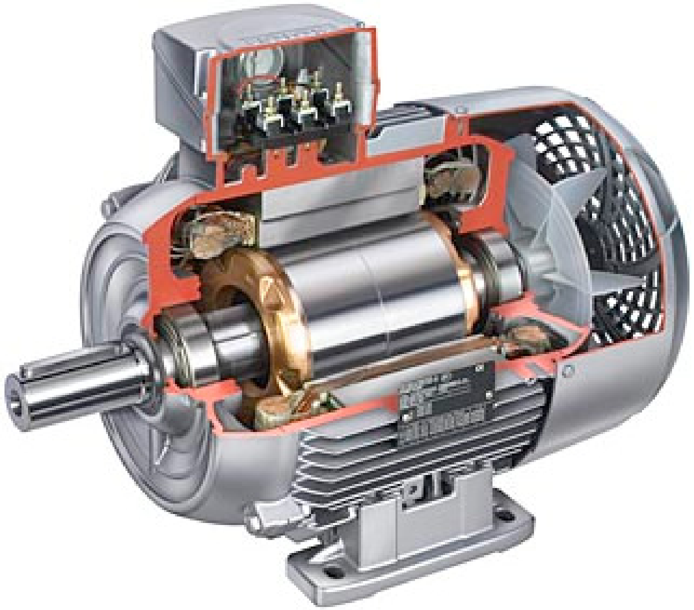
EEE 3352

Electromechanics & Electrical Machines



Lecture 7: Introduction to power systems

Dr A Zulu

7. Introduction to Power Systems

1. Energy: system viewpoint
2. Transmission system
3. HVAC transmission
4. Three phase power systems
    1) balanced star
    2) balanced delta
5. Measurement of power in three phase systems

Objectives:

- at the end of the lecture, students should be able to
    - explain the importance of electrical energy in systems
    - justify the role electrical power in energy systems
    - explain the features of electrical transmission systems
    - justify the use of three phase systems
    - derive relations of one-phase and three-phase quantities in star and delta configurations
    - show effective methods to measure power in three phase systems
    - apply appropriate methods to measure power in three phase systems

7.1 Energy: System Viewpoint

1. Introduction
2. Types of Energy
3. Uses of energy
4. Sources of Energy
5. Conversion of emergy
6. Storage of Energy
7. Transmission of Energy
8. Role of Electric Power
9. Competitive Uses of Natural Sources

7.1.1 Introduction

- Energy is essential for life
- Energy also determines quality of life

- There many sources of energy
- There many uses of energy

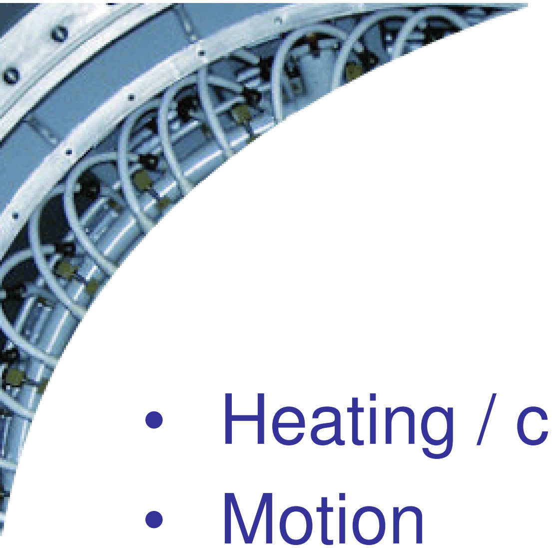
- thus *USES (NEEDS)* vs *SOURCES*

7.1.2 Types of Energy & Power

- “Capacity to do work”
  - Energy >< Power

- **Energy**: term relevant for storage
  - *oil tanker, coal mine, water reservoir, battery, etc*

- **Power**: term relevant for flow of energy
  - *rotating shaft, electric cable, gas pipe-line, etc*



7.1.3 Uses of Energy

- Heating / cooling
- Motion
- Lighting
- Electrochemical processing
- ICT

7.1.4 Sources of Energy

- Non-renewable
  - coal
  - oil
  - natural gas
  - nuclear fuel

Fossil fuels

- Renewable
  - solar
  - hydro
  - wind
  - bio-energy
  - geothermal
  - tidal & ocean

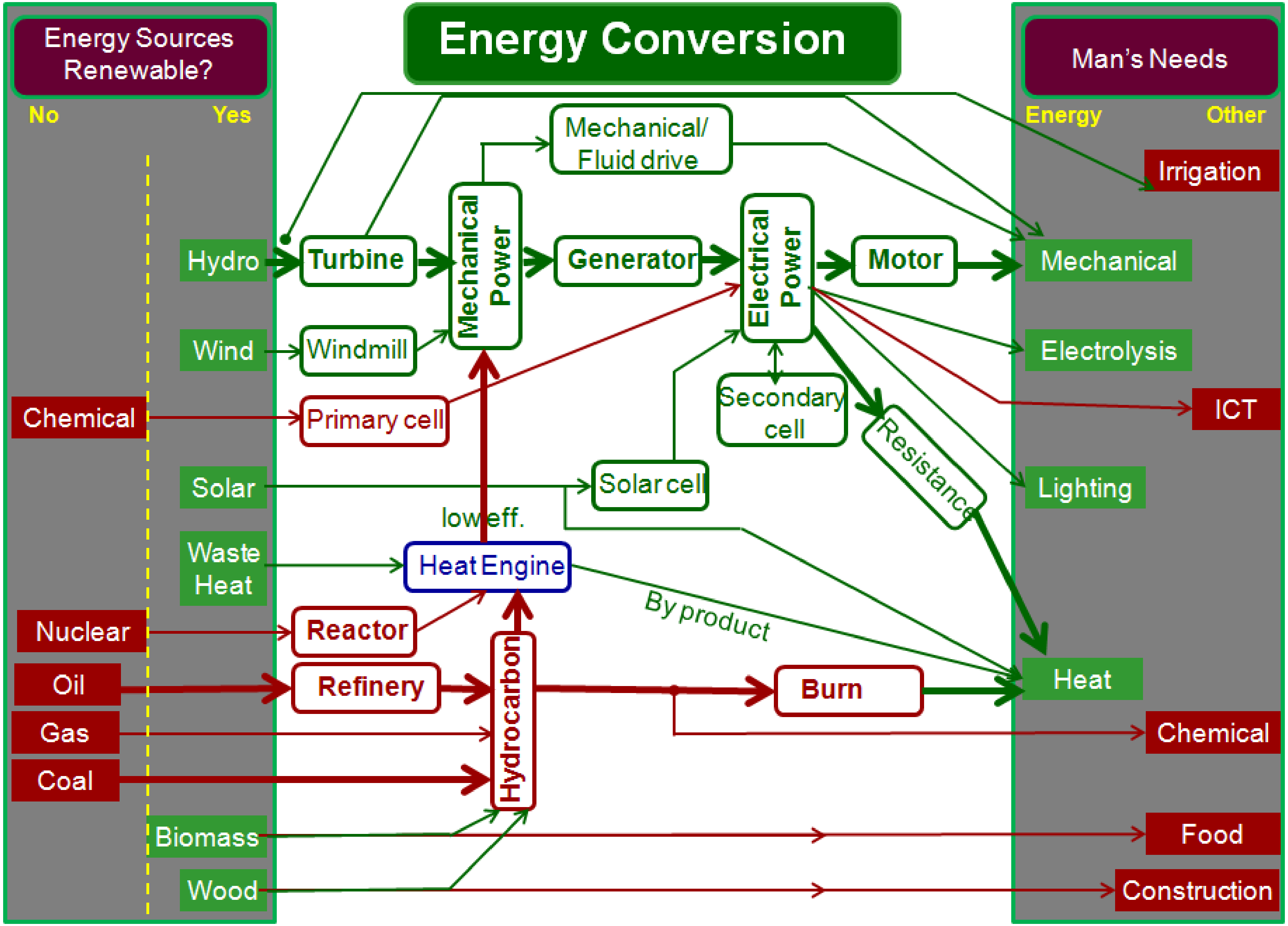
Characteristics of RE & Non RE Energy

	Renewable	**Non Renewable**
Location	Natural local environment	Relatively concentrated regions
Availability	A given average power	A given amount of stored energy
Life time of supply	No limit	Coal: 100-1000 years; oil: 10-100 years
Cost	High capital, but low running costs	Moderate to high capital; Moderate running costs

7.1.5 Energy Conversion

- “law of conservation of energy”
  - conversion processes
    - chemical ↔ thermal : burning wood / endothermic reaction
    - thermal ↔ mechanical : ? / ?
    - thermal ↔ electrical : ? / ?
    - potential ↔ kinetic : ? / ?
    - mechanical ↔ electrical : ? / ?
    - electrical ↔ thermal : ? / ?
    - electrical ↔ chemical : ? / ?
  - think of an example for each of these conversions

Energy Conversion



Energy Sources
Renewable?

No
Yes

Hydro
Wind
Chemical
Solar
Waste Heat
Nuclear
Oil
Gas
Coal
Biomass
Wood

Turbine
Windmill
Primary cell
Mechanical Power
Mechanical/ Fluid drive
Generator
Electrical Power
Motor
Secondary cell
Solar cell
Resistance
low eff.
Heat Engine
Reactor
Refinery
Hydrocarbon
By product
Burn

Man's Needs

Energy
Other

Irrigation
Mechanical
Electrolysis
ICT
Lighting
Heat
Chemical
Food
Construction

7.1.6 Storage of Energy

- **Intermittent Supply**
  - solar -charge batteries
  - wind -fill up water resv
  - river - lake
  - petrol engine -flywheel
  - dc - capacitor/inductor
  - oil tanker
  - mechanical spring
- **Intermittent Demand**
  - pneumatic drill
  - starter motor-battery
  - “pumped storage”
  - steam pressure in boiler
  - capacitors - high spark discharge

7.1.7 Transmission of Energy

- Geographical & geological features of the earth determine the **sources** of energy
  - [oil, coal, hydro power, etc]

- Other different features influence where energy is **needed**
  - [in towns, mining, industry, farming]

- Usually **sources** and places of **utilization** are separate
  - so, **transmission** of energy becomes important

7.1.8 Transmission of Energy

- continuous transmission
- batch transmission

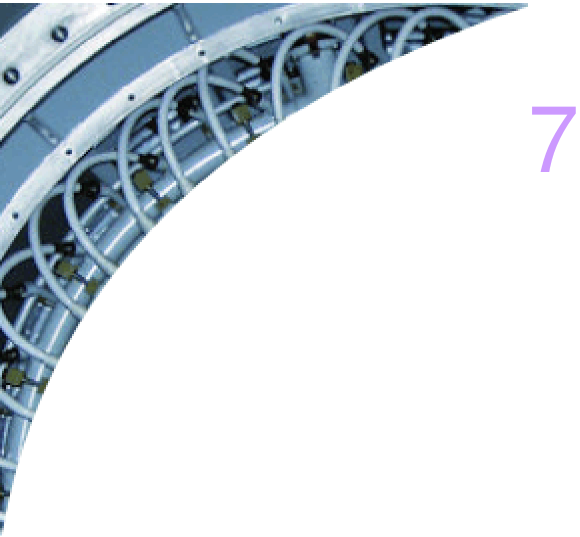
Transmission of Energy

Distance	Continuous	Batch
Long (over 1000 km)	Oil pipeline, gas pipeline, HVAC,HVDC	Oil tanker, coal ships
Medium (1-1000 km)	Oil & gas pipeline, Medium to high voltage	Oil in vehicle, tank, coal in trains, biomas in truck
Short (10m-1km)	Gas pipe, elec(low, high Voltage) conveyor, flues	Biomass in truck, wood
Same building [under 30m]	As in Short	Solid fuel by hand or truck

7.1.9 Role of Electrical Power

- Disadvantages
  - it does not occur naturally
  - not required as end-product (except in electrolysis, communication & computing)
  - Cannot be directly stored

- Advantages
  - high conversion efficiency
  - ease of transmission
  - high transmission efficiency
  - flexible distribution



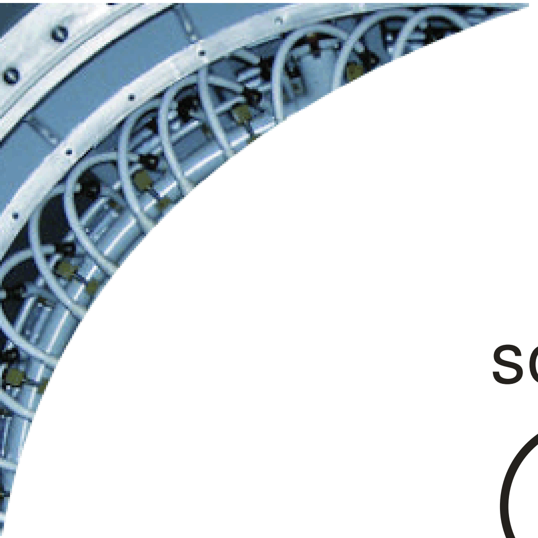
7.1.9 Role of Electrical Power - A summary

Role	Electrical form	Performance
Use	N	N/A
Source	N	N/A
Conversion	Y	High efficiency
Transmission	Y	High efficiency

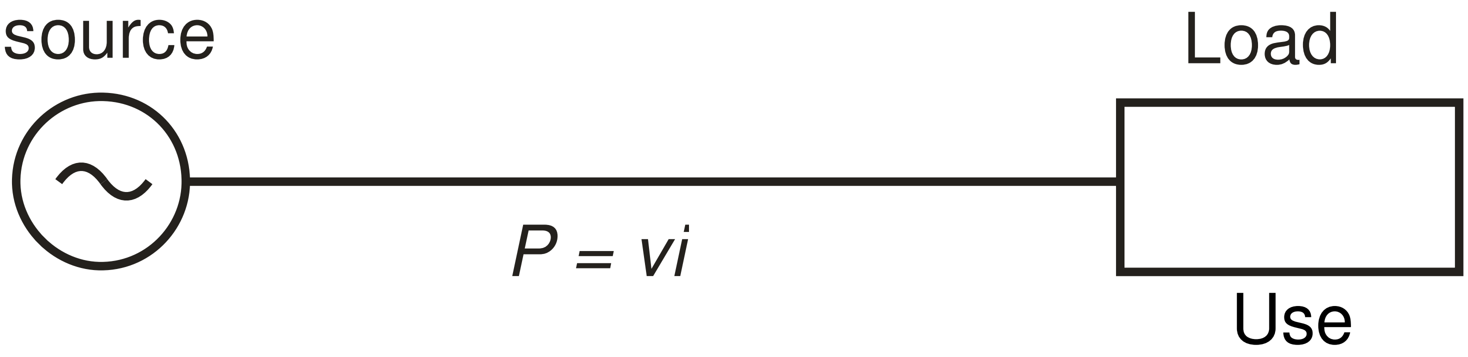
7.1.10 Competitive Uses of Sources

- Best balance of alternative sources and competitive needs

- Environmental issues
  - extra carbon-dioxide and global warming
  - nuclear waste
  - non-renewable resources



7.2 Transmission system



source

Load

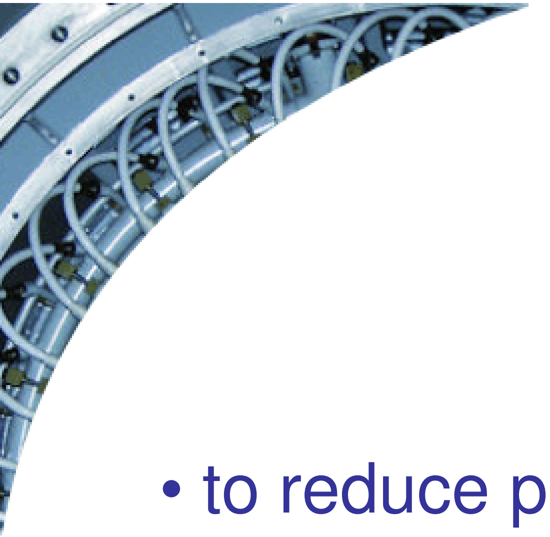
$P = vi$

Use

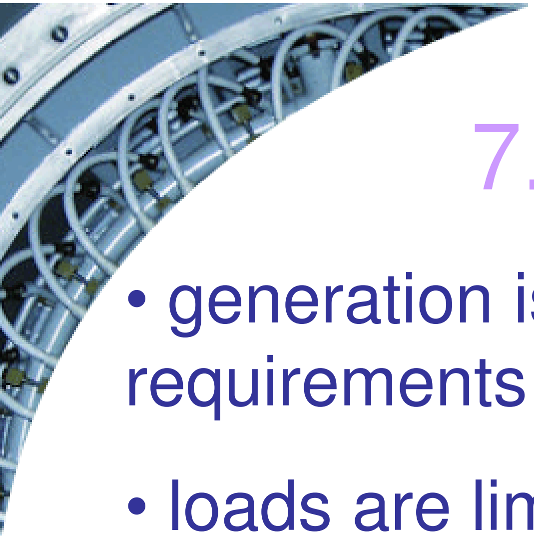
- line losses

$$P_{loss} = 2(i^2 R) = 2\left(i^2 \frac{\rho l}{A}\right)$$

  - for 2 lines – forward and return conductor



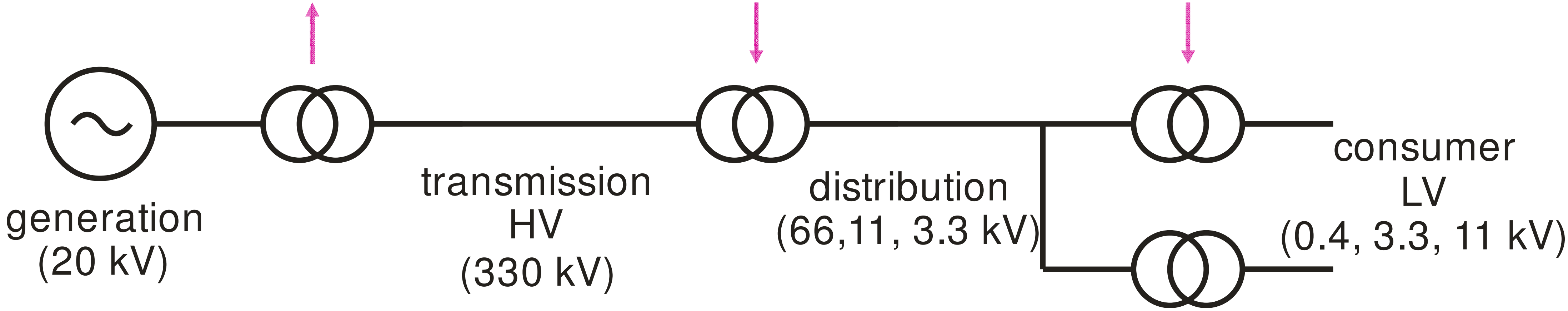
- to reduce power losses
  - reduce R (limited)
  - reduce i
- to transmit the same power, reduce i and increase v
- hence high voltage (HV) transmission systems



7.2.1 HV transmission system

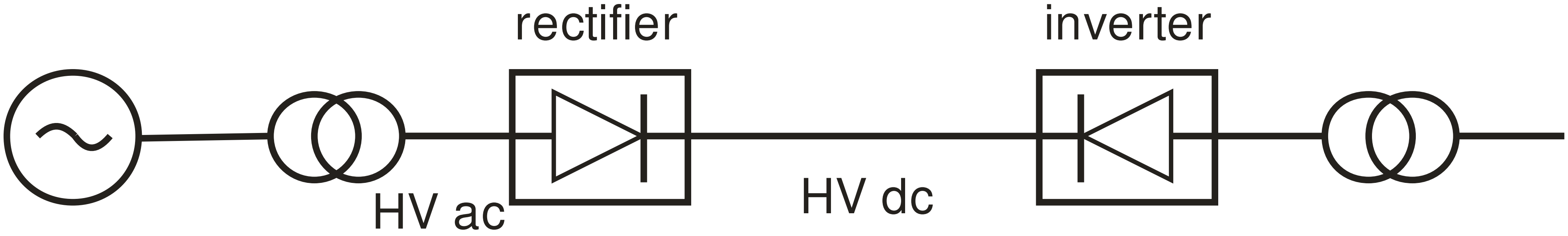
- generation is limited to approx 20 kV, due to insulation requirements
- loads are limited to approx 10 kV due to
    - safety
    - size
    - insulation
- we must change voltage levels to transmit high power
- to change voltage levels, we must use
    - transformer
    - hence ac system

7.2.2 High voltage AC system (HVAC)



- generation
  - up to 25 kV (18 kV)
- transmission
  - 110 kV – 1000 kV (66, 110, 132, 220, 330, 400, 525, 750 kV)
- distribution
  - 3.3 kV – 88 kV (3.3, 6.6, 11, 33 kV)
- consumer
  - 0.19 -15 kV (0.4, 0.55, 3.3, 6.6, 11 kV)

7.2.3 High voltage DC system (HVDC)



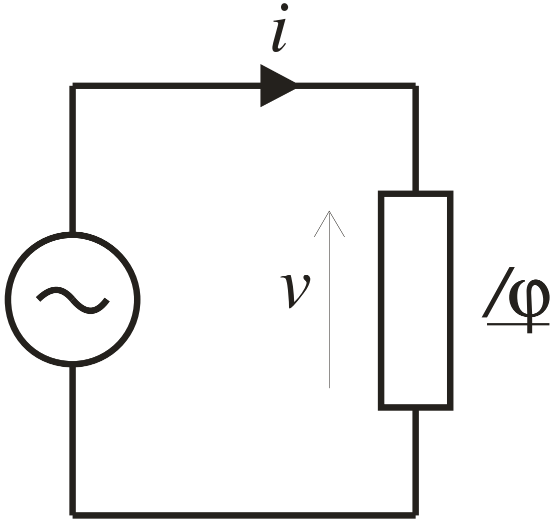
- HVDC is employed where
  - transmission over larger distances (> 500 km)
  - interconnection of systems with different systems
    - (eg 50 Hz to 60 Hz)
  - back-to-back in a substation for power flow control

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

7.3 HVAC

Single phase and 3-phase

Single phase:



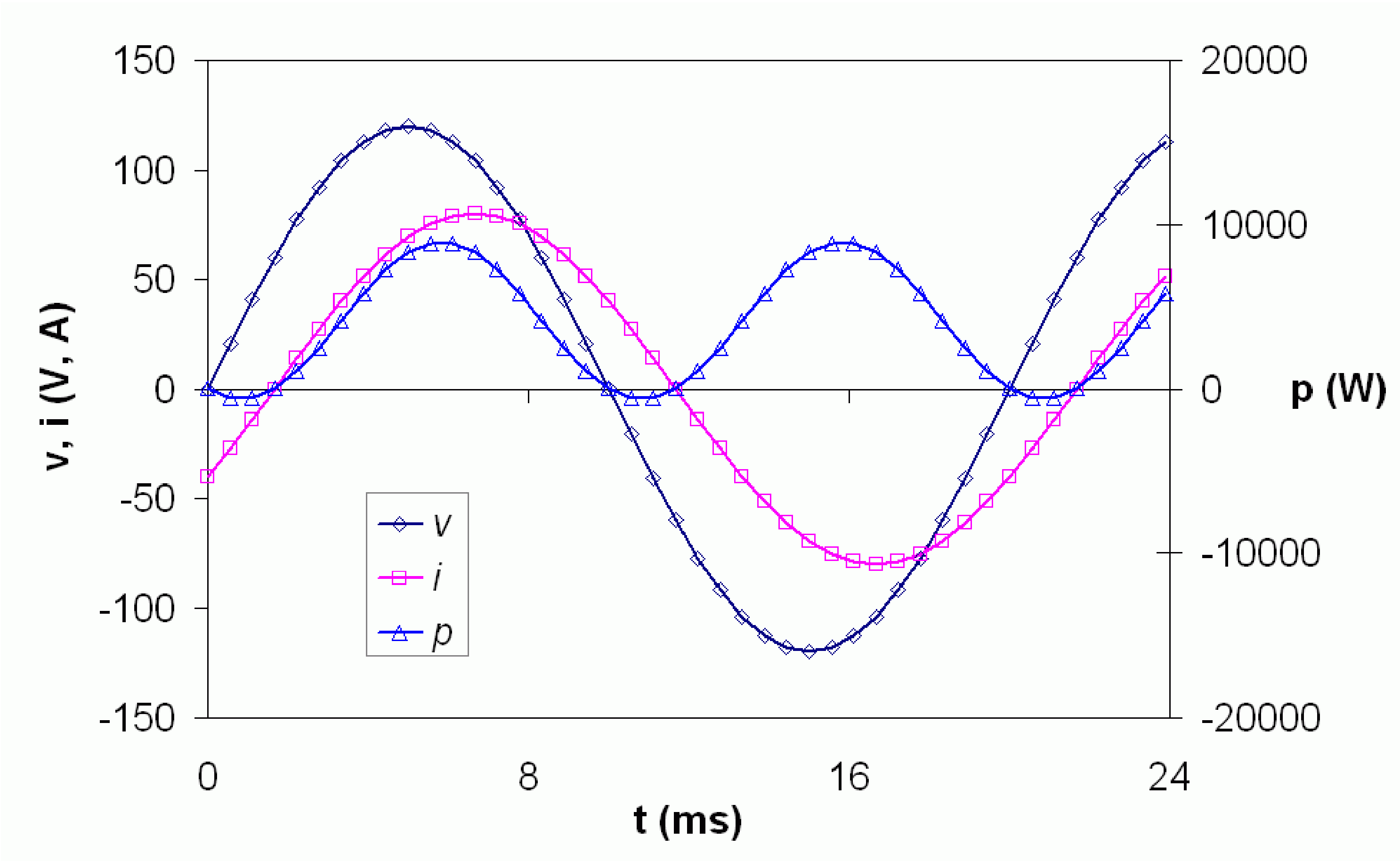
$$v = V_m \sin \omega t$$

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

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

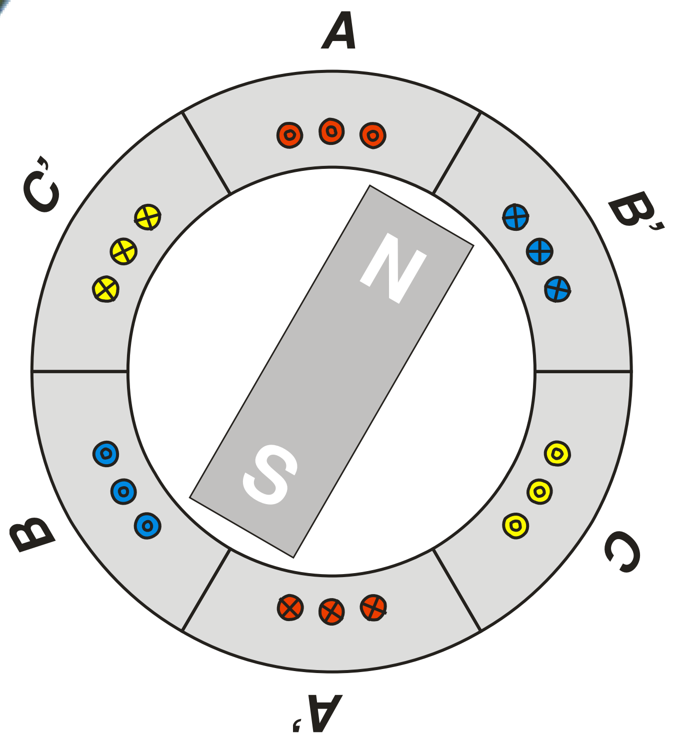
$$P = V_m I_m \tfrac{1}{2}[\cos \phi - \cos(2\omega t - \phi)]$$

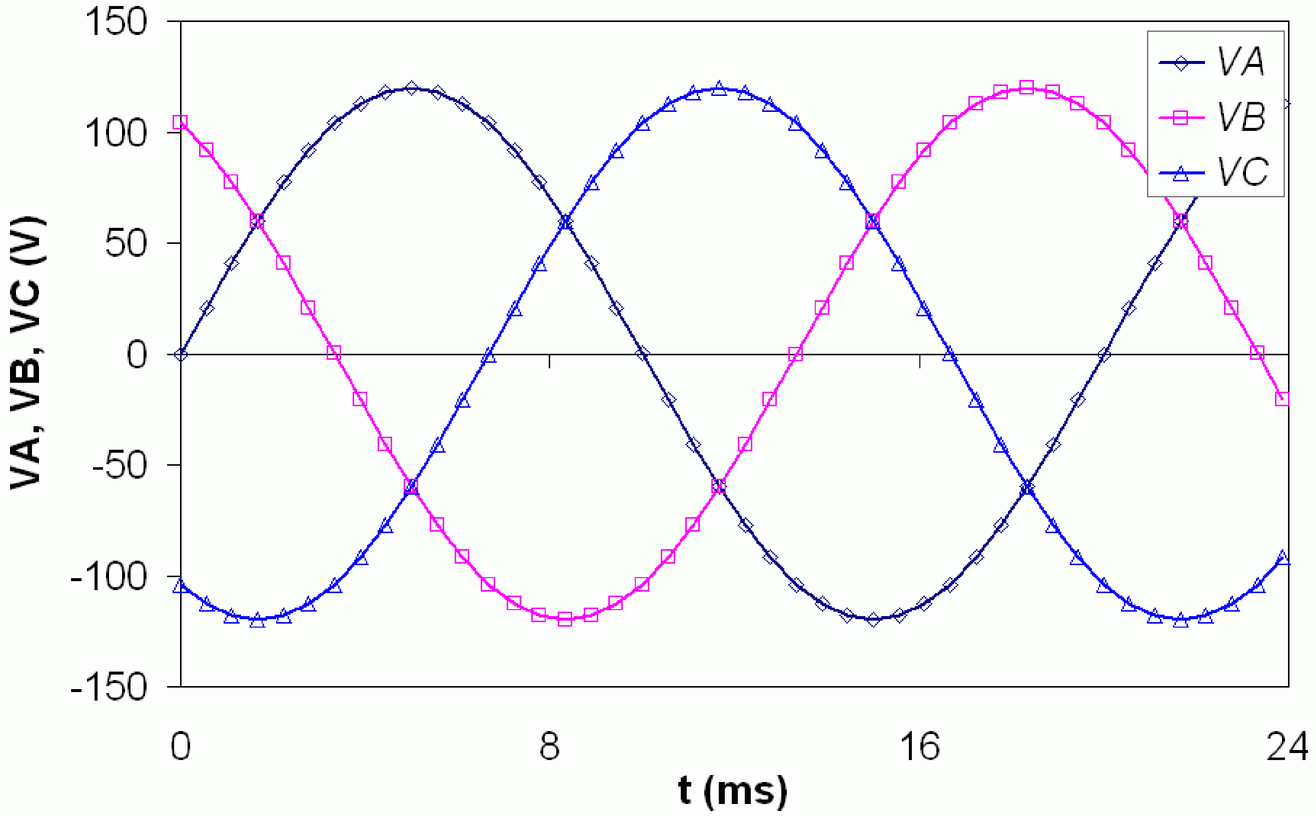
$$P = \underbrace{VI \cos \phi}_{\text{constant}} - \underbrace{VI \cos(2\omega t - \phi)}_{\text{varying at } 2f}$$



- single phase systems:
  - have large and undesirable fluctuations in instantaneous power

Three phase:





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

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

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

power for phase *A*

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

power for phase *B*

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

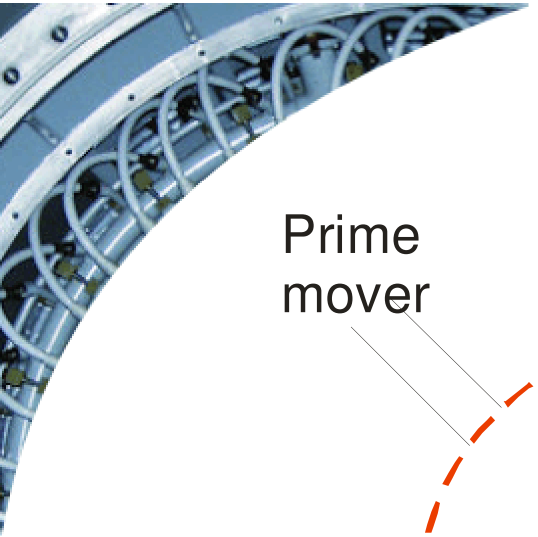
power for phase *C*

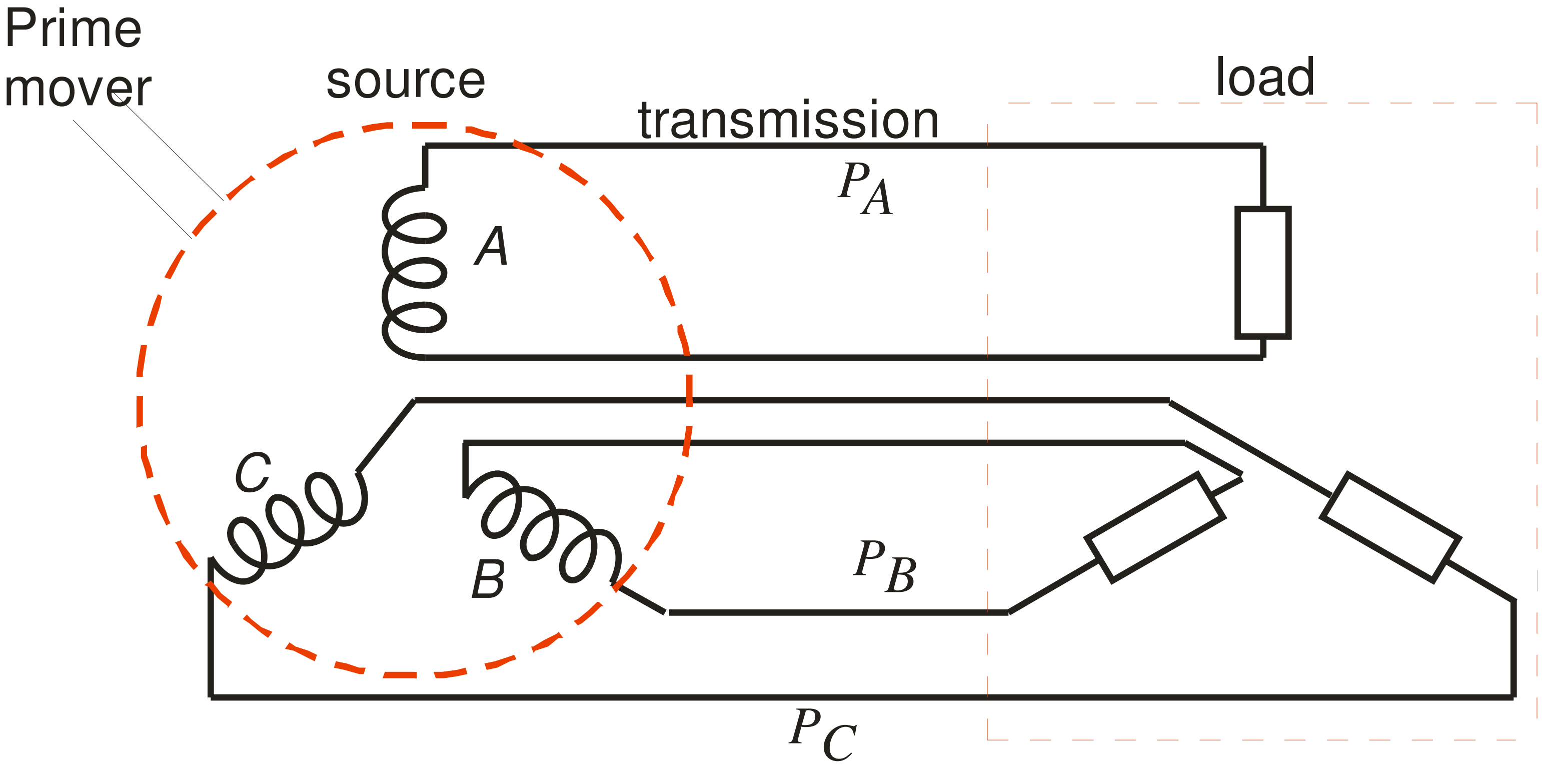
$$P_C = VI\cos\phi - VI\cos(2\omega t - \phi - 480^\circ)$$

total instantaneous power

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

$$P = 3VI\cos\phi$$

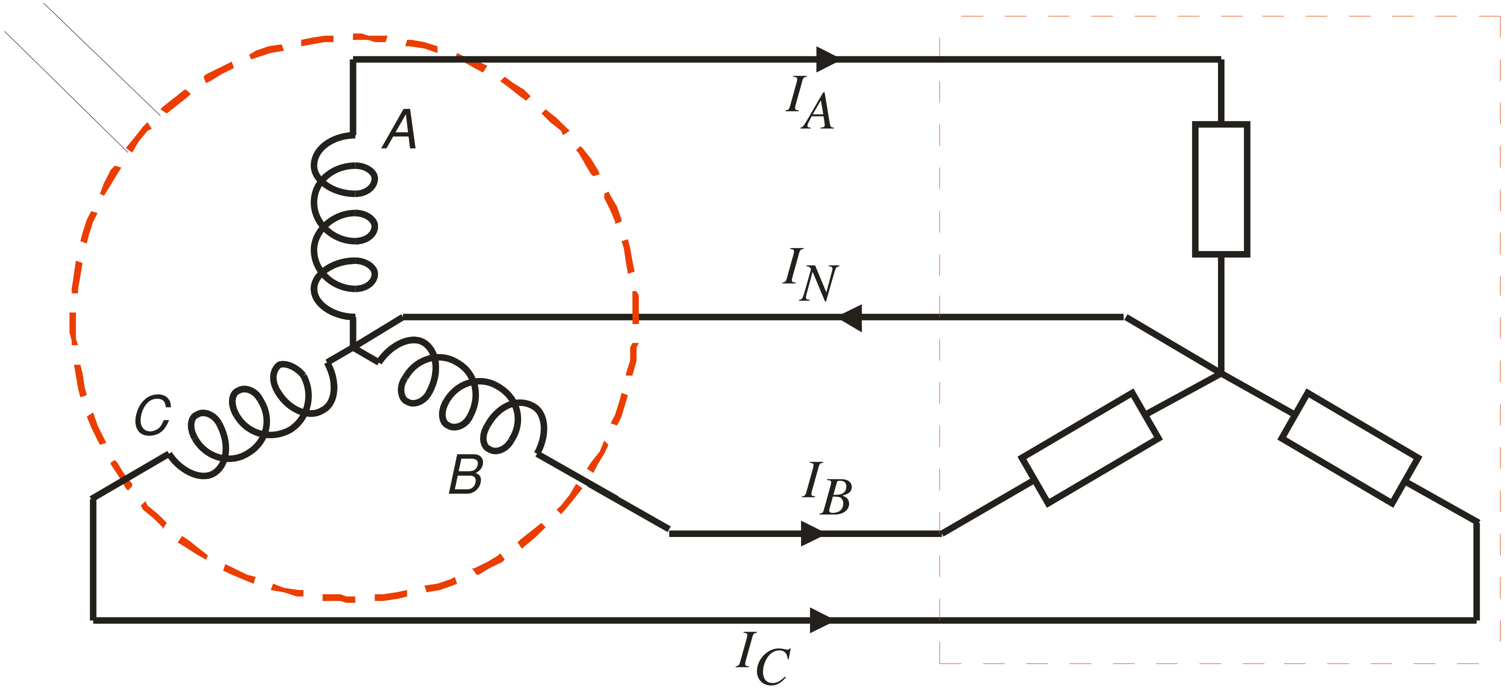


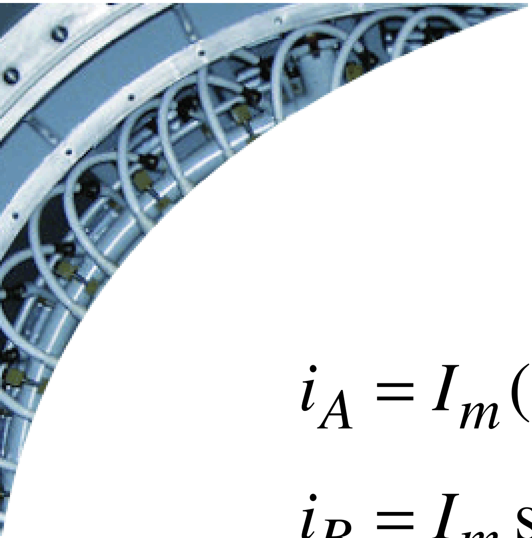


- advantage 1:
    - power from the prime mover to the load is absolutely constant

Three phase transmission:

- instead of 6 conductors between the generator and load,
  - join the windings together as shown and have 4 conductors



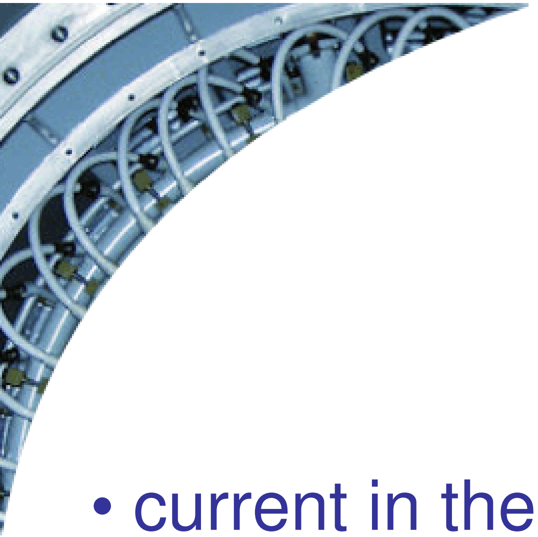


$$i_A = I_m(\sin \omega t - \phi)$$

$$i_B = I_m \sin(\omega t - \phi - 120^\circ)$$

$$i_C = I_m \sin(\omega t - \phi - 240^\circ)$$

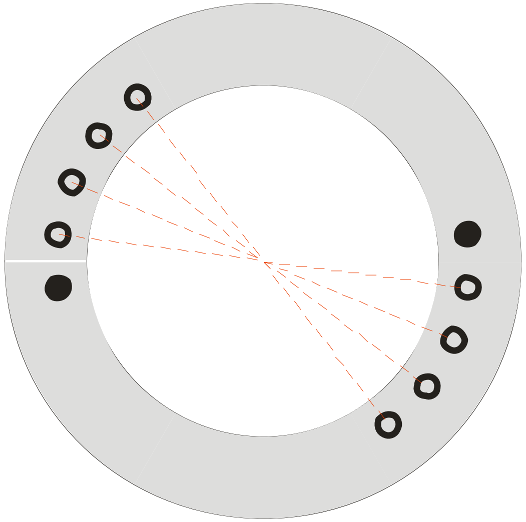
$$\begin{aligned} i_N &= i_A + i_B + i_C \\ &= I_m\left[\sin(\omega t - \phi) + 2\sin(\omega t - \phi)\cos 120^\circ\right] \\ &= 0 \end{aligned}$$

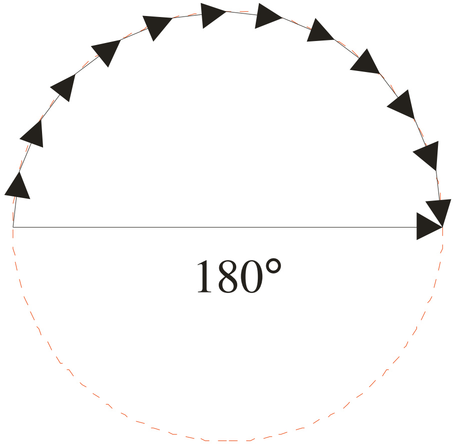


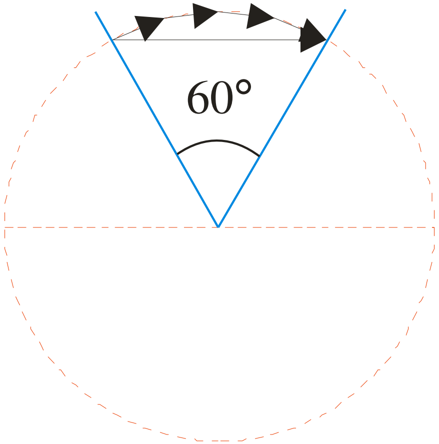
- current in the neutral conductor under balanced conditions is zero
- we need only have 3 conductors for our three-phase system

- advantage 2:
    - there is a big saving in transmission conductors

Space factor of machines



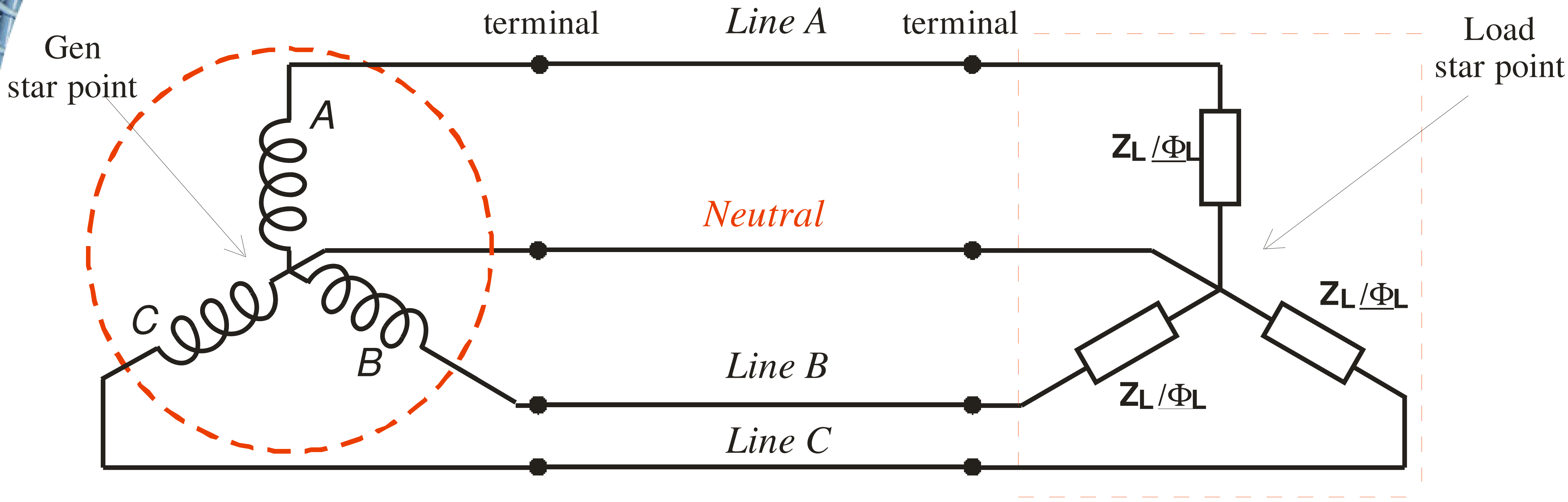




- if stator of the generator is wound for 3 separate phases instead of just one single phase,
  - we obtain a higher value of distribution factor
  - the result of this is that there is bigger value of space factor

- advantage 3:
  - output per unit volume of three phase machines is higher than for single phase machines

7.4 3-phase power systems



- balanced supply:
  - same magnitude of voltage every 120°

$$V_A = V_p \underline{/0^\circ}$$

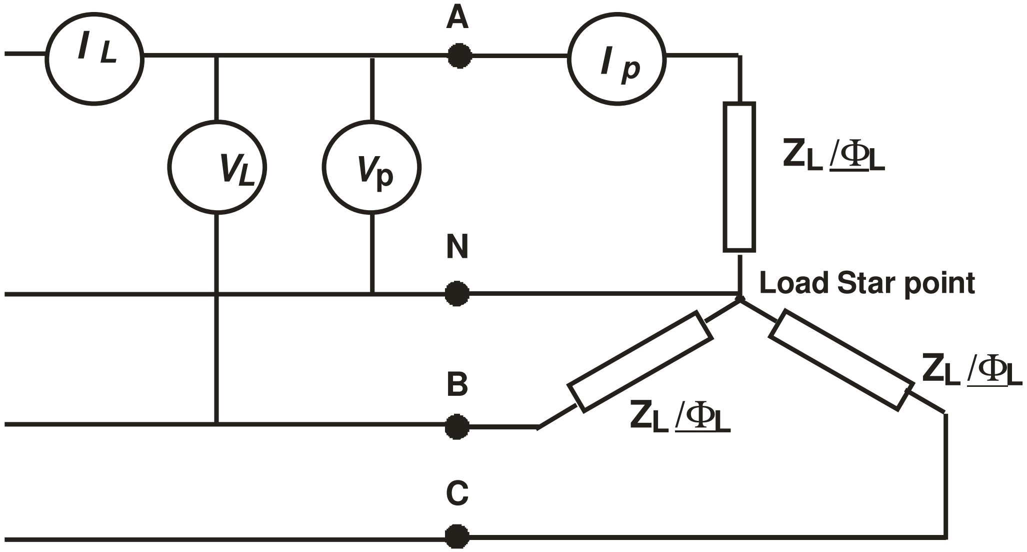
$$V_B = V_p \underline{/120^\circ}$$

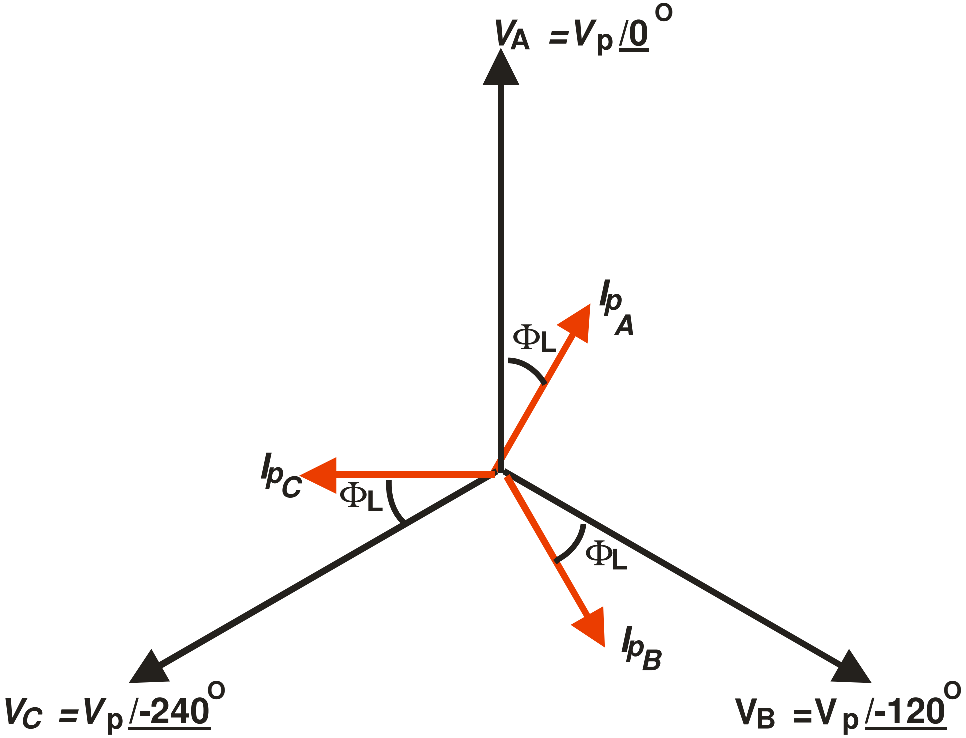
$$V_C = V_p \underline{/240^\circ}$$

- balanced load
  - same impedance in each phase every 120°
    - same magnitude and phase
    - $\overline{\boldsymbol{Z_L}} = Z_L \underline{/\phi}$
  - this is normal for large 3-phase loads,
    - not so for individual single-phase loads

- balanced system
    - both supply and load are balanced

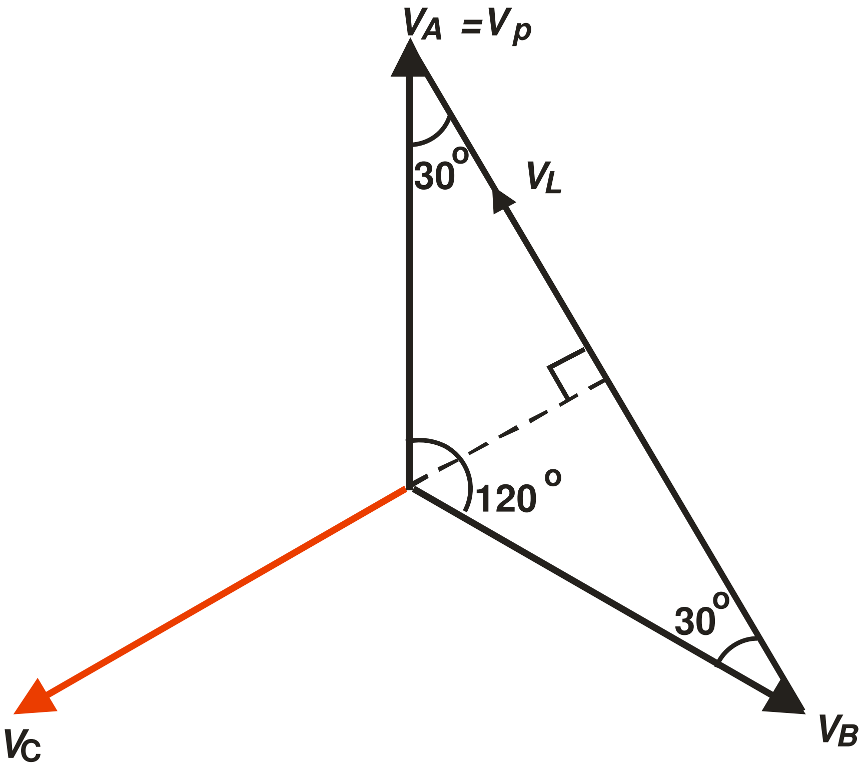
7.4.1 balanced system star-connected load





- subscript *p*: phase,
  - means looking at one phase
- subscript *L*: line,
  - means looking at three phases

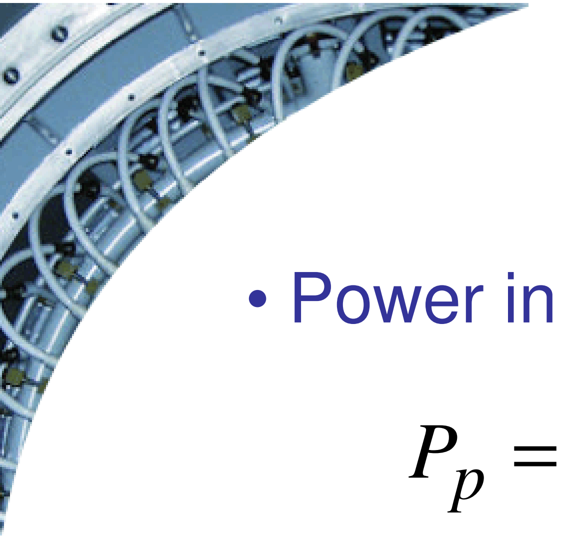
- A balanced supply voltage applied to a balanced load gives
  - a balanced set of phase currents
    - same magnitude and displaced every 120°



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

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

$$I_L = I_p$$



- Power in one phase

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

V_p: phase voltage magnitude

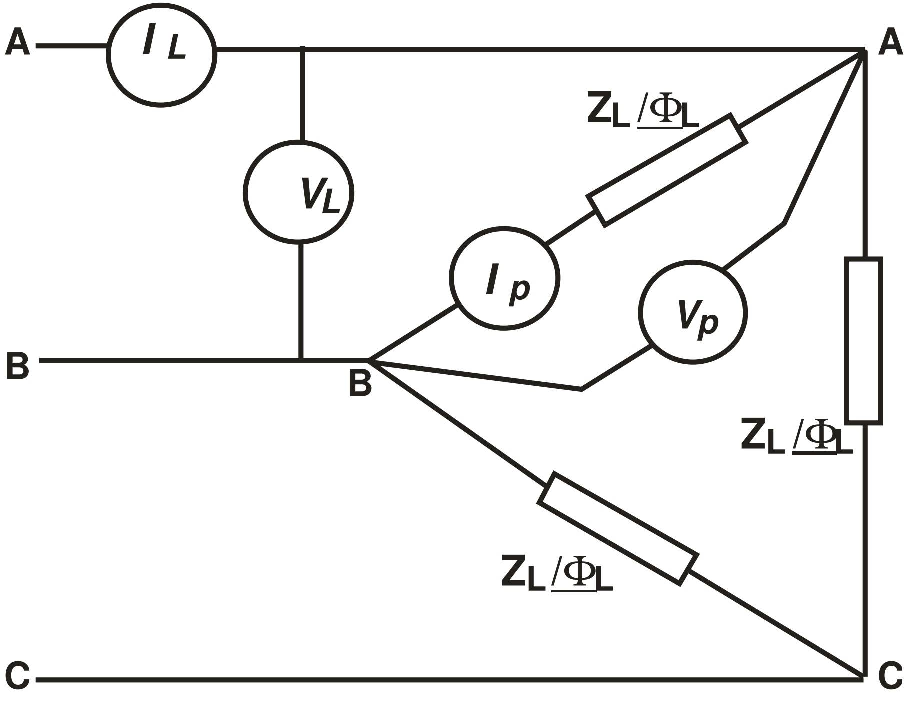
I_p: phase current magnitude

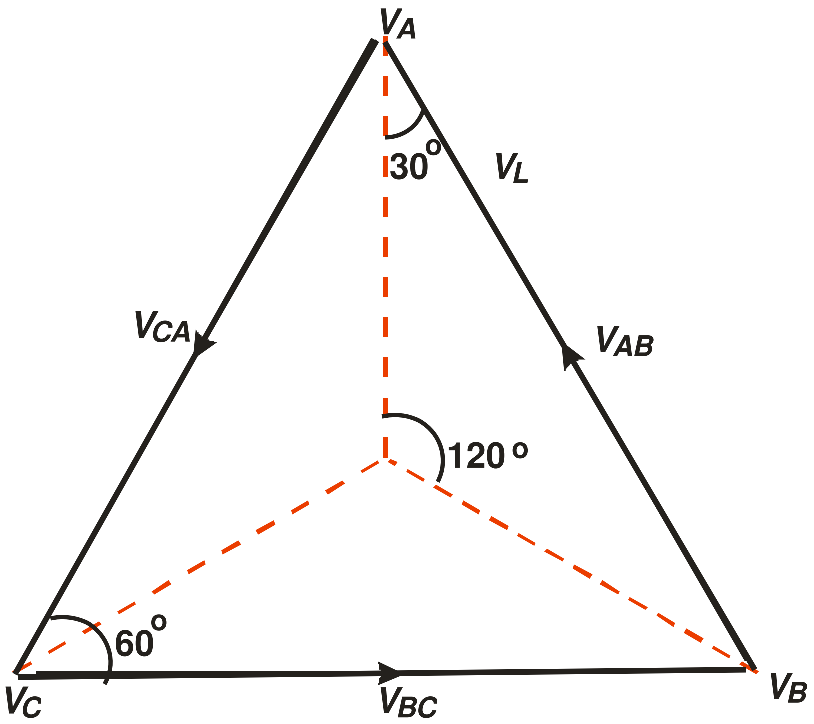
ϕ_L: angle between V_p and I_p

- Total power in three phase

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

7.4.2 balanced system delta-connected load

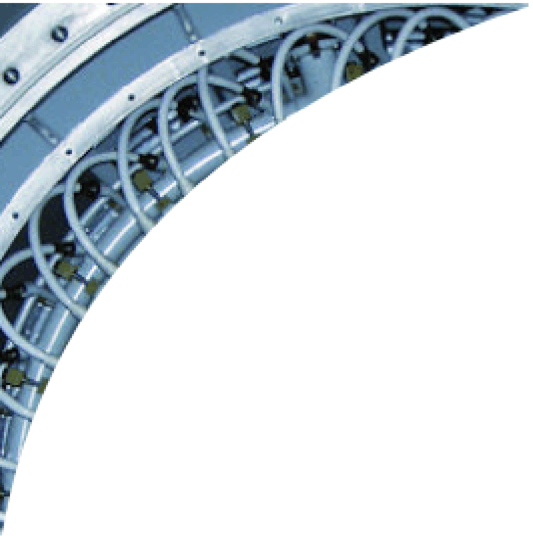




$$V_L = V_p$$

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

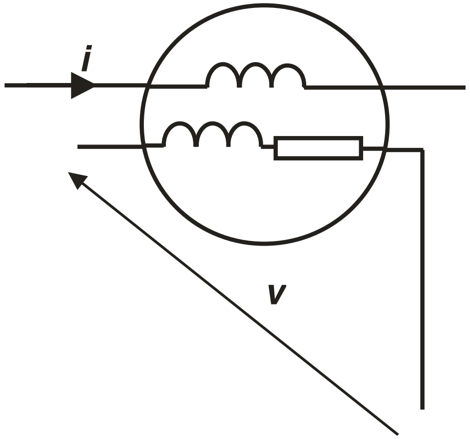
$$\overline{I}_A = \overline{I}_{AB} - \overline{I}_{CA}$$

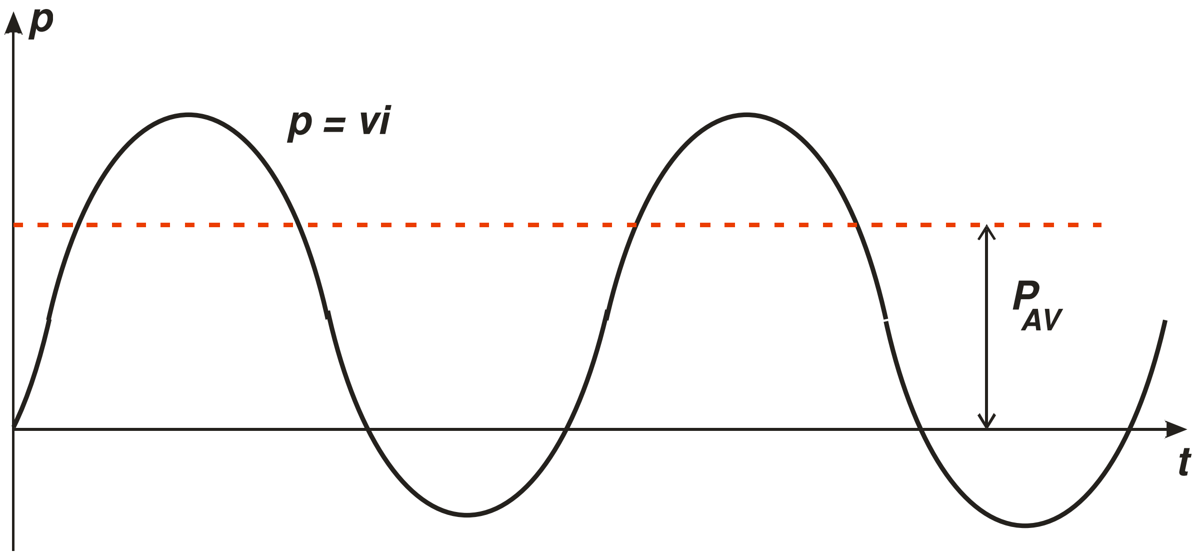


$$P_p = V_p I_p \cos \phi_L$$

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

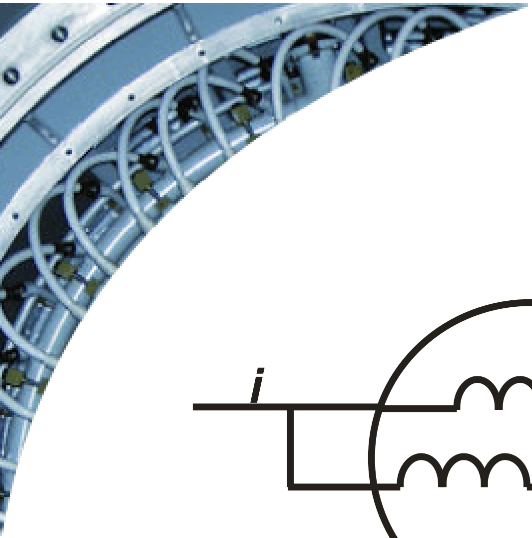
7.5 Measurement of Power in 3-phase Systems

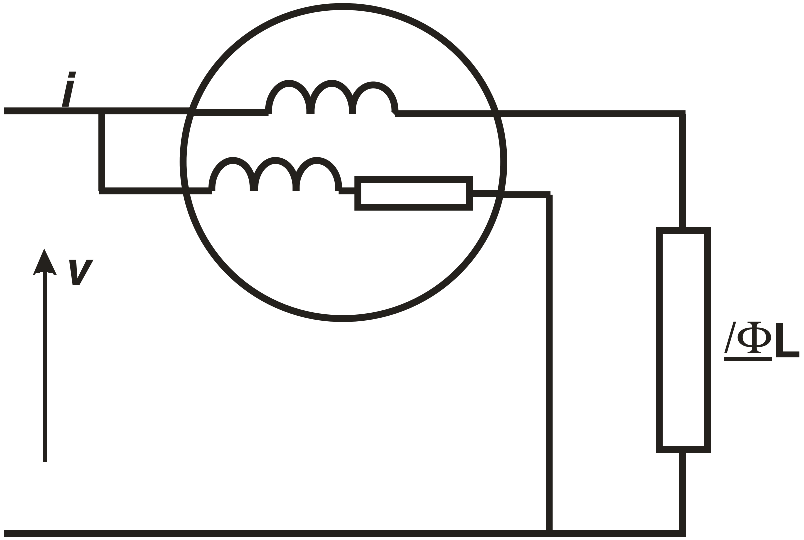




- Wattmeter responds to average power

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





In this circuit

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

where

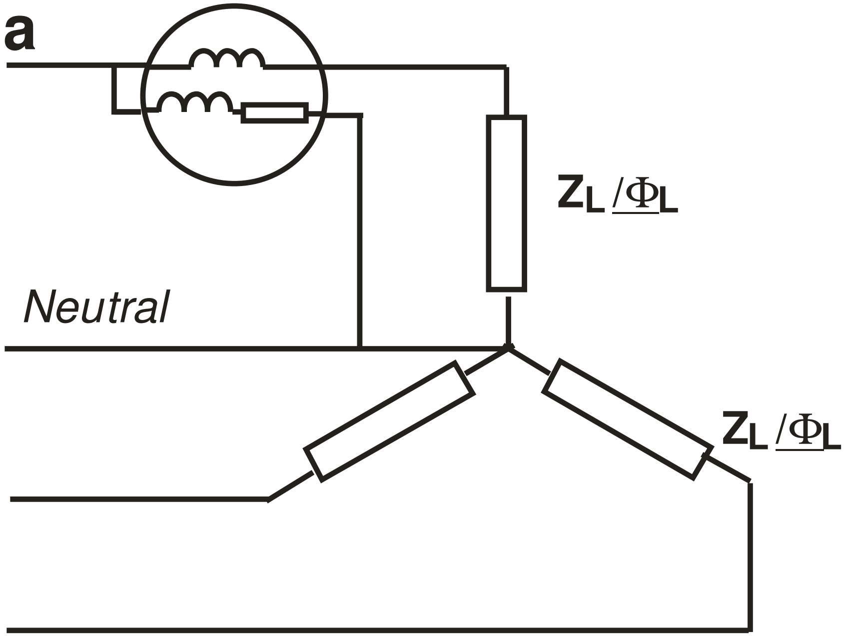
V : rms voltage at terminal of meter

I : rms current into meter

ϕ_L: angle between *V* and *I* supplied to the meter

7.5.1. 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

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

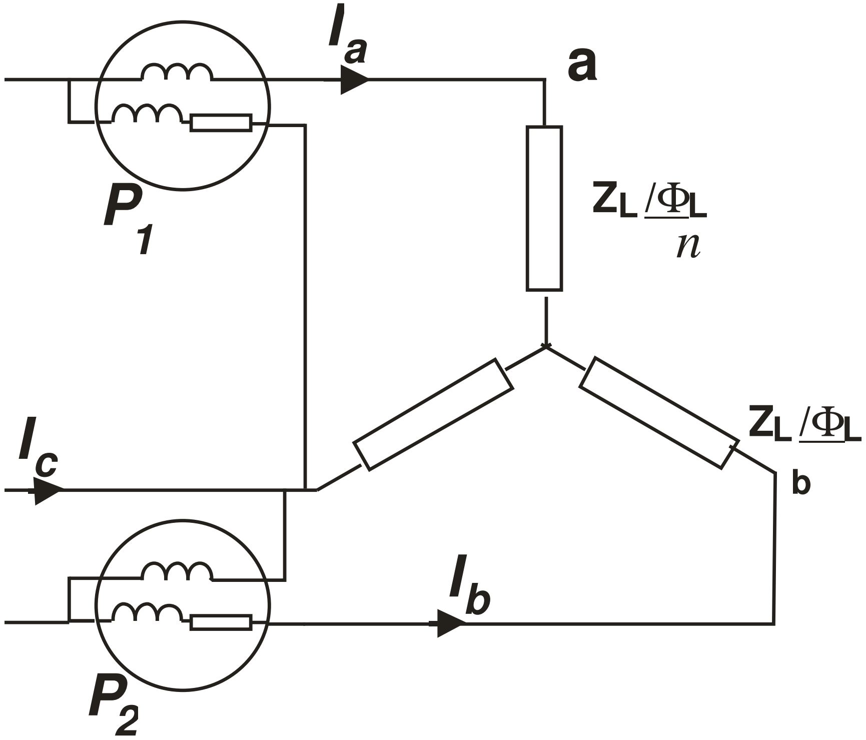
total power

$$P_T = 3P_p$$

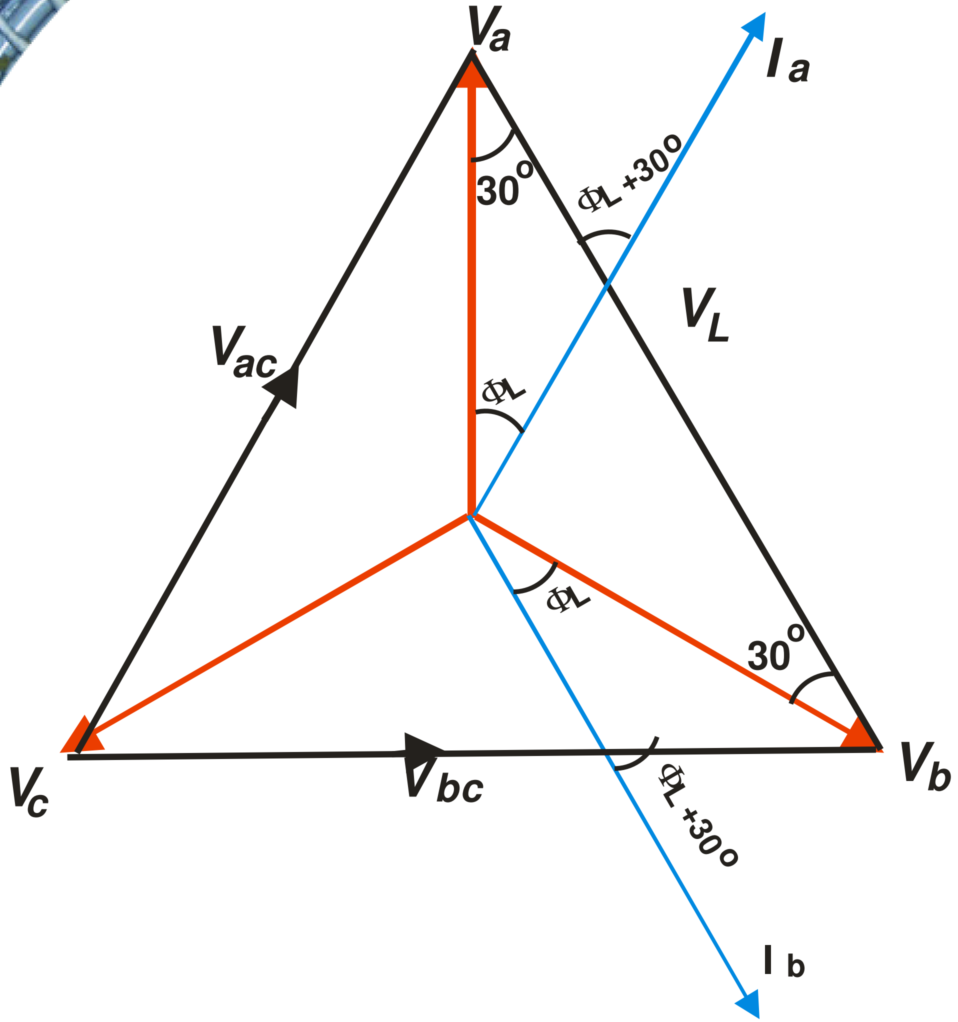
$$= 3V_p I_p \cos\phi_L$$

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

7.5.2 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



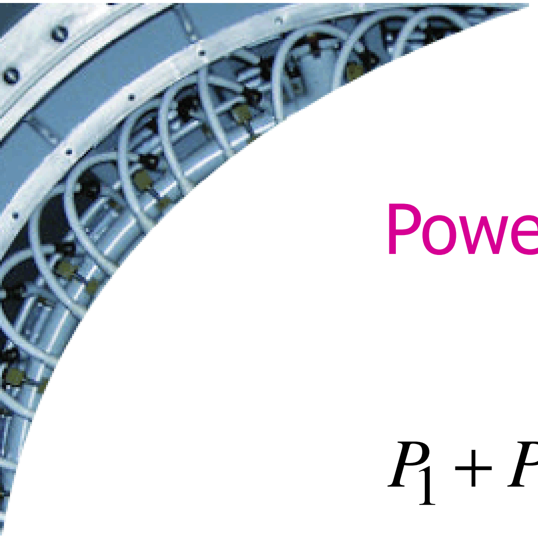
Meter Readings:

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

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

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

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



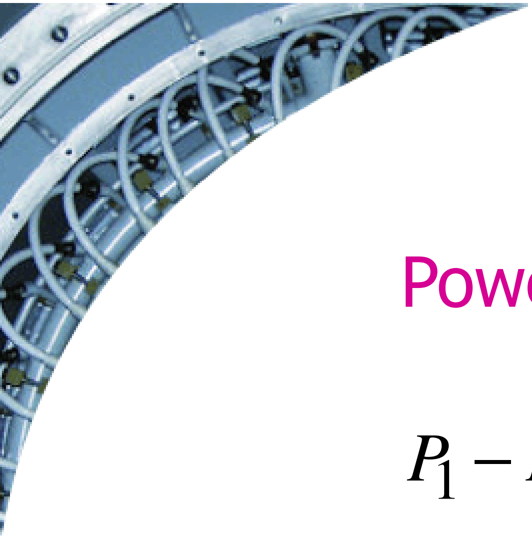
Power:

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

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

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

$$P_1 + P_2 = \text{Total} \quad \text{Power}$$



Power Factor:

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

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

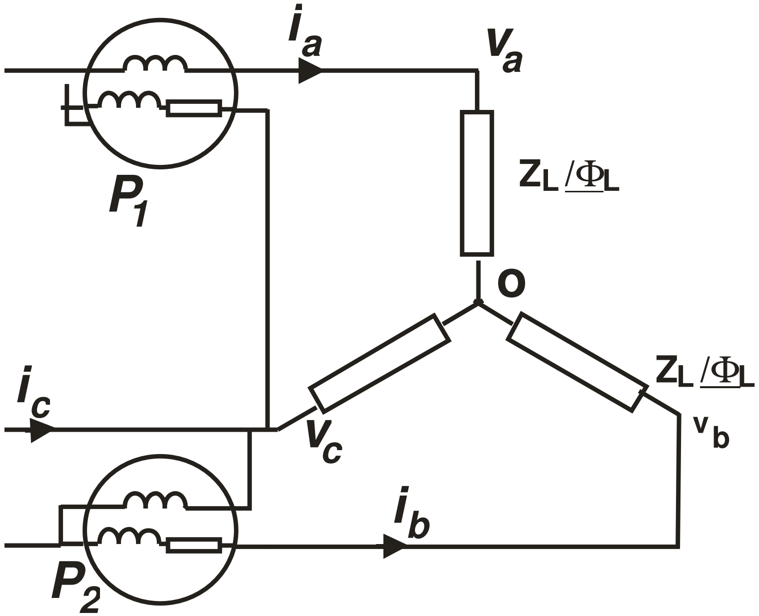
$$= V_L I_L \sin\phi_L$$

$$\frac{P_1 - P_2}{P_1 + P_2} = \frac{V_L I_L \sin\phi_L}{\sqrt{3} V_L I_L \cos\phi_L} = \frac{1}{\sqrt{3}} \tan\phi_L$$

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

- Advantages of two-wattmeter method:
  - neutral is not required, eg neutral may be buried in motor
  - from the two meter readings both total power and power factor can be determined
  - 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



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

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

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

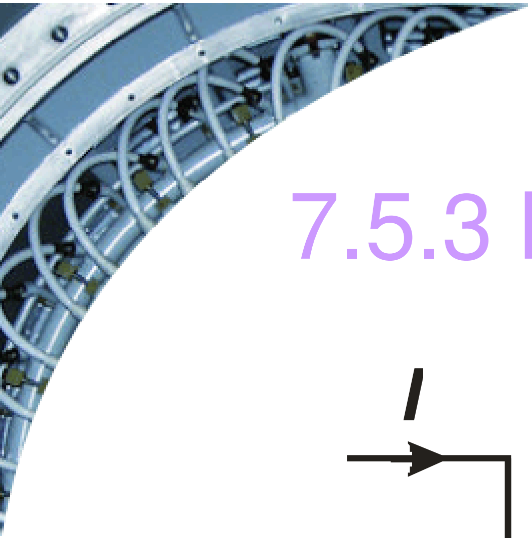
- if there is no neutral

$$i_a + i_b + i_c = 0$$

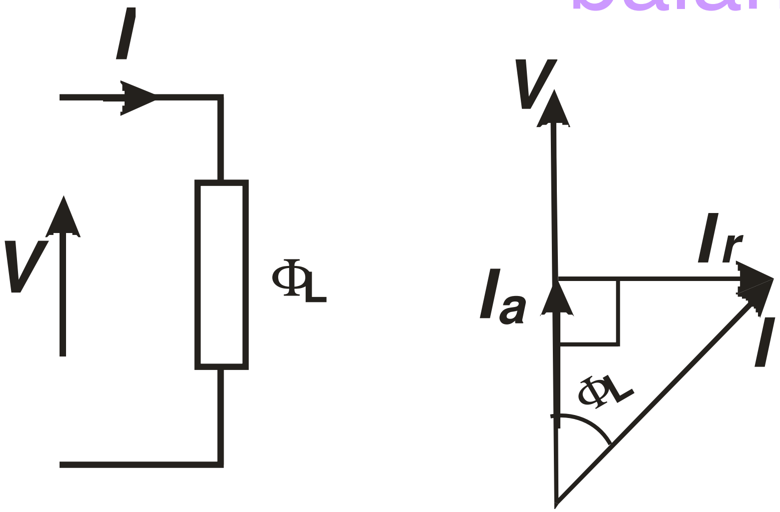
- therefore

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

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



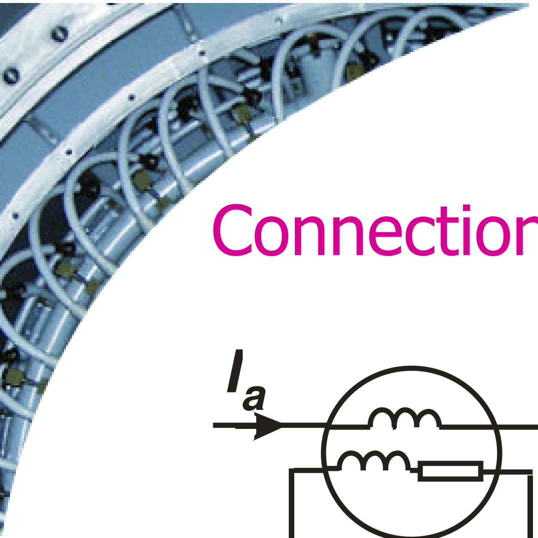
7.5.3 Measurement of reactive power in 3-ph balanced system



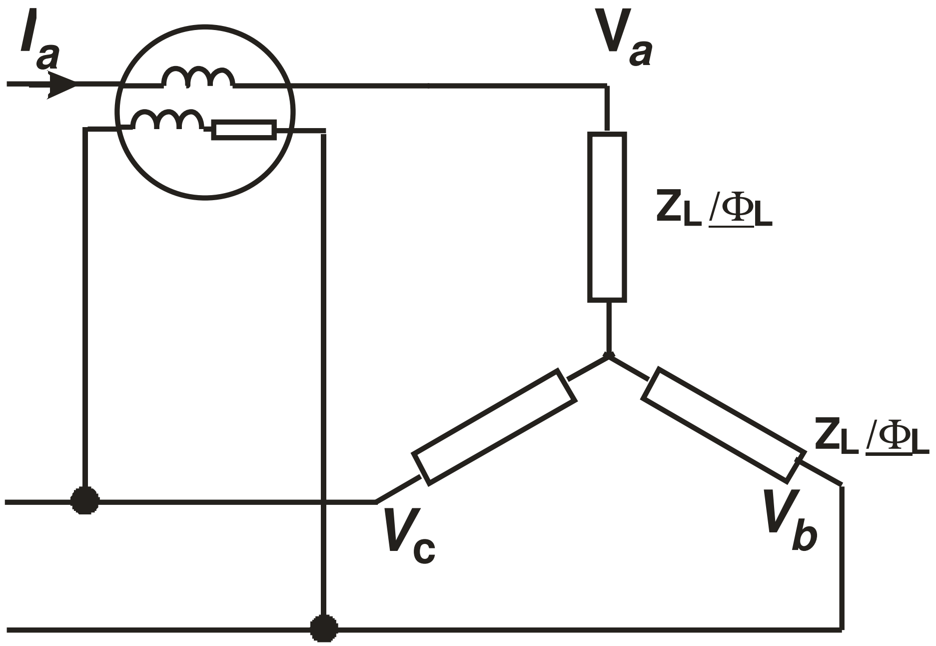
Active power $= P = VI\cos\phi_L \quad = VI_a$ [W] (real power)

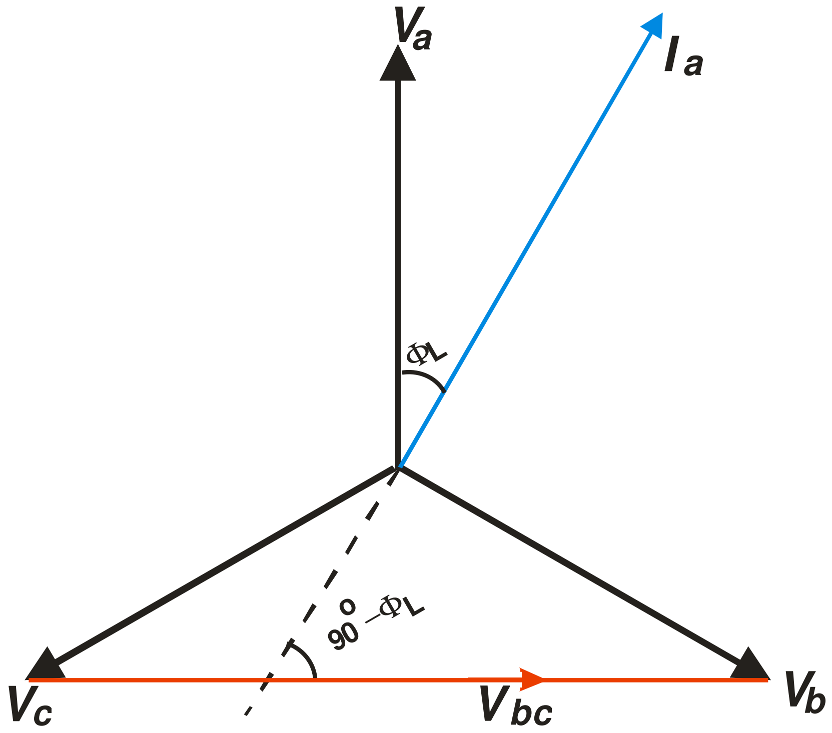
Reactive power $= Q = VI\sin\phi_L \quad = VI_r$ [VAr] (imaginary power)

Apparent power $= S = VI \quad = VI$ [VA] (complex power)

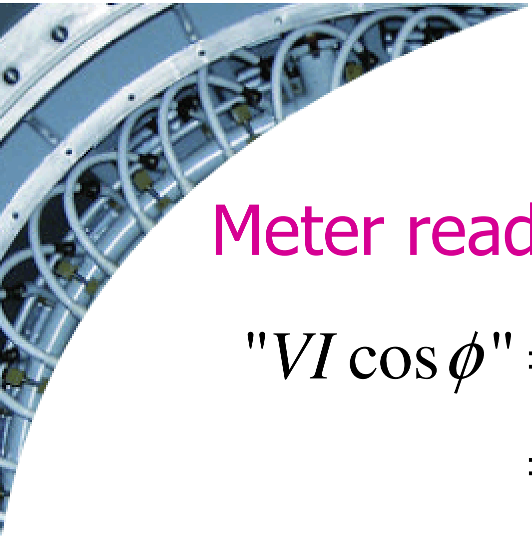


Connection for reactive power measurement





- current coil in one phase
- voltage coil across the other two phases



Meter reading:

$$"VI\cos\phi" = V_{bc} I_a \cos(90^o - \phi_L)$$

$$= V_L I_L \sin\phi_L$$

Reactive power in one phase:

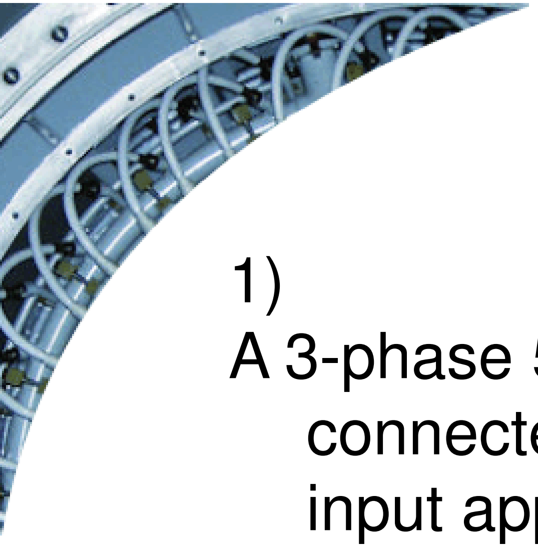
$$= V_p I_p \sin\phi_L$$

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 7

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.

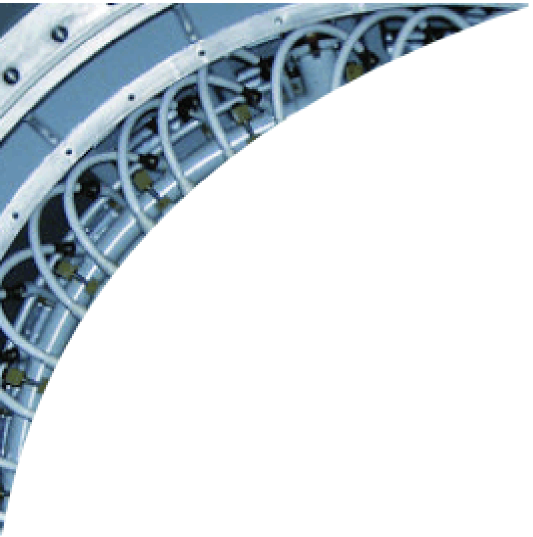
2)

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*.



- End of Lecture 7 -