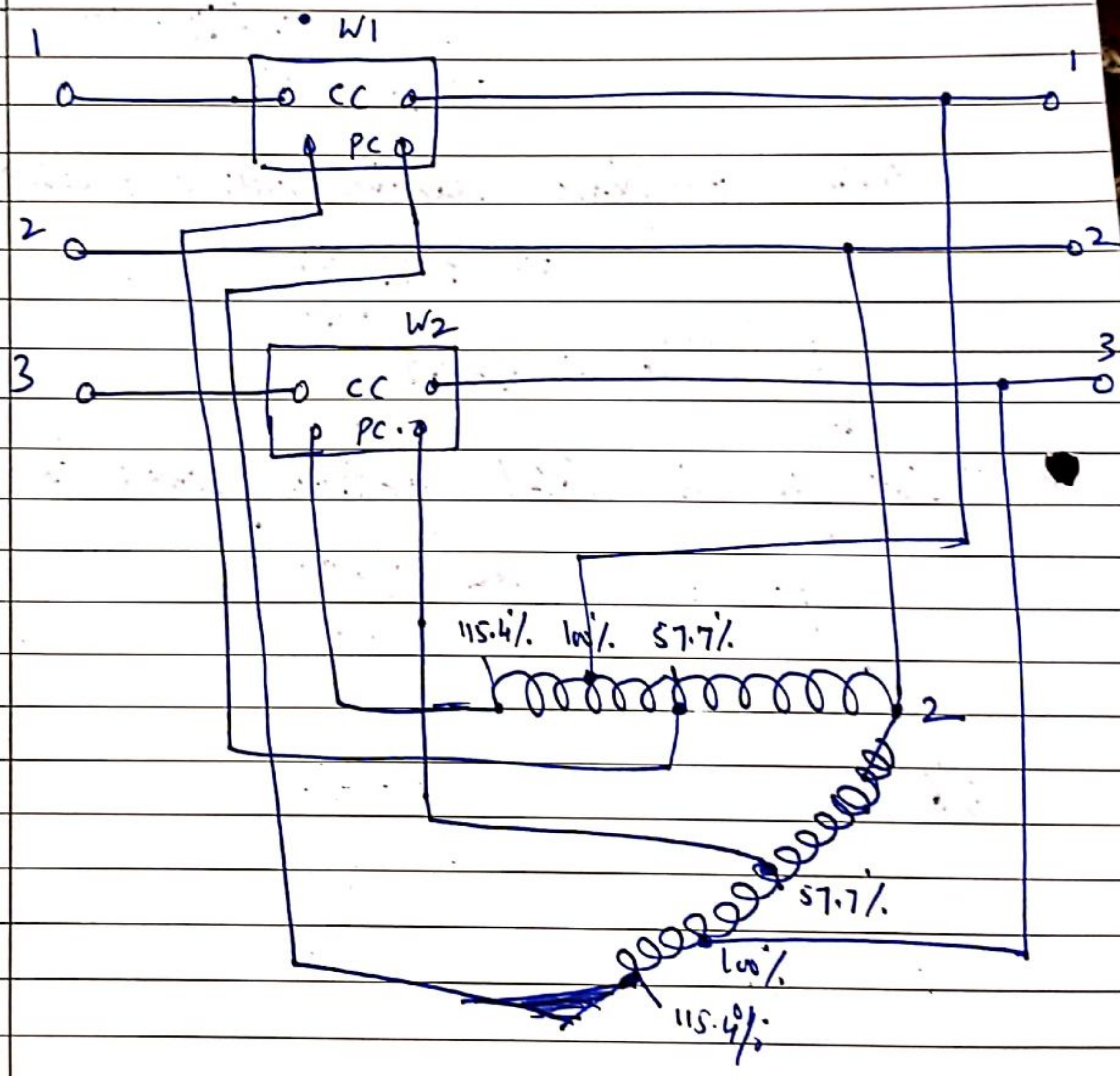
3-phase VAR meter :-

In three phase circuits phase shifting necessary for the measurement of reactive power is usually obtained with the help of phase shifting transformer. This phase shifting may be done with two auto transformers connected in open-delta configuration as shown in following ckt diagram.



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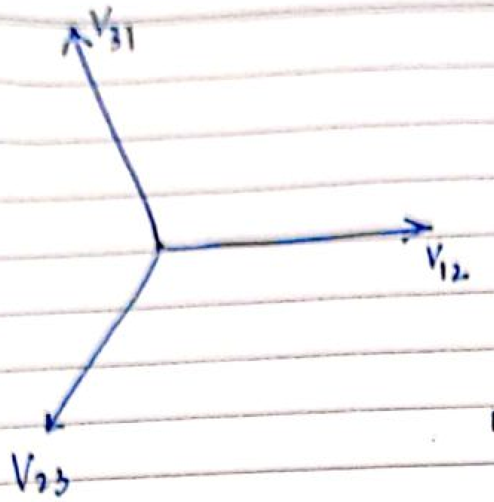

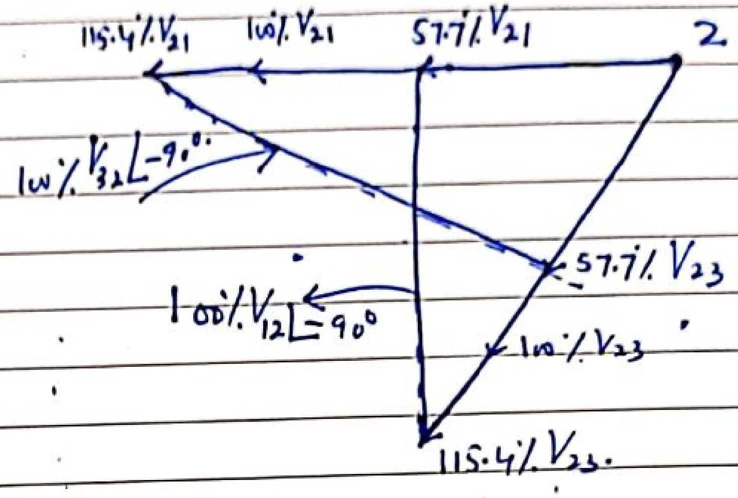

The current coils of the wattmeters are connected in series with the lines as usual. The potential coils are connected as shown. phase 2 is connected to the common terminals of the two autotransformers and phase 1 & 3 lines are connected to 100% taps on the Xmers. Both transformers will produce 115.4% of the line voltage across the total winding.

The pressure coil of wattmeter 1 is connected from 57.7% tap on transformer 1 to the 115.4% tap on transformer 2 which produces a voltage equal to line voltage but shifted by 90° as shown in phasor diagram. The pressure coil of wattmeter 2 is connected in a similar way. Since both coils receive a voltage equal to the line voltage but displaced by 90° the wattmeters indicate the reactive power consumed by load. The total arithmatic sum of two wattmeters gives the total 3-ϕ reactive power.

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