EE240: Power Engineering LAB

Power measurement in balanced 3 phase circuit and power factor improvement

Instructor

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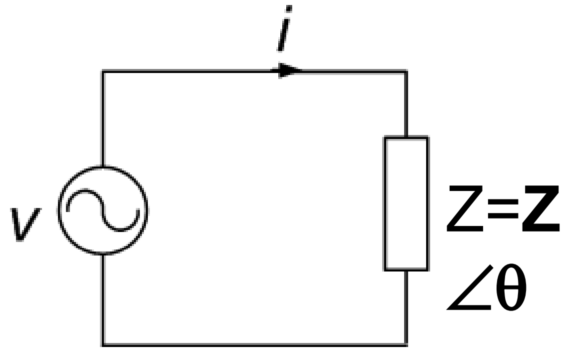
Power in 1-ϕ circuit:



Let $v = \sqrt{2} V \sin(\omega t)$

$\bar{V} = V\angle 0$ is the applied voltage &

$$i = \frac{v}{Z} = \sqrt{2} I \sin(\omega t - \theta), \qquad \bar{I} = \frac{\bar{V}\angle -\theta}{Z} = I e^{-j\theta}$$

Instantaneous power delivered to the load,

$$p = vi$$
$$= 2VI \sin\omega t \sin(\omega t - \theta)$$
$$= VI[\cos\theta - \cos(2\omega t - \theta)]$$

constant term

alternating at twice the supply F

$$= VI\cos\theta - VI\cos\theta\cos 2\omega t - VI\sin\theta\sin 2\omega t$$

$\therefore$ Average power, $P = VI\cos\theta$ W

$$\cos\theta = \frac{P}{VI}$$

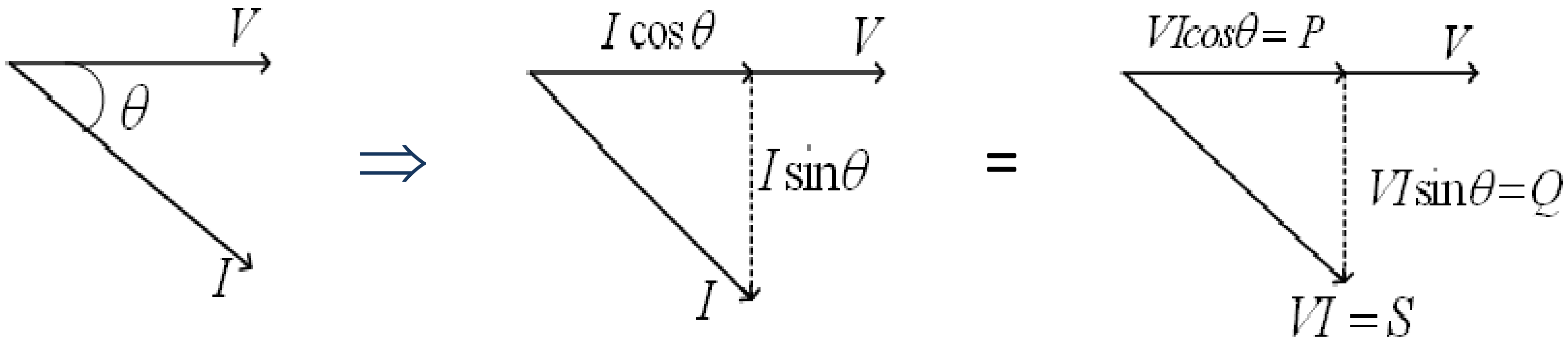
$\Rightarrow$ $\theta = 0$, load = R, 'p' is always +ve

$\Rightarrow$ $\theta \neq 0$, instantaneous power is negative, even though load is passive

$\Rightarrow$ Energy stored in L/C is returned back to source

$\Rightarrow$ 'p' pulsates at 2f. Load may experience vibration

$\Rightarrow$ Requires resilient mountings



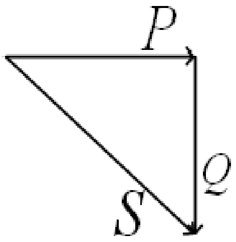
Complex power: $S = P + jQ$

↳Dimensions same as P & Q

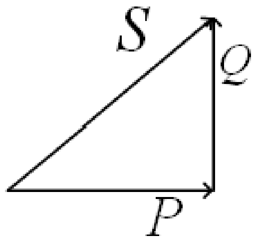
$\Rightarrow$VA (Volt-Ampere)

$$S = VI\cos\theta + jVI\sin\theta$$
$$= VIe^{j\theta} = VI^*$$

Inductive circuit: Source supplies ‘Q’



Capacitive circuit: Source receives ‘Q'

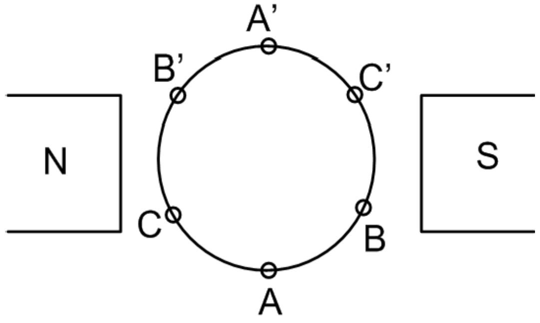


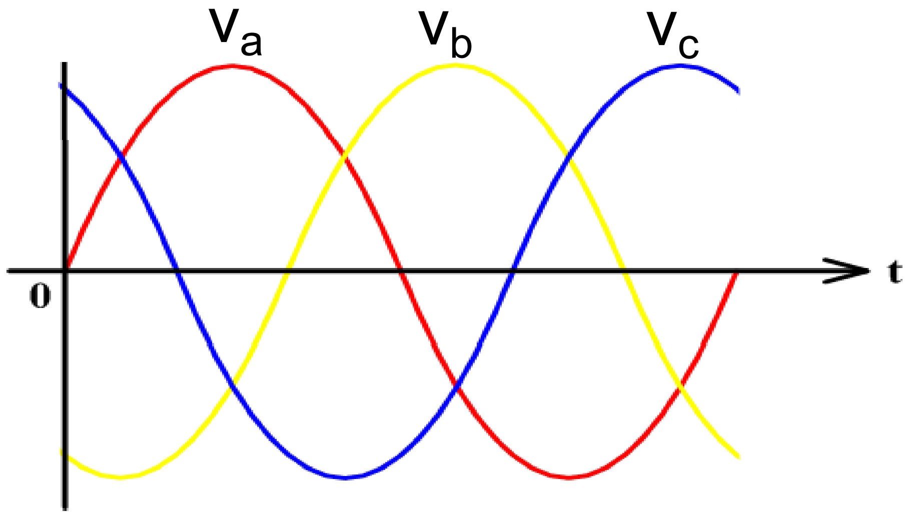
Three Phase AC Circuits

⇒ Generation, Transmission, Distribution & utilization of large blocks of power are accomplished by means of 3- Ø circuits.

⇒ 1-Ø supply is generated from 3-Ø supply.

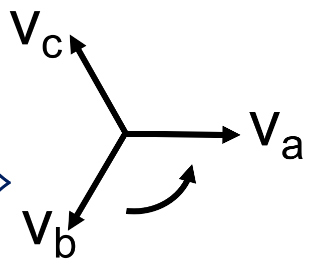
⇒ A balanced 3-Ø system consists of 3 single phase voltages having same amplitude & f , but out of phase with each other by 120^0.





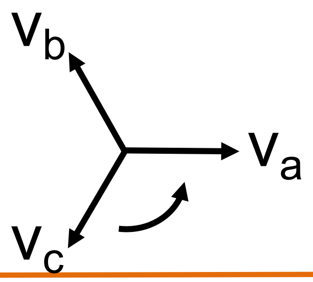
⇒ 'v' in coil AA' reaches peak followed by BB' & CC'

⇒ Phase relationship is ABC ⇒



⇒ Also known as 'phase sequence'

⇒ phase relationship is ACB ⇒



$$v_{aa'} = \sqrt{2}V \sin \omega t \qquad \bar{V}_{aa'} = V\angle 0 = \bar{V}_a$$

$$v_{bb'} = \sqrt{2}V \sin(\omega t - \frac{2\pi}{3}) \qquad \bar{V}_{bb'} = V\angle -\frac{2\pi}{3} = \bar{V}_b$$

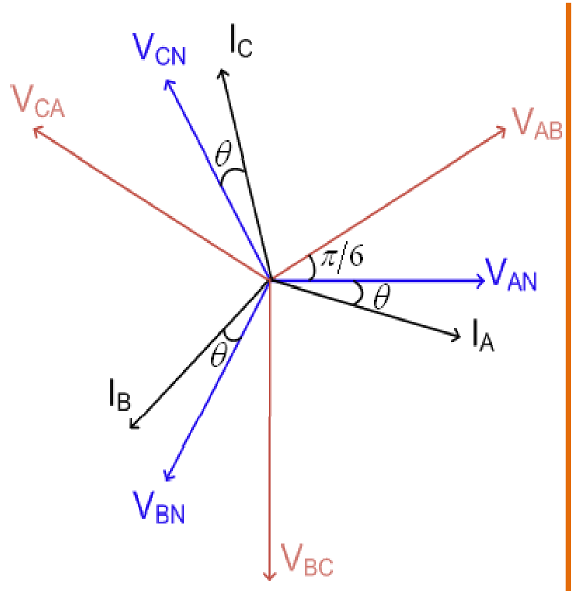
$$v_{cc'} = \sqrt{2}V \sin(\omega t - \frac{4\pi}{3}) \qquad \bar{V}_{cc'} = V\angle -\frac{4\pi}{3} = \bar{V}_c$$

$v_{aa} + v_{bb} + v_{cc} = 0$ or $\bar{V}_a + \bar{V}_b + \bar{V}_c = 0$

$\Rightarrow$ In balanced 3-phase system, sum of three phase voltages is zero

Three Phase connection

Y Connection:



⇒ Potential difference between any line and common point (also known as neutral) known as phase voltage

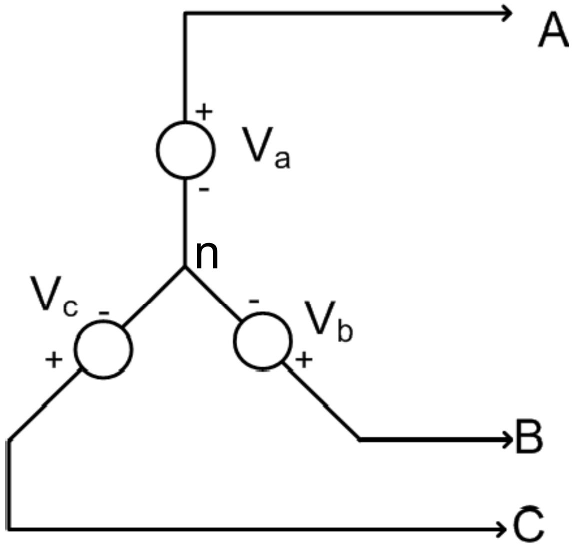
$$\overline{V}_{an},\ \overline{V}_{bn}\ \ \&\ \overline{V}_{cn}$$

⇒ Potential difference between any two lines = Line voltage or line-line voltage

$$\overline{V}_{AB} = pot.\ of\ \ A\ \ w.r.t\ \ B$$

$$= -V_{bn} + V_{an} = V_{an} - V_{bn}$$

$$V_{BC} = V_{bn} + V_{nc},\quad V_{CA} = V_{cn} + V_{na}$$



Y connected load -Balanced Load:

Magnitude & phase angle are the same in all 3 phases

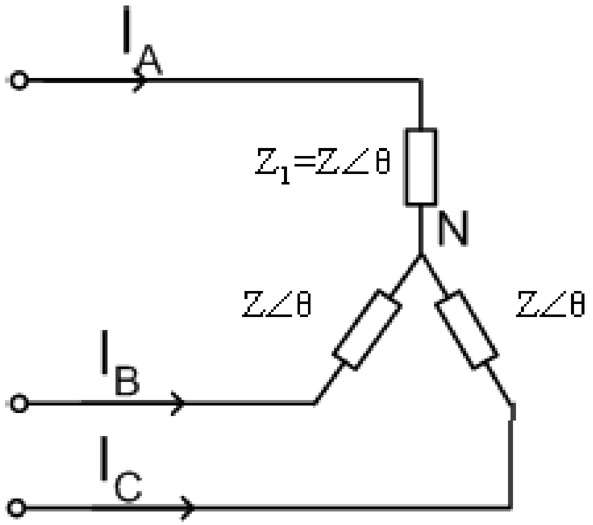
Assume ABC phase sequence

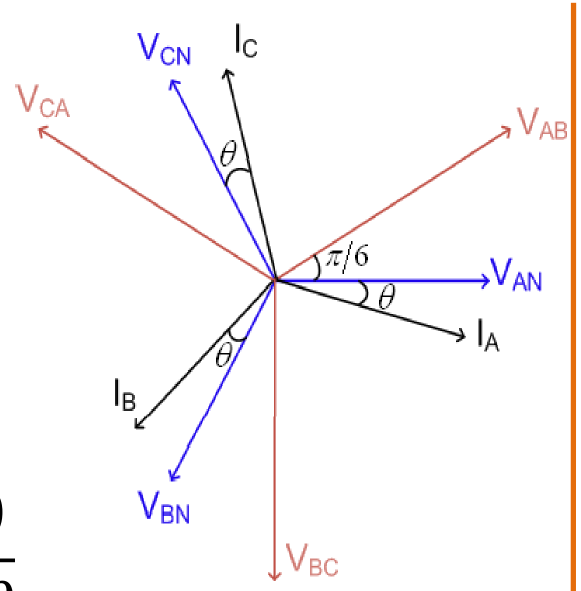
and $V_{AN} = V\angle 0$ as the reference phasor

$$\therefore \; V_{AN} = V\angle 0$$

$$V_{BN} = V\angle \frac{-2\pi}{3}$$

$$V_{CN} = V\angle \frac{-4\pi}{3}$$





$$\bar{I}_A = \frac{\bar{V}_{AN}}{Z_A} = \frac{V\angle 0}{Z\angle \theta}$$

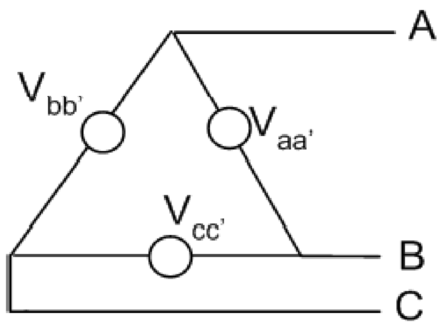
$$\bar{I}_B = \frac{\bar{V}_{BN}}{Z_B} = I\angle -(\frac{2\pi}{3} + \theta)$$

$$\bar{I}_C = \frac{\bar{V}_{CN}}{Z_C} = I\angle -(\frac{4}{3} + \theta)$$

$\Rightarrow$ Line ‘I’ = Phase ‘I’

Δ-Connection:

Line V = Phase V



Assume, $V_{AB} = V\angle 0$,

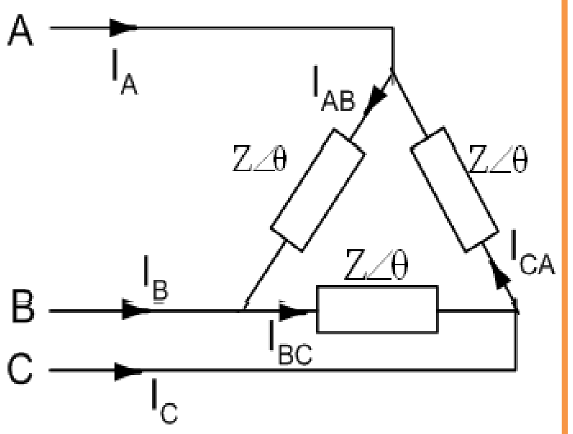
$V_{BC} = V\angle{-2\pi/3}$, $V_{CA} = V\angle{-4\pi/3}$

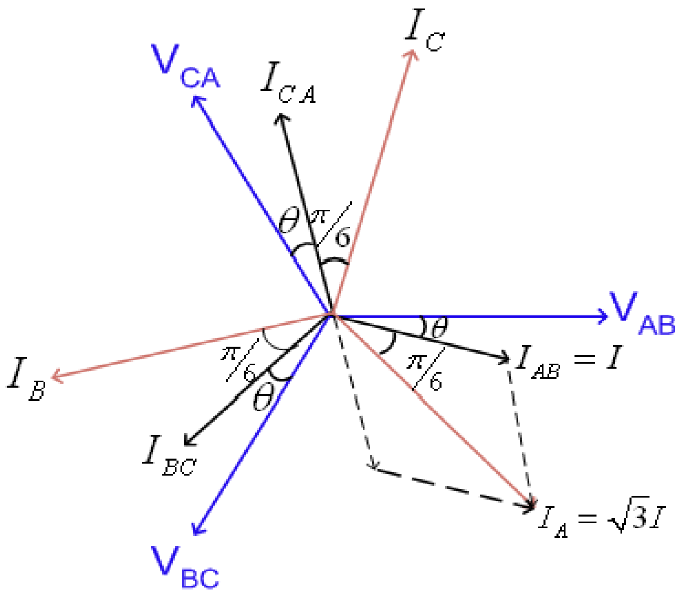
Load connection:

$$\bar{I}_{AB} = \frac{\bar{V}_{AB}}{Z_{AB}} = \frac{V\angle 0}{Z\angle\theta} = I\angle-\theta$$

$$\bar{I}_{BC} = \frac{\bar{V}_{BC}}{Z_{BC}} = I\angle-(\frac{2\pi}{3}+\theta)$$

$$\bar{I}_{CA} = \frac{\bar{V}_{CA}}{Z_{CA}} = I\angle-(\frac{4\pi}{3}+\theta)$$





$$\therefore I_A = I_{AB} - I_{CA}$$

$$= I\left[1\angle-\theta - 1\angle-(\frac{4\pi}{3}+\theta)\right]$$

$$= \sqrt{3}I\angle-\left(\frac{\pi}{6}+\theta\right)$$

$$|Line\ I| = \sqrt{3}\ |I_{Phase}|$$

Line I lags the phase I by π/6

Power in 3-Φ circuits:

$\Rightarrow$ Recall p in 1Φ circuits pulsates at 2f

$\therefore$ 1-Φ motors require special resilient mountings

$$v_a = \sqrt{2}V\sin\omega t,\ v_b = \sqrt{2}V\sin(\omega t - \frac{2\pi}{3}), v_c = \sqrt{2}V\sin(\omega t - \frac{4\pi}{3})$$

$$i_a = \sqrt{2}I sin(\omega t - \theta), i_b = \sqrt{2}I sin\left(\omega t - \frac{2\pi}{3} - \theta\right), i_c = \sqrt{2}I sin\left(\omega t - \frac{4\pi}{3} - \theta\right)$$

$\therefore$ Instantaneous power

$$p_a = v_a i_a = VI\left[cos\,\theta - \cos\left(2\omega t - \theta\right)\right]$$

$$p_b = v_b i_b = VI\left[\cos\theta - \cos\left(2\omega t - \theta - 240^0\right)\right]$$

$$p_c = v_c i_c = VI\left[\cos\theta - \cos\left(2\omega t - \theta - 480^0\right)\right]$$

$\therefore$ Total instantaneous 3-Φ power $= 3VI\cos\theta$

$= 3V_{ph}I_{ph}\cos\theta$

= Average power

= Constant

$$\theta = \angle_{V_{ph}}^{I_{ph}}$$

If system is 'Y' connected

$$v_{ph} = \frac{v_L}{\sqrt{3}}, \quad I_{ph} = I_L \qquad \therefore P = \sqrt{3} V_L I_L \cos\theta$$

If Load is delta connected $V_L = V_{Ph,} \quad I_L = \sqrt{3} I_{Ph}$

$$\therefore \mathrm{P} = \sqrt{3}\; V_L I_L \cos\theta \;\; \mathrm{W}$$

Independent of type of connection

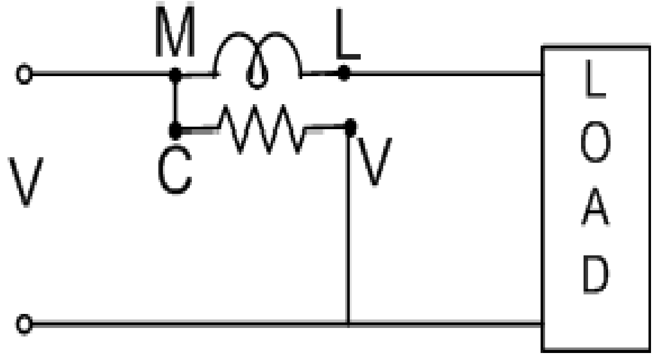
$$\therefore \mathrm{Q} = \sqrt{3}\; V\, I\, \sin\theta \;\; \mathrm{VAr} \qquad \mathrm{S} = \sqrt{3}\; V\, I^* \;\; \mathrm{VA}$$

Measurement of Power

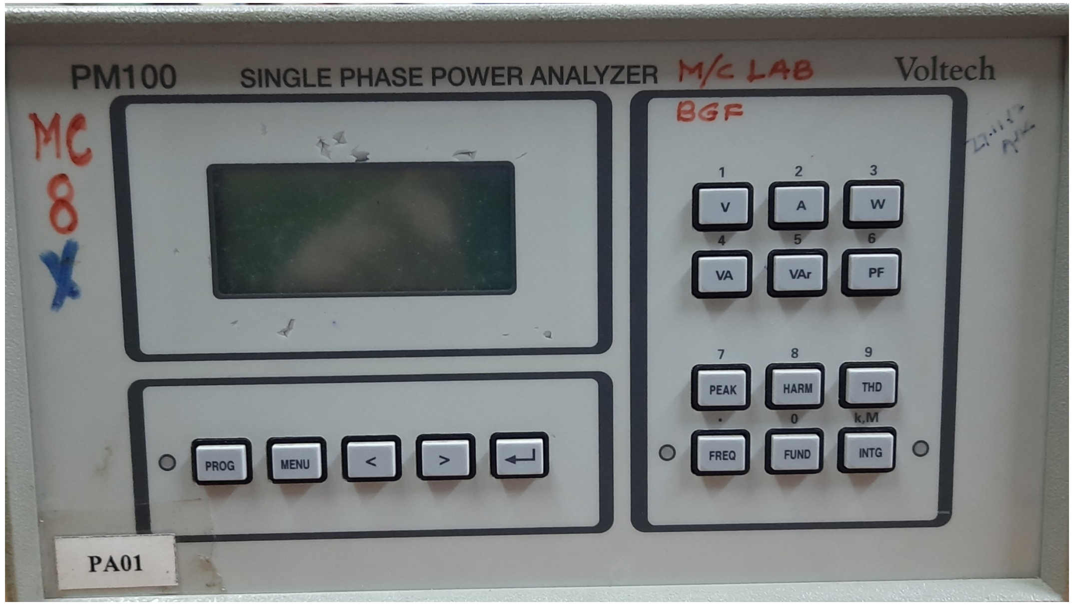
⇒ Using wattmeter

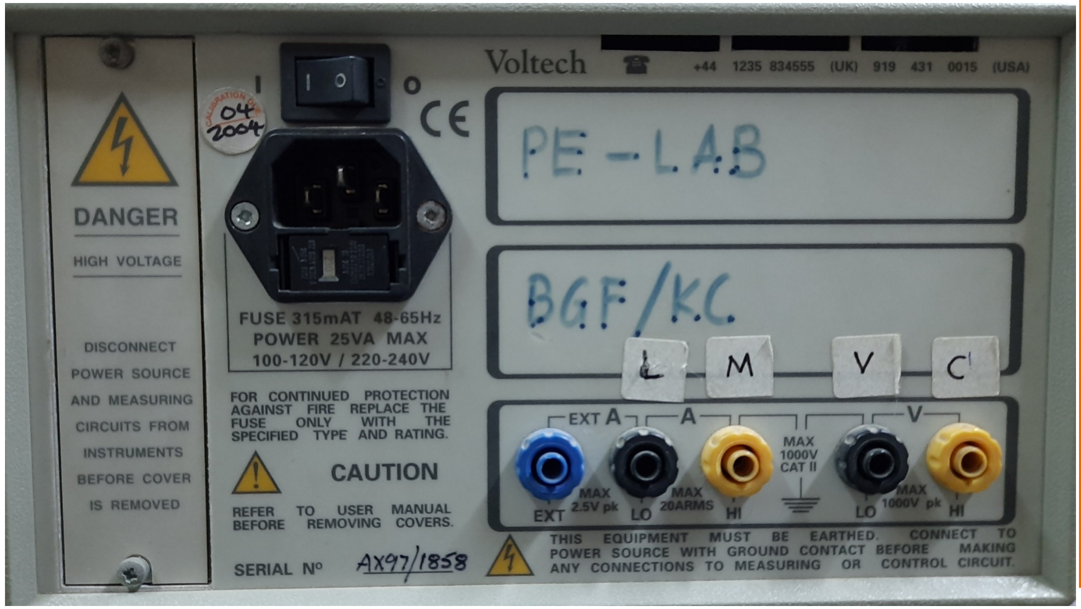
⇒ Has 2 coils: → Current coil, → Voltage coil

M → Mains
L → Load
C → Common
V → Voltage



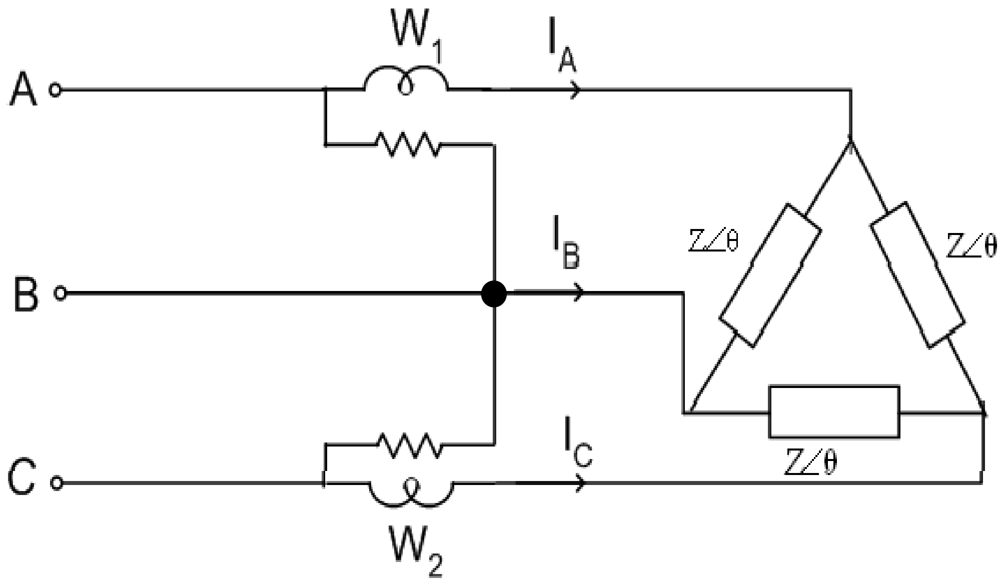
'W' reading $= I_{Flowing} V_{Applied} \cos\angle_{V_{Applied}}^{I_{Flowing}}$

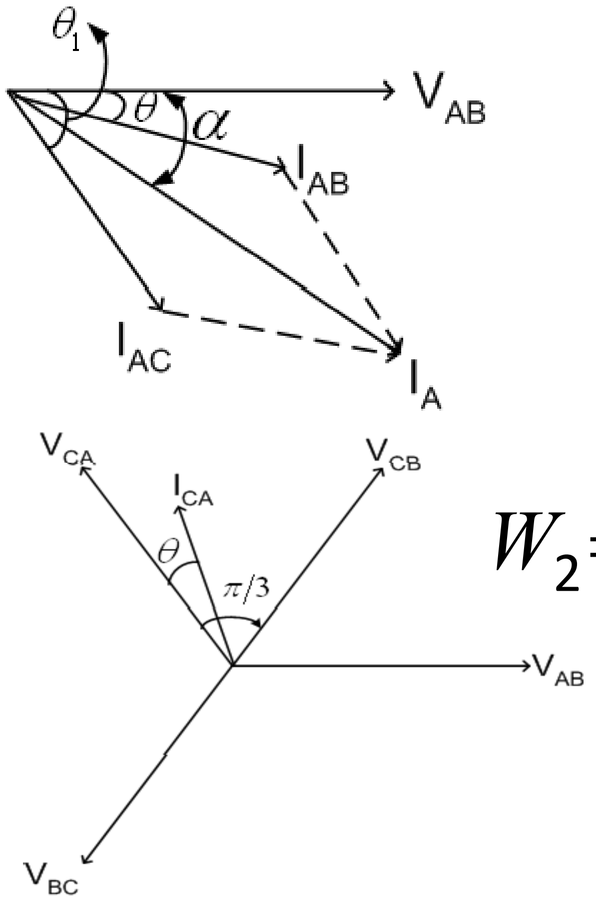




In case of 3-phase 3 wire load:

Two wattmeter method:





$$W_1 = V_{AB} I_A \cos\alpha$$

$$W_2 = V_{CB} I_C \cos\angle_{V_{CB}}^{I_C}$$

Observations:

If load is balanced

$$\theta = \angle_{V_{ph}}^{I_{ph}}$$

$$\Rightarrow \sqrt{3} V_L I_L \cos\theta = W_1 + W_2$$

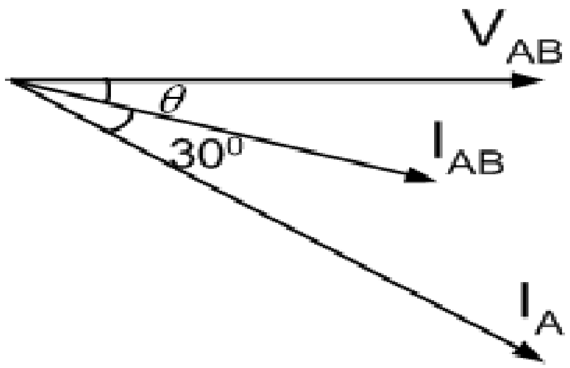
If load is unbalanced

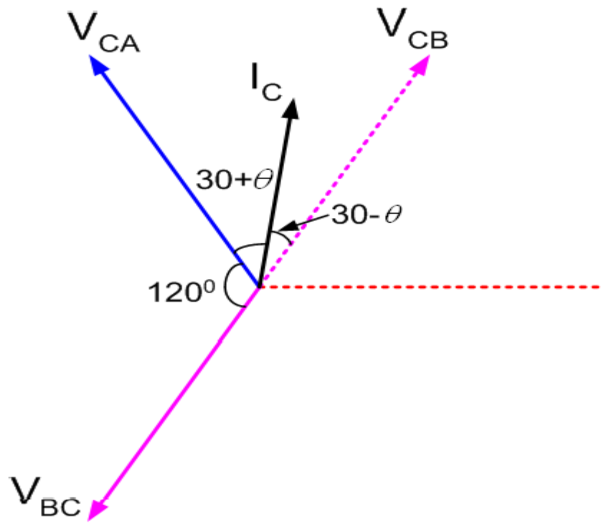
$$W_1 + W_2 = P_A + P_B + P_C \neq \sqrt{3} V_L I_L \cos\theta$$

Power in phase A

$$W_1 = V_{AB} I_A \cos \angle_{V_{AB}}^{I_A}$$
$$= V_L I_L \cos(30+\theta)$$

$$W_2 = V_{CB} I_C \cos \angle_{V_{CB}}^{I_C}$$
$$= V_L I_L \cos(30-\theta)$$





If θ = 0 ⇒ Load is 'R', $W_1 = W_2$

If θ = π/3, one of the Wattmeter would read zero

⇒ If θ > π/3, read -ve (interchange M & L)

$$\theta = \tan^{-1} \sqrt{3} \left[\frac{W_2 - W_1}{W_1 + W_2} \right]$$

Note: Phase sequence & lines in which they are connected should be known to determine whether θ is +ve or -ve

Concept of Reactive Power

1 kVA, 200V, 50 Hz Generator

$\Rightarrow$ Rated current = 5A

$\Rightarrow$ Assume load = 1 kVAr, 200V

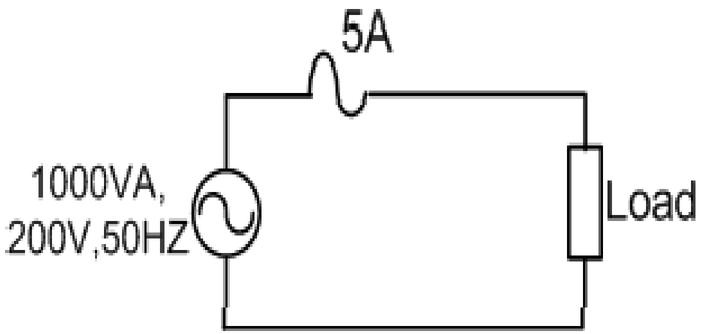
$\Rightarrow$ Current drawn by the load = 5A
= rated current of generator

$\Rightarrow$ Power consumed by the load =0

Assume generator is ideal (losses = 0)

$\therefore$ Input power = o/p power + loss = 0

$\Rightarrow$ No input is required.



$\Rightarrow$ Source has the capability to supply P

$\Rightarrow$ If additional load (P) is connected

$\Rightarrow$ If losses are taken into account, I/P power = losses

For any I $\neq$ 0 $\Rightarrow I_s = \sqrt{I_a^2 + 5^2} \geq 5$

$\Rightarrow$ Fuse will operate

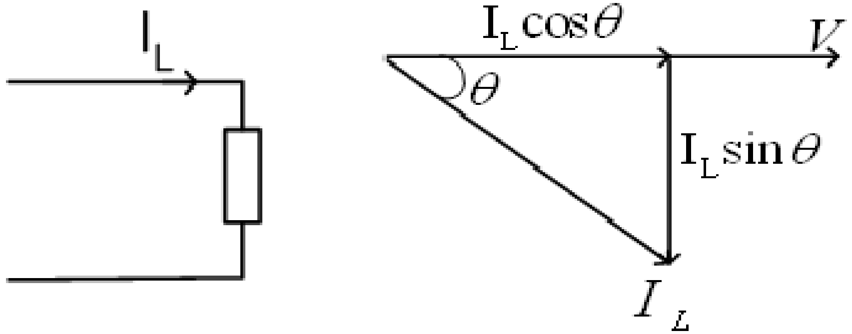
$\Rightarrow$ Else I^2R losses $\uparrow$,
$\hookrightarrow$ RMS value

$\Rightarrow$ Temperature rise

$\Rightarrow$ Cooling requirement

$\Rightarrow$ Though 'L' does not consume any P, source capacity can not be utilized to cater other loads

$\Rightarrow$ Energy meter reading α power α VI cosθ α I cosθ



Load is drawing I_L

$\Rightarrow$ Energy Meter reading α $I_L\cos\theta$

$\therefore$ Tariff α $I_L\cos\theta$

Who pays for $I_L\sin\theta$?

$\Rightarrow$ Fuel (power input) to supply Q may not be required

$\Rightarrow$ Utilities may not be able to cater other loads

$\Rightarrow$ Returns are low

$\Rightarrow$ Utilization and returns are maximum at unity p.f

$\Rightarrow$ Load requires reactive power

$\Rightarrow$ Generate reactive power locally

$\Rightarrow$ Capacitor draws leading I

$\Rightarrow$ If $I_C = I_L \sin\theta$, $I_s = I_L \cos\theta$

$\Rightarrow$ Overhead line loss & drop

$\Rightarrow$ Voltage profile at the load end also improves

Power factor Correction

- In DC, if P & V are known, I can be determined
- However in AC, P, V & cosϴ or V & S should be known to determine I

For a given P

- I drawn by load ↑ as cos θ (P.F.) ↓

$\Rightarrow$ Drop in the line ↑

$\Rightarrow$ I^2R , I^2X in the line ↑ and therefore 'S' of source ↑

$\Rightarrow$ I^2R loss in source also increases

- $V_L < V_s$ for lagging & unity P.F.
- $V_L \leq V_S$ or $V_L > V_S$ for leading P.F.