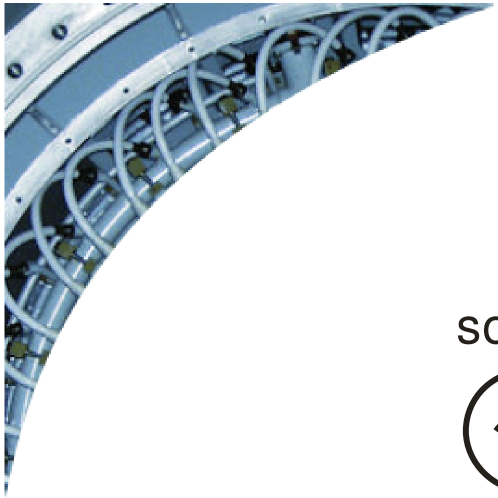
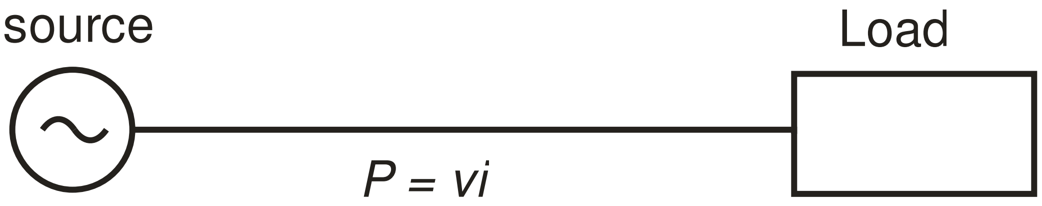


Transmission system



⇒ line losses:

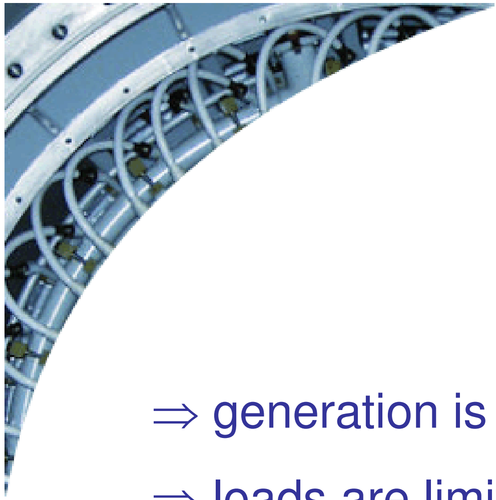
$$2 \cdot i^2 R = 2 \cdot i^2 \frac{\rho l}{A}$$ i.e. for 2 lines

⇒ to reduces losses

- reduce *R* (limited)
- reduce *i*

⇒ to transmit the same power, reduce *i* and increase *v*

⇒ hence high voltage (HV) transmission systems



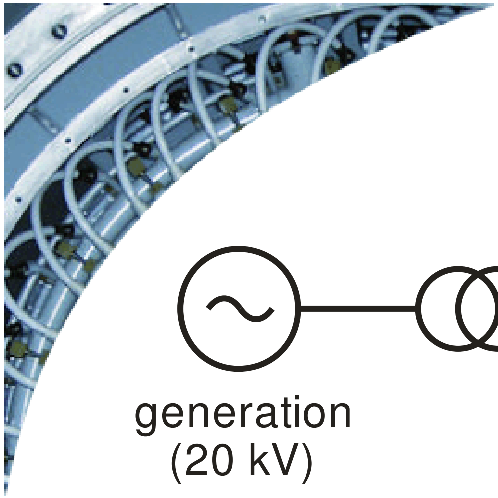
HV transmission system

⇒ generation is limited to approx 20 kV, due to insulation requirements

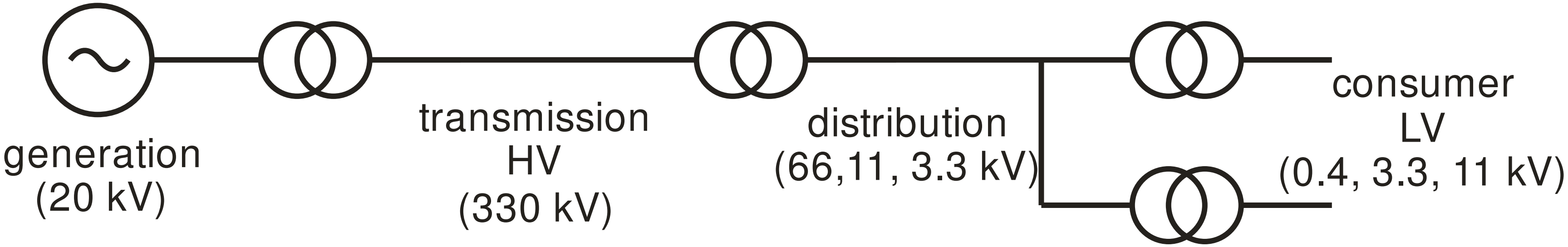
⇒ loads are limited to approx 10 kV due to
  - safety
  - size
  - insulation

⇒ we must change voltage levels to transmit high power

⇒ to change voltage levels, we must use
  - transformer
  - ac system



High voltage AC system (HVAC)



generation
(20 kV)

transmission
HV
(330 kV)

distribution
(66,11, 3.3 kV)

consumer
LV
(0.4, 3.3, 11 kV)

⇒ generation

- up to 25 kV

⇒ transmission

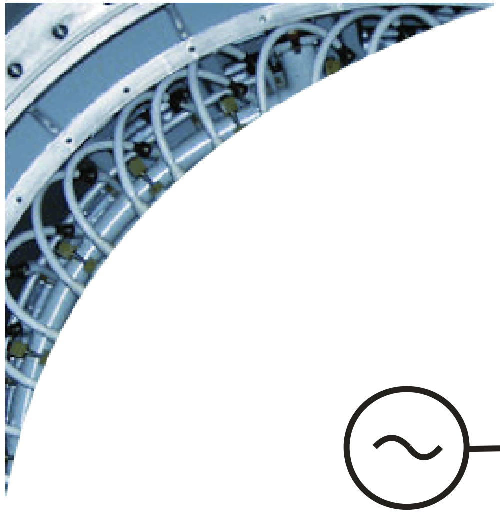
- 110 kV – 1000 kV (110, 132, 220, 330, 400, 525, 750 kV)

⇒ distribution

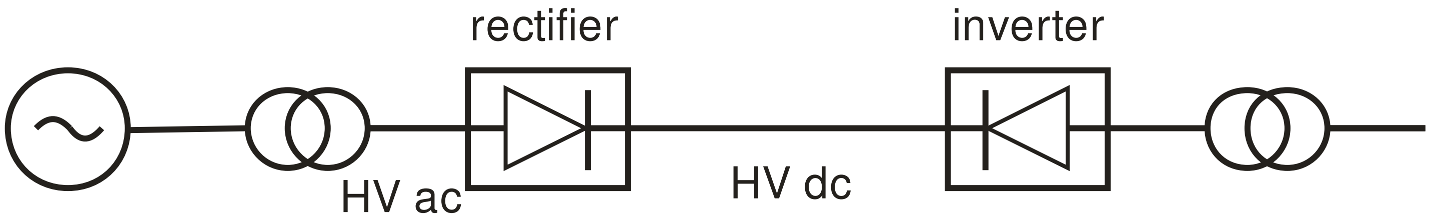
- 3.3 kV – 88 kV (3.3, 6.6, 11, 33, 66 kV)

⇒ consumer

- 0.19 -15 kV (0.4, 0.55, 3.3, 6.6, 11 kV)



High voltage DC system (HVDC)

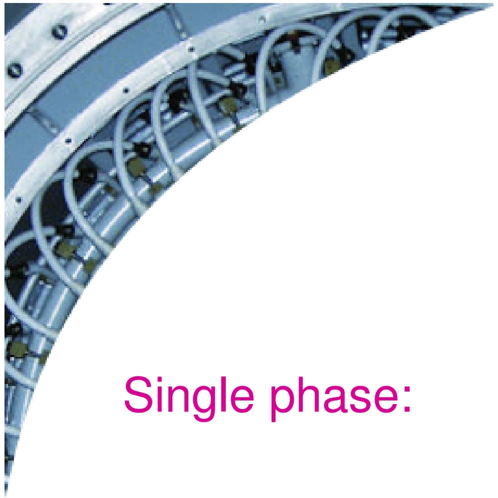


⇒ HVDC is employed where

- transmission over larger distances (>500 km)
- interconnection of systems with different systems (eg 50 Hz to 60 Hz)
- back-to-back in a substation for power flow control

⇒ Examples

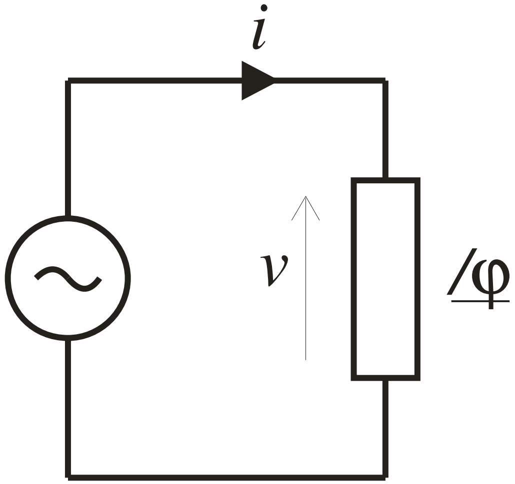
- Gotland – mainland Sweden (1954) –submarine cable
- Xiangjiaba – Shanghai (2071 km, 6400 MW) -longest
- Inga-Shaba (Congo)
- Cabora-Bossa – RSA?



HVAC

Single phase and 3-phase

Single phase:



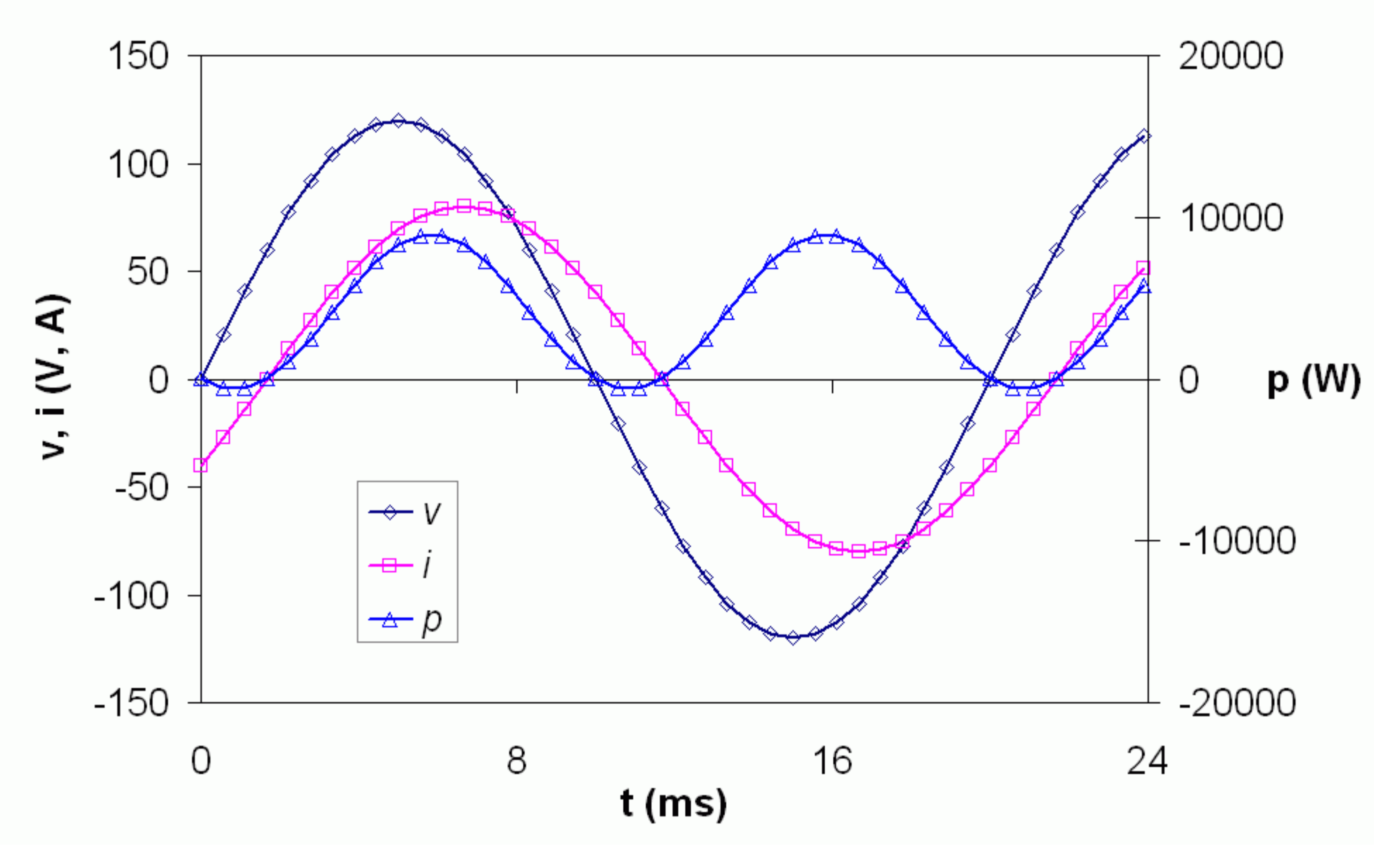
$$v = V_m \sin \omega t$$

$$i = I_m \sin(\omega t - \varphi)$$

$$P = V_m I_m \sin \omega t \cdot \sin(\omega t - \varphi)$$

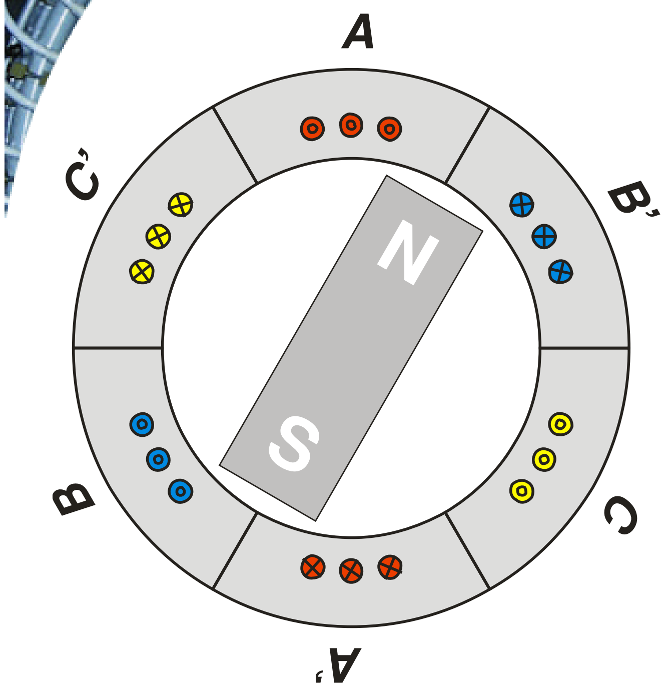
$$= V_m I_m \tfrac{1}{2}\left[\cos \varphi - \cos(2\omega t - \varphi)\right]$$

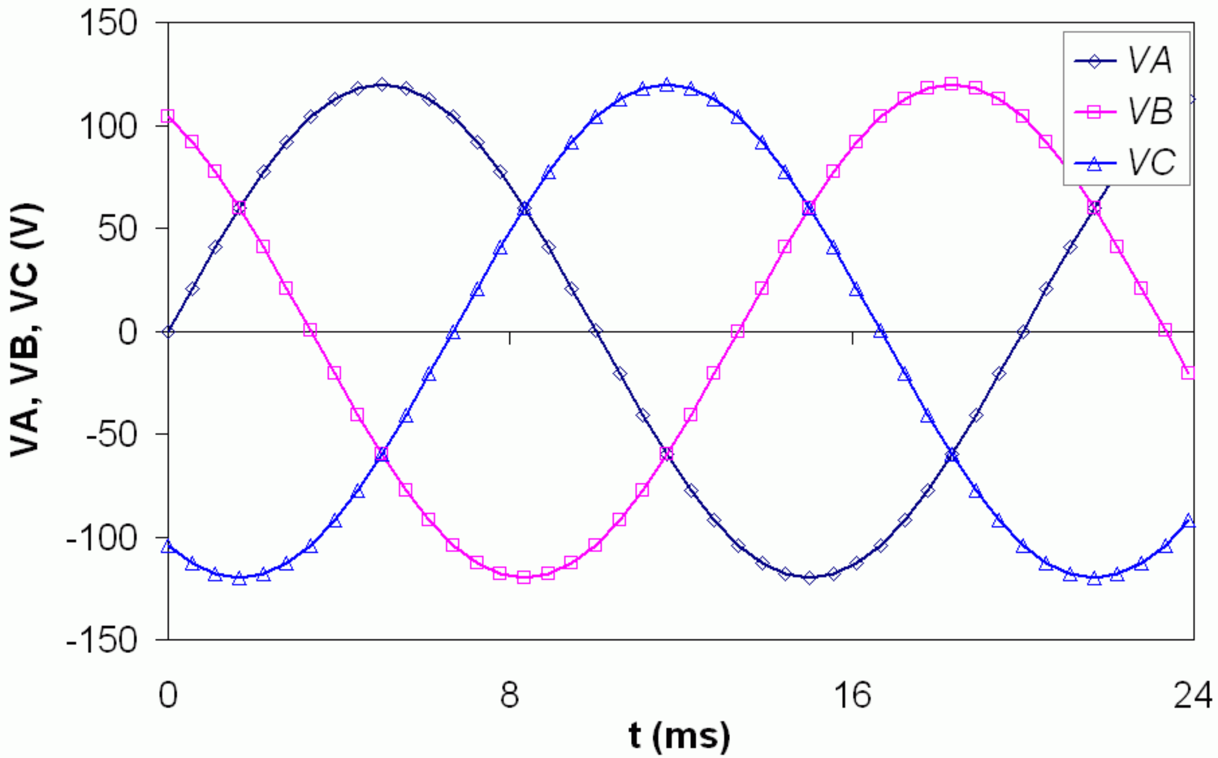
$$P = \underbrace{VI \cos \varphi}_{\text{constant}} - \underbrace{\cos(2\omega t - \varphi)}_{\text{varying at } 2f}$$



⇒ single phase systems have large and undesirable fluctuations in instantaneous power

Three phase:

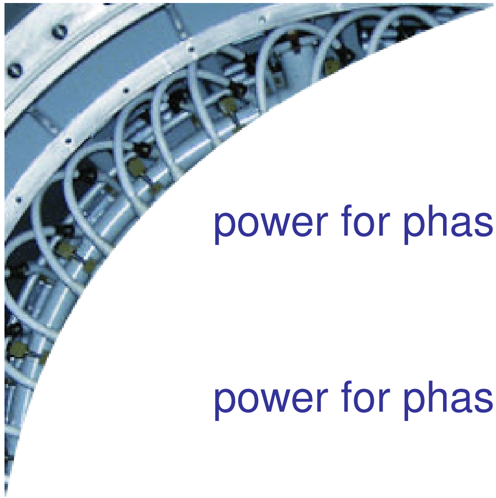




$$v_A = V_m \sin \omega t$$

$$v_B = V_m \sin(\omega t - 120^\circ)$$

$$v_B = V_m \sin(\omega t - 240^\circ)$$



power for phase *A*

$$P_A = VI\cos\varphi - \cos(2\omega t - \varphi)$$

power for phase *B*

$$P_B = VI\cos\varphi - \cos(2\omega t - \varphi - 240^\circ)$$

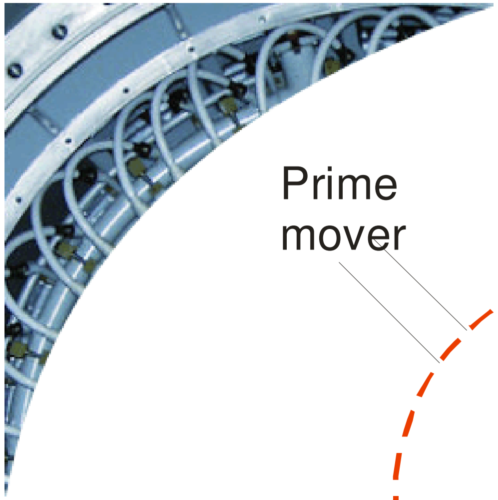
power for phase *C*

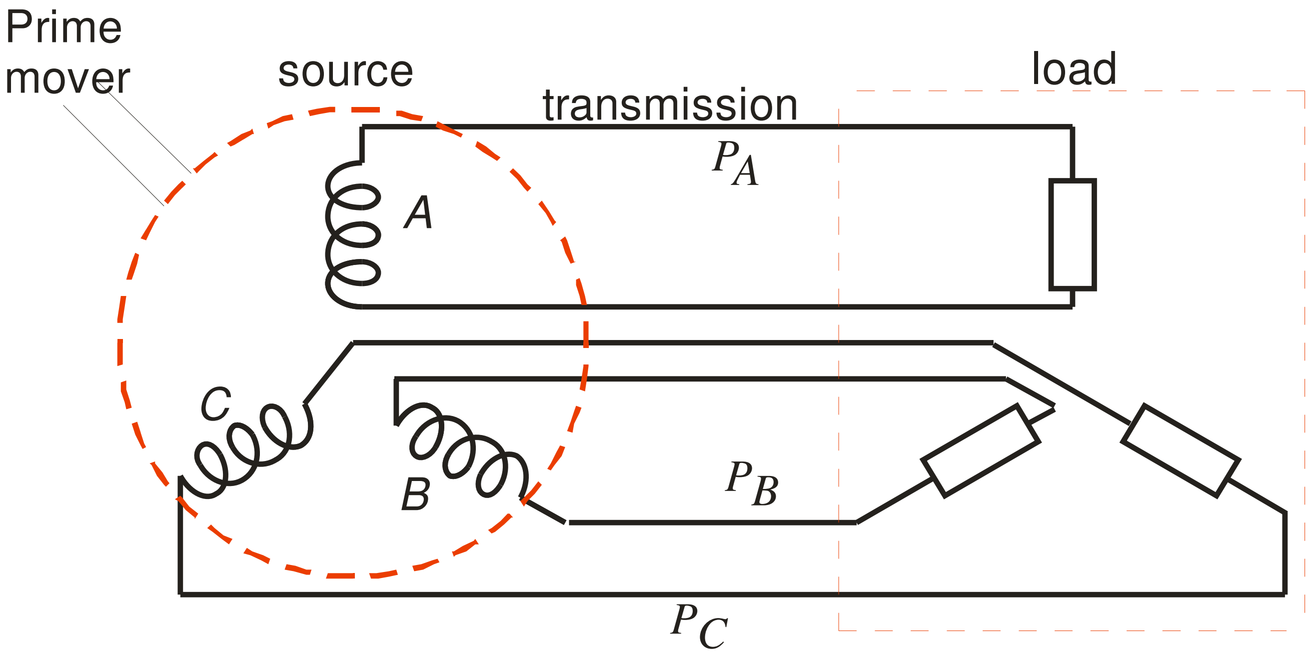
$$P_C = VI\cos\varphi - \cos(2\omega t - \varphi - 480^\circ)$$

total instantaneous power

$$\begin{aligned} P &= P_A + P_B + P_C \\ &= 3VI\cos\varphi - VI\left[\cos(2\omega t - \varphi) + 2\cos(2\omega t - \varphi - 180^\circ)\cos 60^\circ\right] \\ &= 3VI\cos\varphi - VI\left[\cos(2\omega t - \varphi) - \cos(2\omega t - \varphi)\right] \\ &= 3VI\cos\varphi - 0 \end{aligned}$$

$$P = 3VI\cos\varphi$$



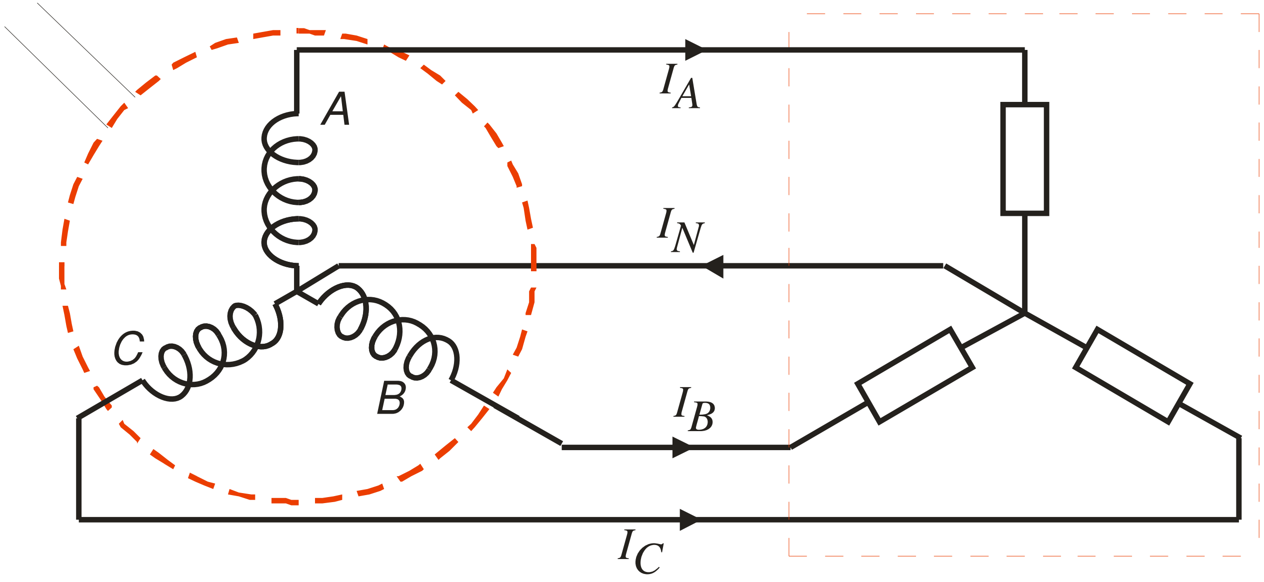


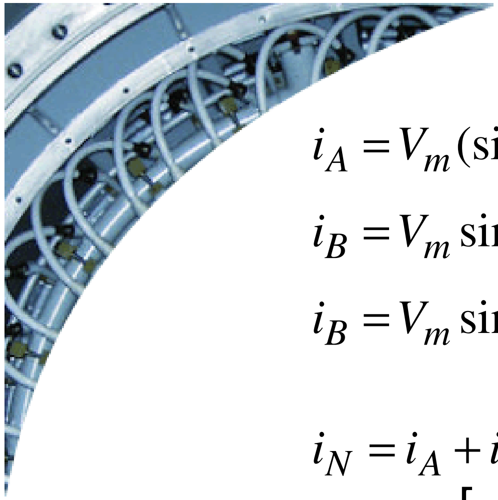
⇒ advantage 1:

- power right from the prime mover to the load is absolutely constant

Three phase transmission:

⇒ instead of having 6 conductors between the generator and load, we can join the windings together as shown and simply have 4 conductors





$$i_A = V_m(\sin \omega t - \varphi)$$

$$i_B = V_m \sin(\omega t - \varphi - 120^\circ)$$

$$i_B = V_m \sin(\omega t - \varphi - 240^\circ)$$

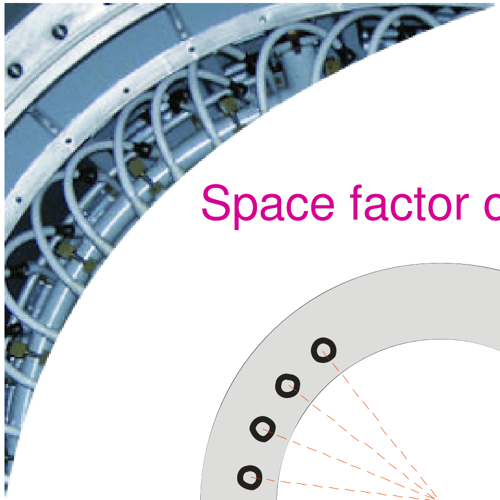
$$\begin{aligned} i_N &= i_A + i_B + i_C \\ &= I_m\left[\sin(\omega t - \varphi) + 2\sin(\omega t - \varphi)\cos 120^\circ\right] \\ &= 0 \end{aligned}$$

⇒ the current in the neutral conductor under balanced conditions is zero

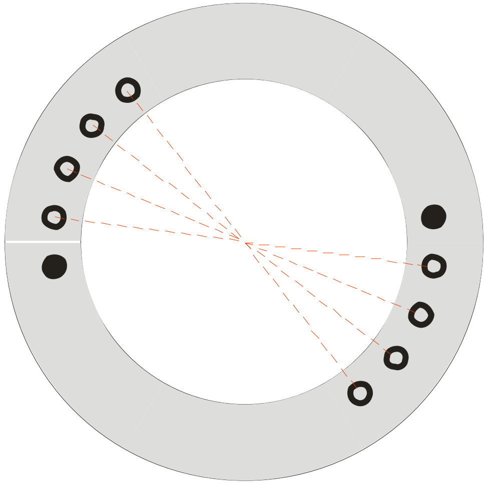
⇒ therefore, we need only have 3 conductors for our three-phase system

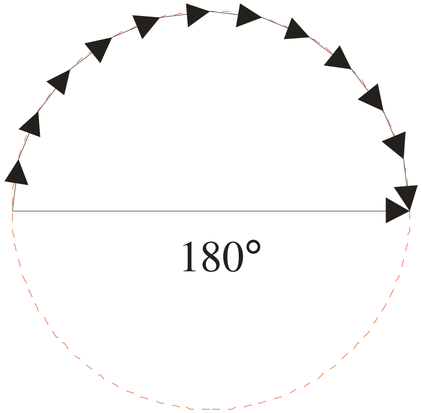
⇒ advantage 2:

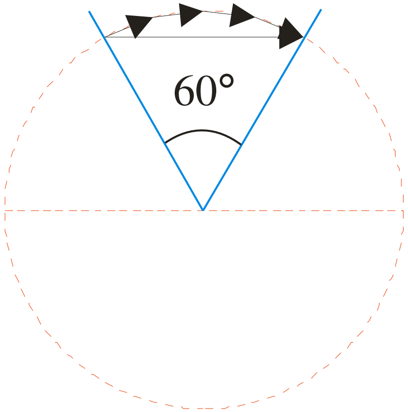
- there is a big saving in transmission conductors



Space factor of machines







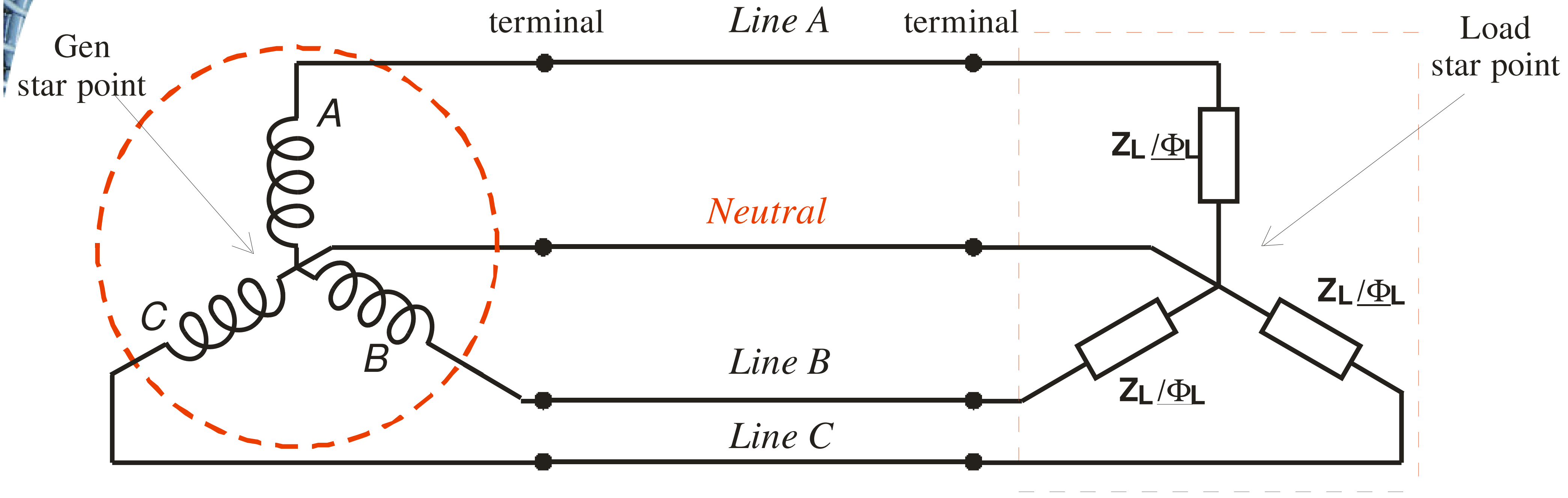
⇒ if the stator of the generator is wound for 3 separate phases instead of just one single phase, we obtain a higher value of distribution factor

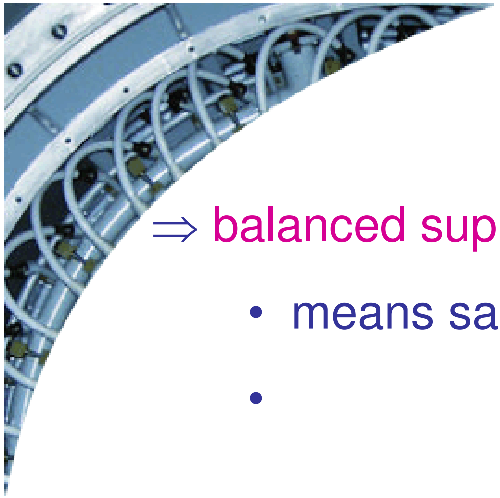
⇒ the result of this is that there is bigger value of space factor

⇒ advantage 3:

- output per unit volume of three phase machines is higher than for single phase machines

3-phase power systems





⇒ balanced supply:

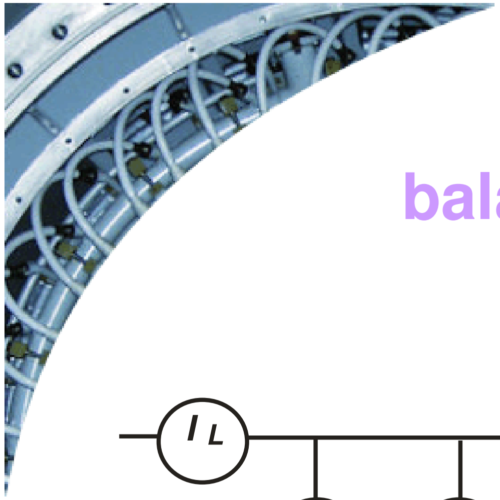
- means same magnitude of voltage every 120°
- $$V_A = V_p \underline{/0}$$
  $$V_B = V_p \underline{/120^\circ}$$
  $$V_C = V_p \underline{/240^\circ}$$

⇒ balanced load:

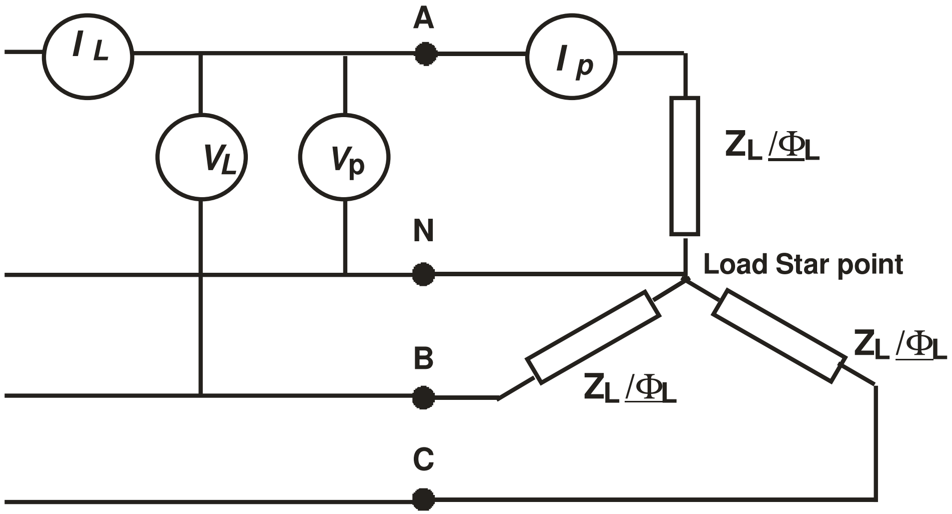
- means same impedance in each phase every 120° $\overline{Z_\text{L}} = Z_L \underline{/\varphi}$
- same magnitude and phase
- this is normal large 3-phase loads, not so for individual single-phase loads

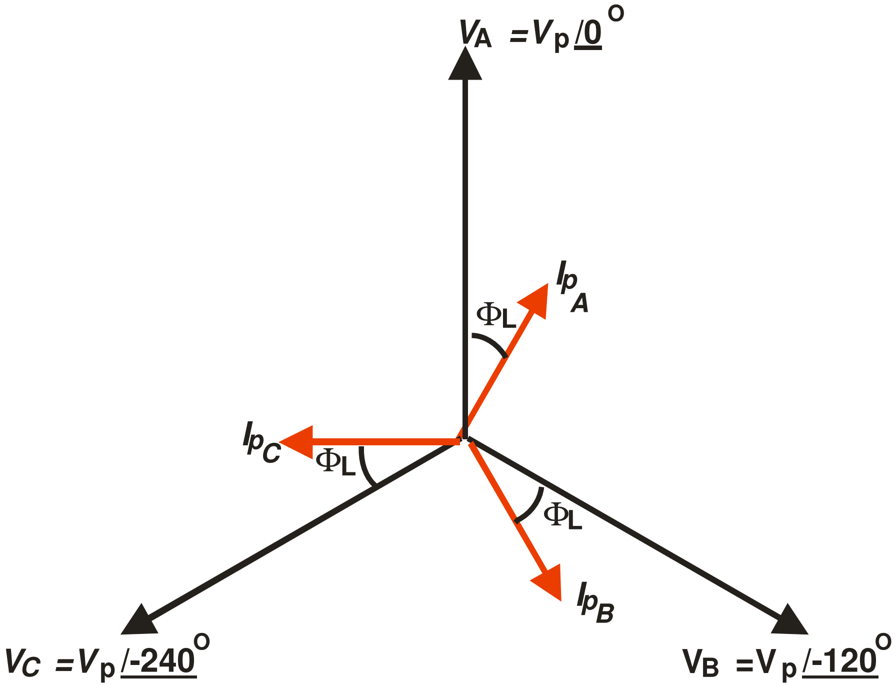
⇒ balanced system:

- means both supply and load are balanced



balanced system star-connected load



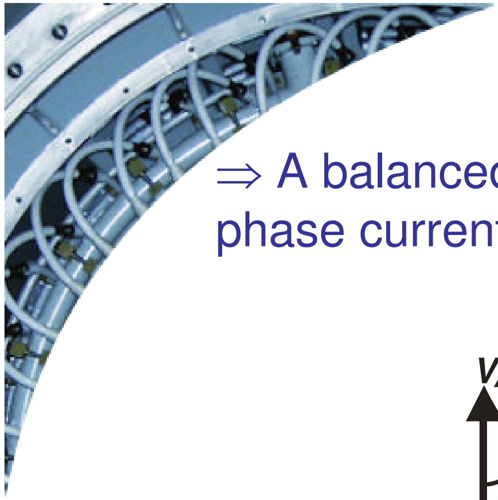


⇒ subscript *p*: phase,

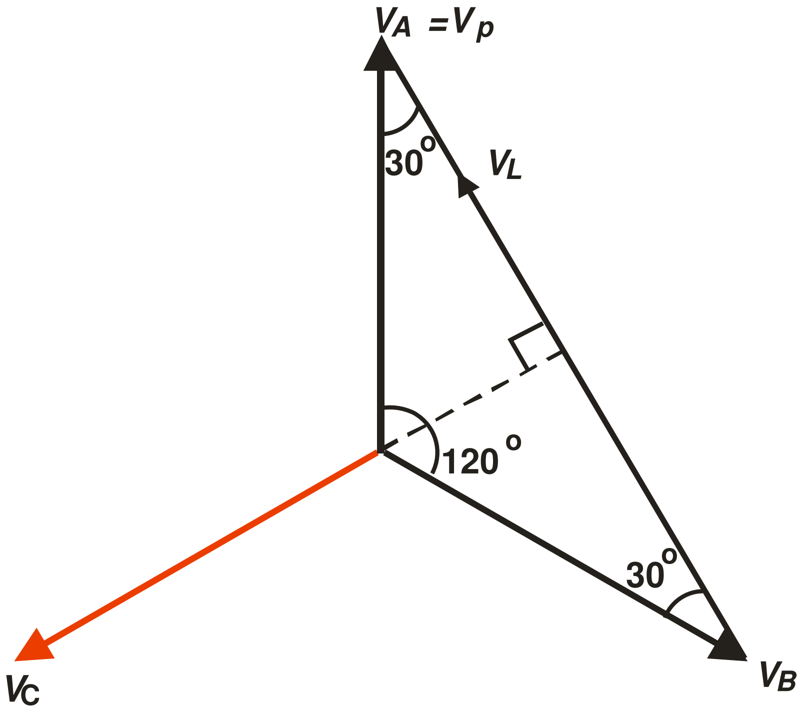
- means looking at one phase

⇒ subscript *L*: line,

- means looking at three phases



⇒ A balanced supply voltage applied to a balanced load gives a balanced set of phase currents, same magnitude and displaced every 120°



$$\frac{V_L}{2} = V_p \cos 30^\circ$$

$$V_L = \sqrt{3} V_p$$

$$I_L = I_p$$

Power in one phase $P_p = V_p I_p \cos \varphi_L$

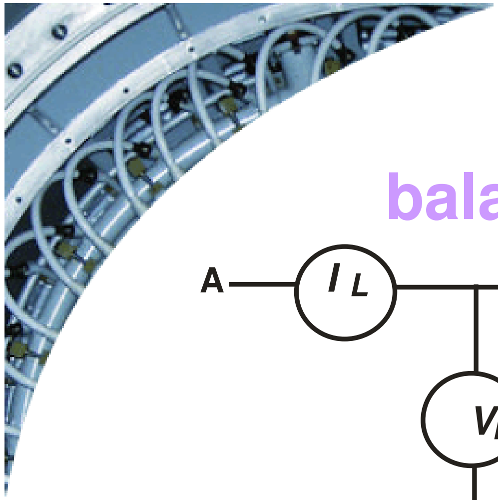
V_p: phase voltage magnitude

I_p: phae current magnitude

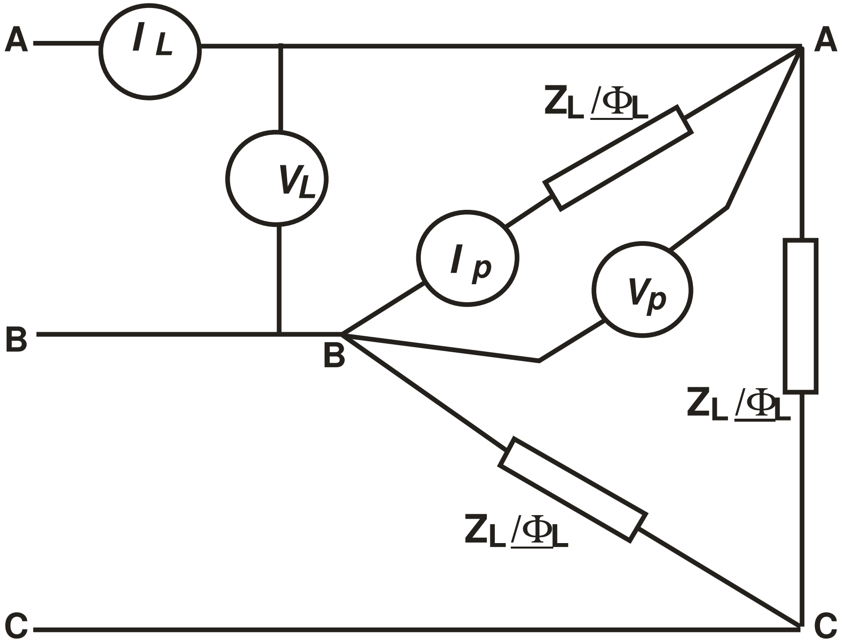
φ_L: angle between V_p and I_p

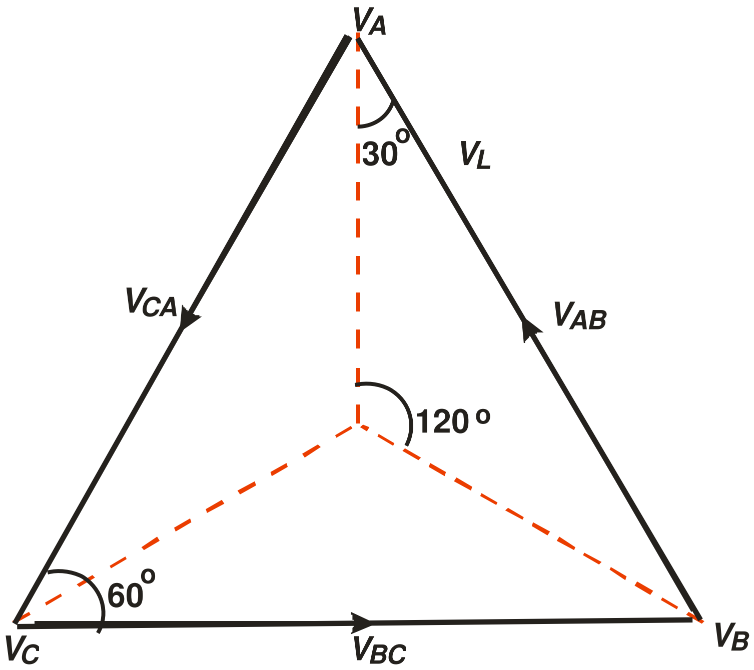
Total power in three phase

$$P_T = 3P_p = 3V_p I_p \cos \phi_L = \sqrt{3} V_L I_L$$



balanced system delta-connected load





$$\bar{I}_A = \bar{I}_{AB} - \bar{I}_{CA}$$

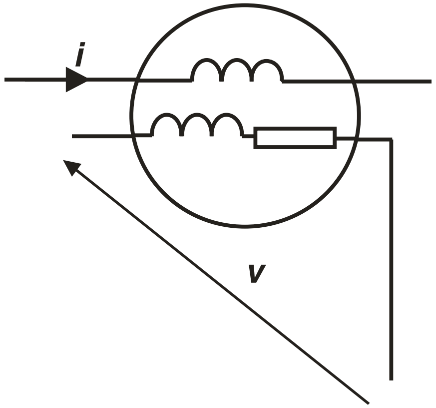
$$V_L = V_p$$

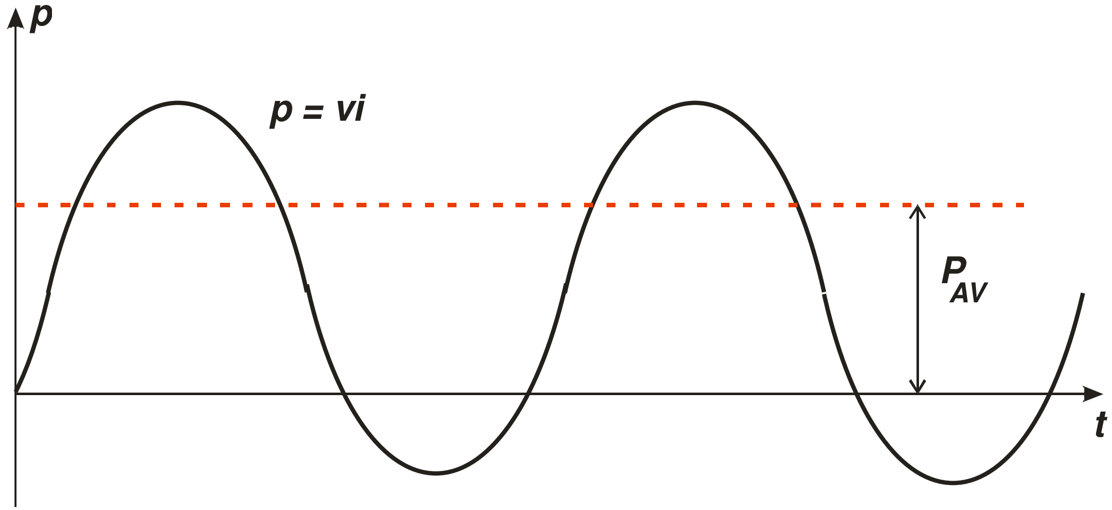
$$I_L = \sqrt{3} I_p$$

$$P_p = V_p I_p \cos\phi_L$$

$$P_T = 3P_p = 3V_p I_p \cos\phi_L = \sqrt{3} V_L I_L \cos\phi_L$$

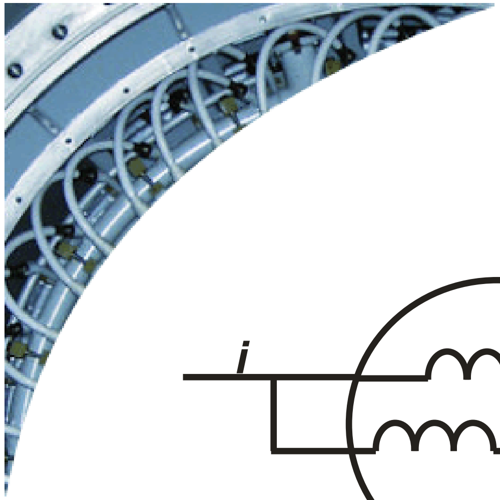
Measurement of Power in 3-phase Systems

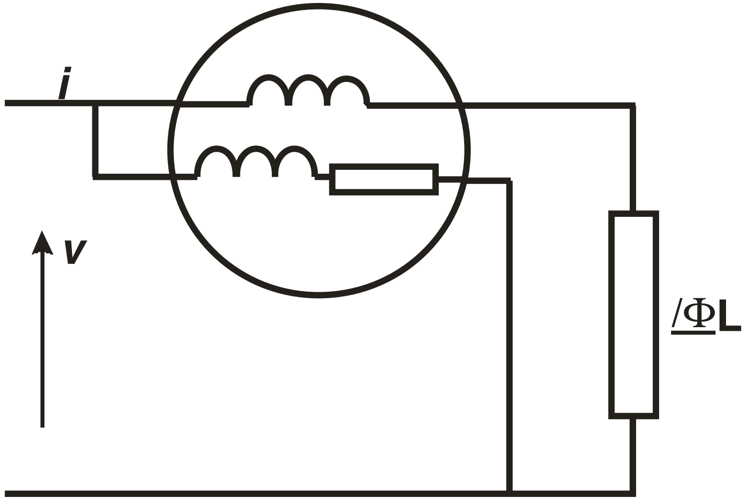




Wattmeter responds to average power

$$P_{AV} = vi\big|_{AV}$$





In this circuit

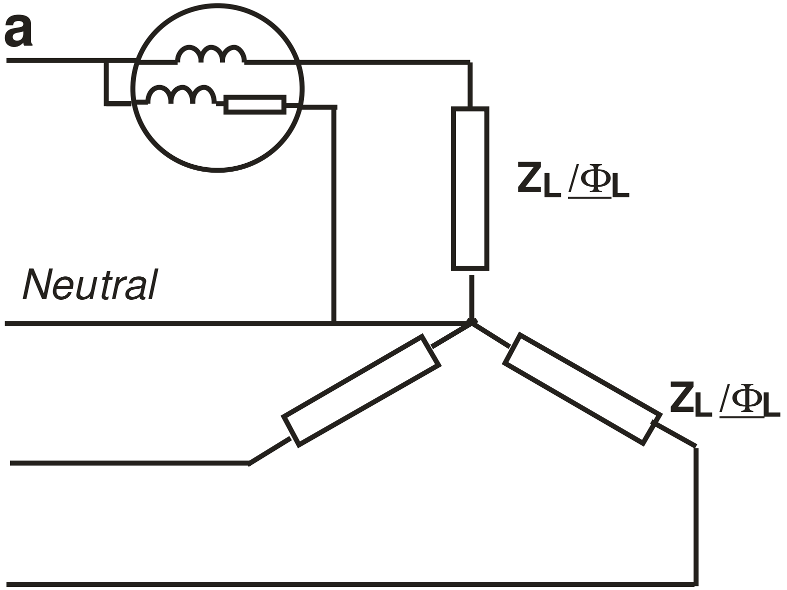
$$P_{AV} = vi\big|_{AV} = "VI\cos\phi_L"$$

where

V :	rms voltage at terminal of meter
I :	rms current into meter
$\phi_{L:}$	angle between *V* and *I* supplied to the meter

One-wattmeter method

With a balanced load



$$\text{"Reading"} = \text{"}VI\cos\phi_L\text{"}$$
$$= V_p I_p \cos\phi_L$$

power in one phase

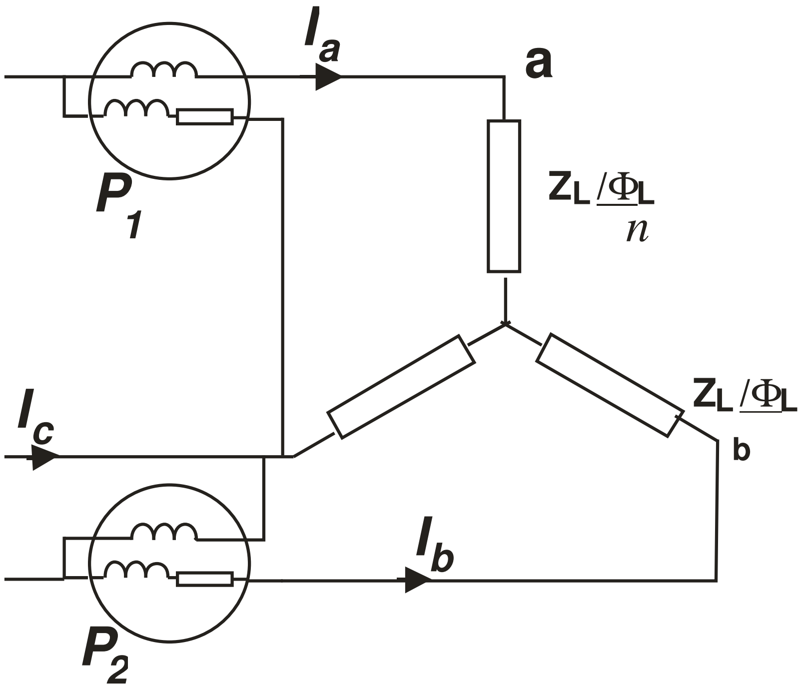
$$P_p = V_p I_p \cos\phi_L$$

total power

$$P_T = 3P_p$$
$$= 3V_p I_p \cos\phi_L$$

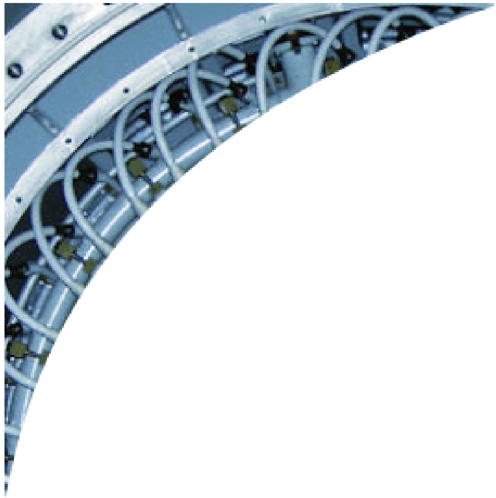
$$P_T = 3 \times \text{"meter reading"}$$

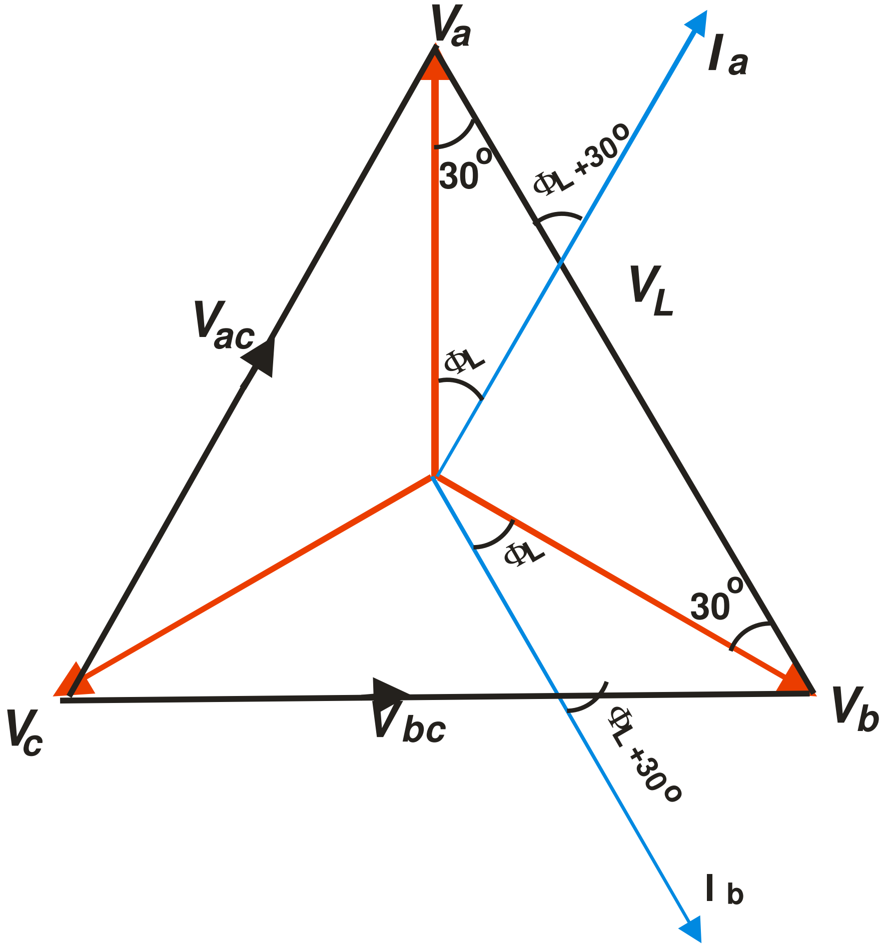
Two-wattmeter method



⇒ connection:

- current coil of P_1 and P_2 in any two of the phases
- negative of voltage coil of P_1 and P_2 both connected to the 3rd phase





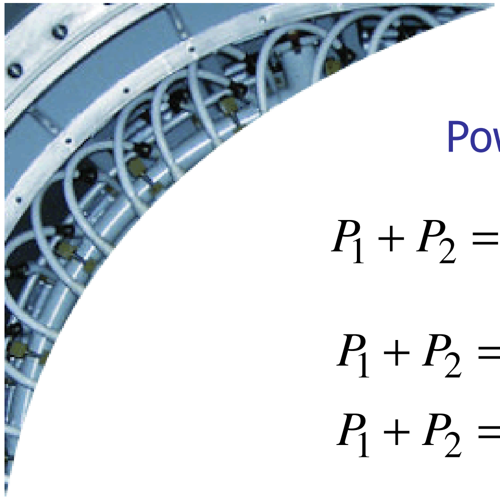
Meter Readings:

$$P_1 = "VI\cos\phi" = V_{ac} I_a \cos(\phi_L - 30^\circ)$$

$$P_2 = "VI\cos\phi" = V_{bc} I_b \cos(\phi_L + 30^\circ)$$

$$P_1 = V_L I_L \cos(\phi_L - 30^\circ)$$

$$P_2 = V_L I_L \cos(\phi_L + 30^\circ)$$



Power:

$$P_1 + P_2 = V_L I_L \left[\cos(\phi_L - 30^\circ) + \cos(\phi_L + 30^\circ)\right]$$

$$P_1 + P_2 = V_L I_L 2\cos\phi_L \cos 30^o$$

$$P_1 + P_2 = \sqrt{3} V_L I_L \cos\phi_L$$

$$= \text{Total} \quad \text{Power}$$

Power Factor:

$$P_1 - P_2 = V_L I_L \left[\cos(\phi_L - 30^\circ) - \cos(\phi_L + 30^\circ)\right]$$

$$= V_L I_L 2\sin\phi_L \sin 30^o$$

$$= V_L I_L \sin\phi_L$$

$$\frac{P_1 - P_2}{P_1 + P_2} = \frac{V_L I_L \sin\phi_L}{\sqrt{3} V_L I_L \cos\phi_L}$$

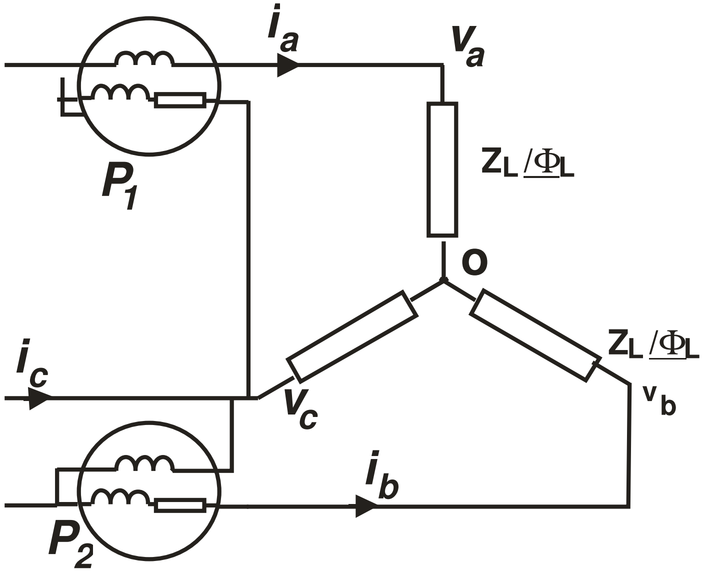
$$= \frac{1}{\sqrt{3}} \tan\varphi_L$$

$$\text{Power} \quad \text{factor} = \cos\phi_L$$

⇒ advantages of two-wattmeter method:

- no neutral is required, eg neutral may be buried in motor
- from the two meter readings both total power and power factor can be determined
- this method is valid even for unbalanced situations, ie total power is equal to the sum of the readings.

To show that $P_1 + P_2 = P_T$ even for unbalanced situations



$$P_1 = (v_{ac} i_a)\big|_{AV} = (v_a - v_b) i_a\big|_{AV}$$

$$P_2 = (v_{bc} i_b)\big|_{AV} = (v_b - v_c) i_b\big|_{AV}$$

$$P_1 + P_2 = (v_a i_a)\big|_{AV} + (v_b i_b)\big|_{AV} - v_c (i_a + i_b)\big|_{AV}$$

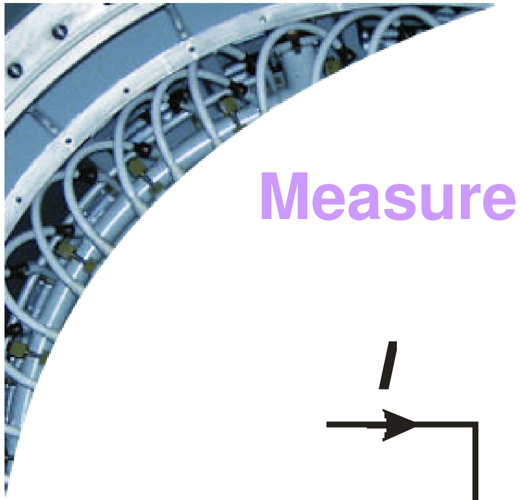
- if there is no neutral

$$i_a + i_b + i_c = 0$$

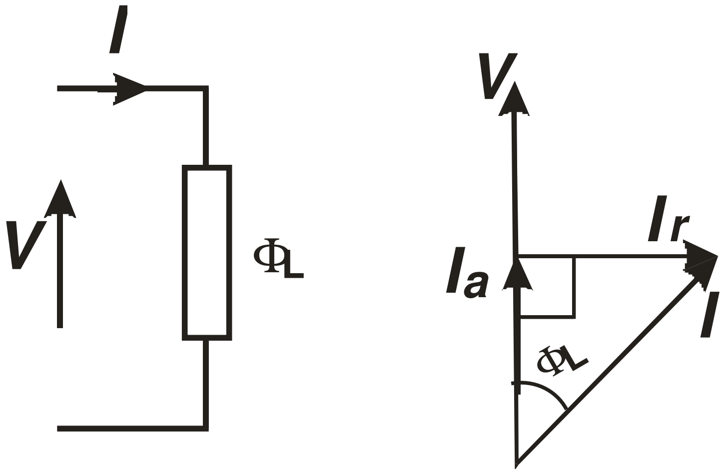
- therefore

$$P_1 + P_2 = (v_a i_a)\big|_{AV} + (v_b i_b)\big|_{AV} + (v_c i_c)\big|_{AV}$$

$$P_1 + P_2 = P_a + P_b + P_c$$



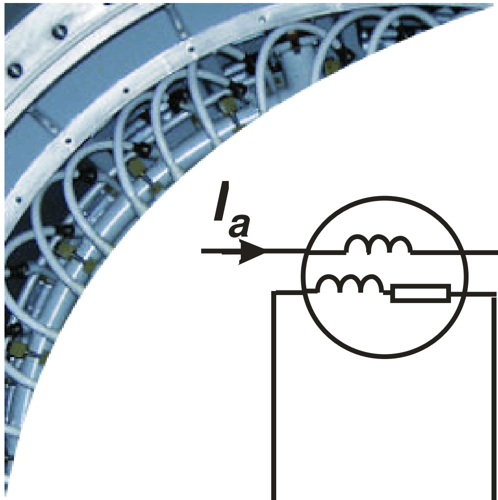
Measurement of reactive power in 3-ph balanced system

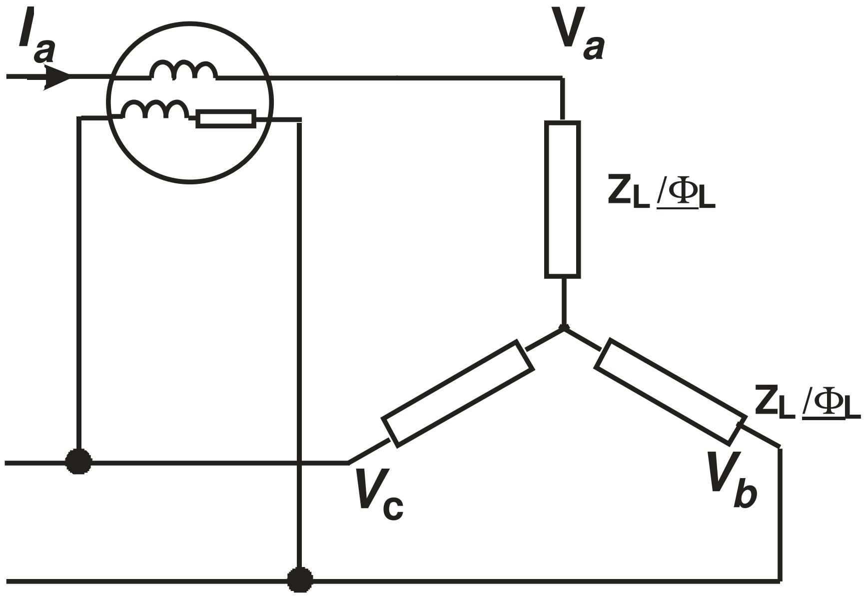


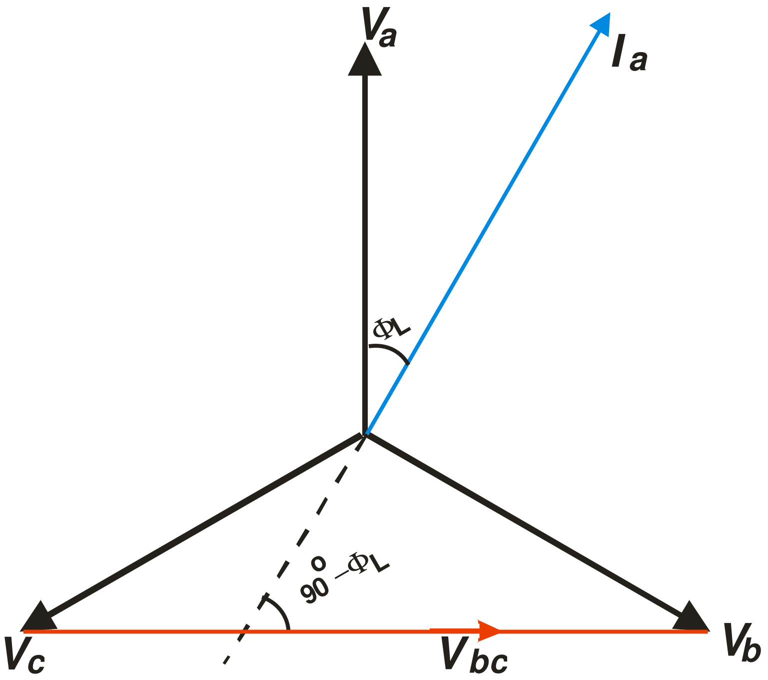
Real power $= P = VI\cos\varphi_L \quad = VI_a$ [W]

Reactive power $= Q = VI\sin\varphi_L \quad = VI_r$ [VAr]

Apparent power $= S = VI \quad = VI$ [VA]



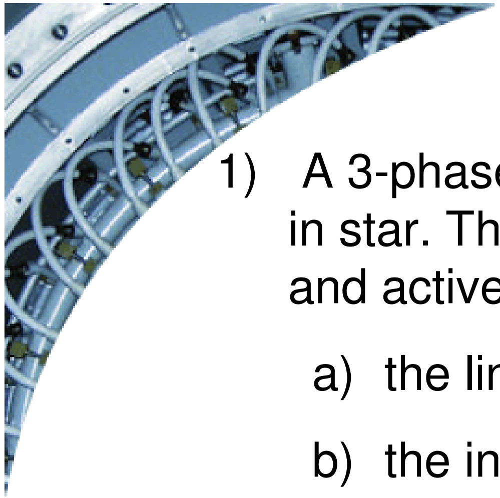




$$\text{Meter Reading} = \text{"}VI\cos\phi\text{"} = V_{bc} I_a \cos(90^o - \phi_L) = V_L I_L \sin\phi_L$$

$$\text{Reactive Power in one phase} = V_p I_p \sin\phi_L$$

$$\text{Total Reactive Power } Q_T = 3V_p I_p \sin\phi_L = \sqrt{3} V_L I_L \sin\phi_L = \sqrt{3} \times \text{Wattmeter Reading}$$



Examples

1) A 3-phase 50-Hz supply has a load comprising three similar coils connected to it in star. The line current is 20 A, with associated input apparent power of 20 kVA and active power of 11 kW. Determine
   a) the line and phase voltages
   b) the input reactive power
   c) the resistance and inductance of the coil.

   If the coils are connected in delta to the same supply, find
   d) the line current
   e) the active power.
2) Each phase of a delta connected load consists of a resistor *R* and a capacitor *C* in parallel. When connected to a balanced 3-phase supply the “two-wattmeter” method gave readings of 1000 W and 500 W, the line voltage being 400 V, 50 Hz and the line current being 2.5 A.
   a) Calculate the load power factor using the total power, voltage and current
   b) Calculate the load power factor using the two wattmeter readings only
   c) Determine the values of *R* and *C*.