POWER ENGINEERING

#05 THREE-PHASE AC POWER SYSTEMS

THREE-PHASE CIRCUITS

2018

University of Glasgow

Three Phase AC Systems

3 Phase Power Networks are the de facto standard in the industrialised world. In today's lecture you will get an understanding of why 3 phase systems are used and the basics of this approach.

Today we will investigate:

- Why 3 Phase?
- 3 Phase Generator Voltages
- 3 Phase Transmission
- A (balanced) STAR connected 3 phase load
- A (balanced) DELTA connected 3 phase load

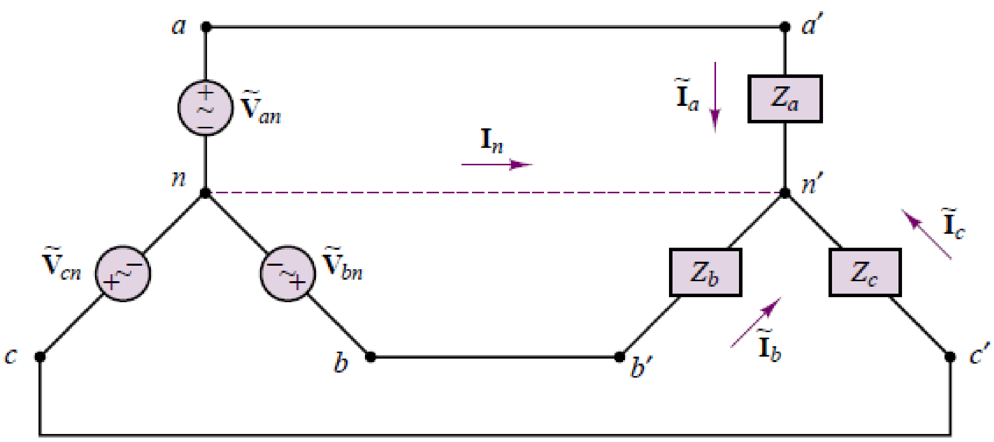
Why 3 Phase?

- The ‘workhorse’ of industry; the 3 phase induction motor requires a 3 phase AC power supply
- A balanced 3 phase system will lead to **constant instantaneous power demand** on the generator – results in a smoother running generator
- A 3 phase generator has far better energy density compared to a single phase machine, hence it is smaller for a given output power (see next slides)
- The weight of the conductors and other components in a three-phase system is much lower than in a single-phase system delivering the same amount of power.



BALANCED THREE-PHASE SYSTEM

Voltages of equal amplitude and frequency displaced in phase by 120∘— has the property of delivering constant instantaneous power.



Balanced three-phase AC circuit
in **wye** (or **Y**) **configuration**

$$\tilde{\mathbf{V}}_{an} = \tilde{V}_{an}\angle 0^\circ$$

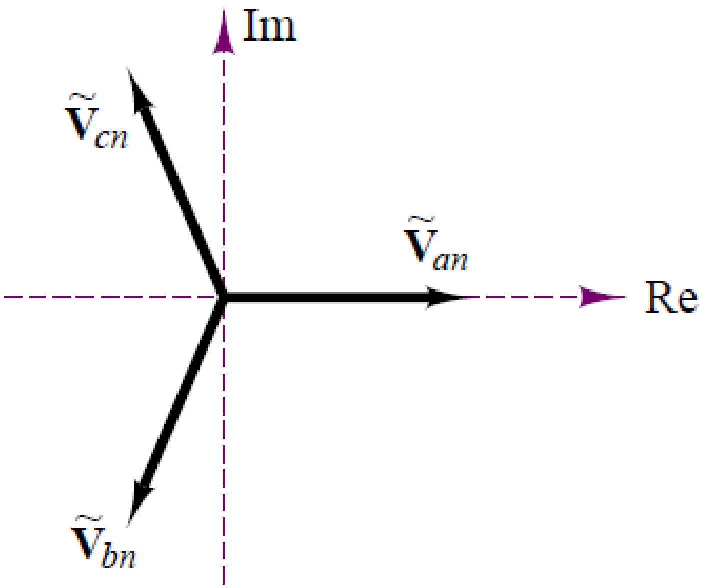
$$\tilde{\mathbf{V}}_{bn} = \tilde{V}_{bn}\angle -120^\circ$$

$$\tilde{\mathbf{V}}_{cn} = \tilde{V}_{cn}\angle -240^\circ = \tilde{V}_{cn}\angle 120^\circ$$

$$\tilde{V}_{an} = \tilde{V}_{bn} = \tilde{V}_{cn} = \tilde{V}$$

$$\Downarrow$$

$$\tilde{\mathbf{V}}_{an} + \tilde{\mathbf{V}}_{bn} + \tilde{\mathbf{V}}_{cn} = 0$$



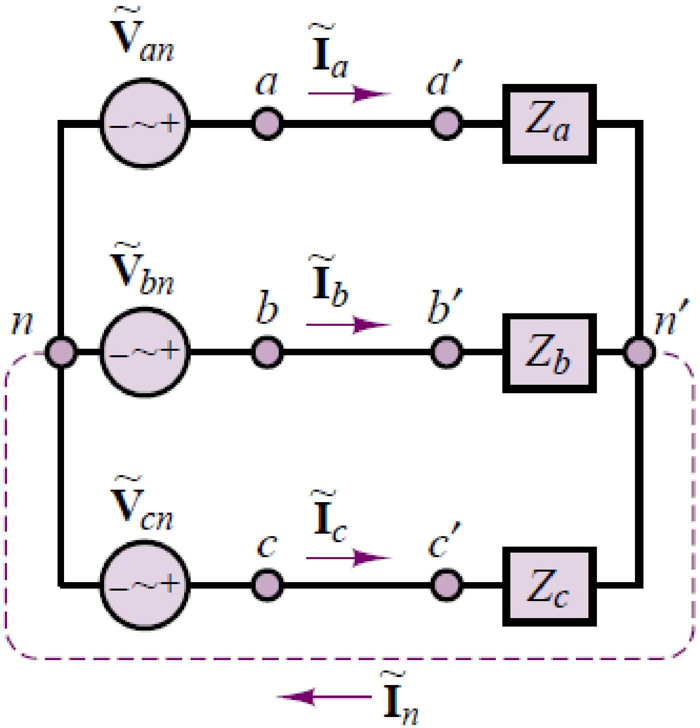
$$\tilde{\mathbf{V}}_{ab} = \tilde{\mathbf{V}}_{an} + \tilde{\mathbf{V}}_{nb} = \tilde{\mathbf{V}}_{an} - \tilde{\mathbf{V}}_{bn}$$

$$\tilde{\mathbf{V}}_{ab} = \tilde{V}\angle 0^\circ - \tilde{V}\angle{-120^\circ} = \sqrt{3}\tilde{V}\angle 30^\circ$$

$$\tilde{\mathbf{V}}_{bc} = \tilde{V}\angle{-120^\circ} - \tilde{V}\angle 120^\circ = \sqrt{3}\tilde{V}\angle{-90^\circ}$$

$$\tilde{\mathbf{V}}_{ca} = \tilde{V}\angle 120^\circ - \tilde{V}\angle 0^\circ = \sqrt{3}\tilde{V}\angle 150^\circ$$

$$\begin{aligned}\tilde{\mathbf{I}}_n &= (\tilde{\mathbf{I}}_a + \tilde{\mathbf{I}}_b + \tilde{\mathbf{I}}_c) \\ &= \frac{1}{Z}(\tilde{\mathbf{V}}_{an} + \tilde{\mathbf{V}}_{bn} + \tilde{\mathbf{V}}_{cn}) \\ &= 0\end{aligned}$$



$$p_a(t) = \frac{\tilde{V}^2}{R}(1 + \cos 2\omega t)$$

$$p_b(t) = \frac{\tilde{V}^2}{R}[1 + \cos(2\omega t - 120^\circ)]$$

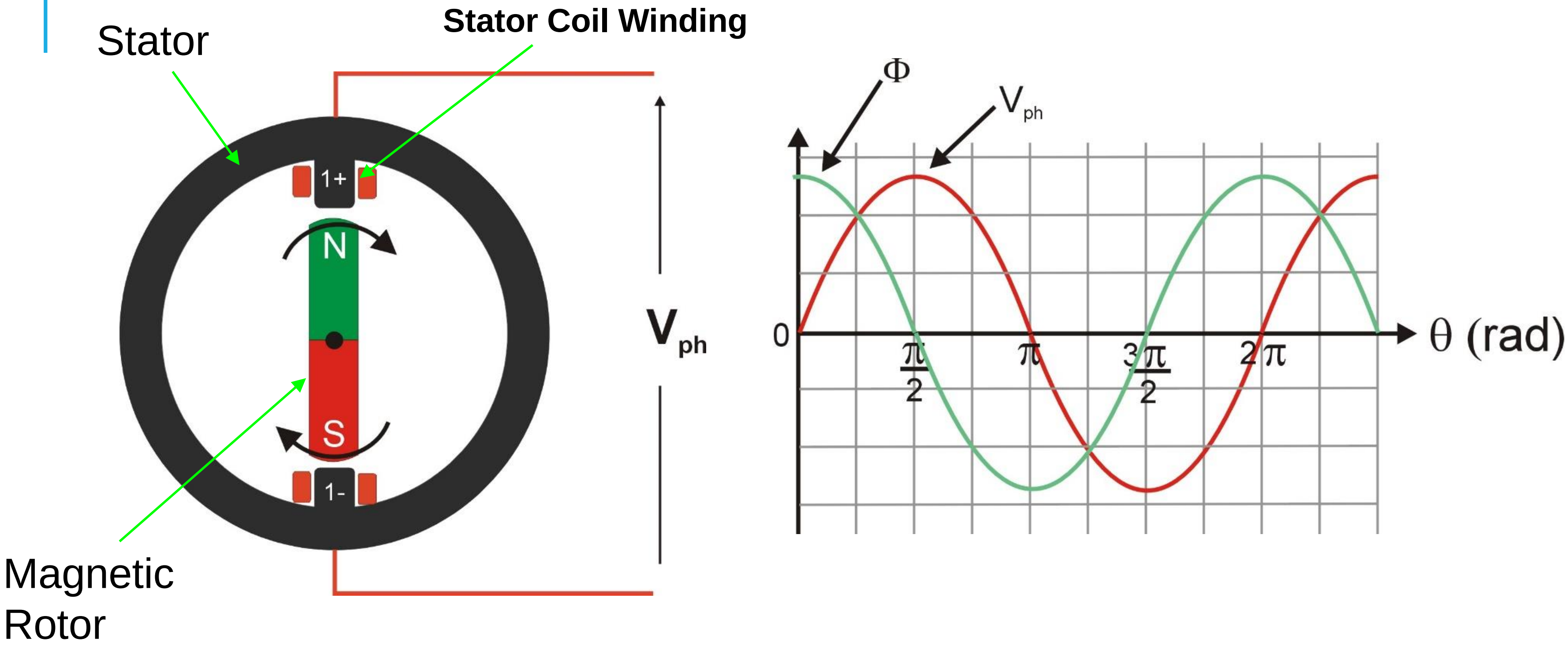
$$p_c(t) = \frac{\tilde{V}^2}{R}[1 + \cos(2\omega t + 120^\circ)]$$

$$p(t) = p_a(t) + p_b(t) + p_c(t)$$

$$= \frac{3\tilde{V}^2}{R} + \frac{\tilde{V}^2}{R}[\cos 2\omega t + \cos(2\omega t - 120^\circ) + \cos(2\omega t + 120^\circ)]$$

$$= \frac{3\tilde{V}^2}{R} = \text{a constant!}$$

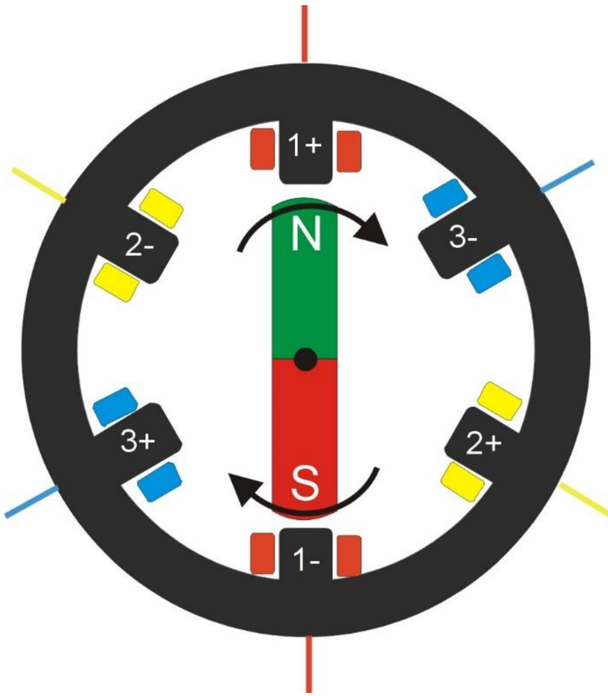
Single Phase AC Generator

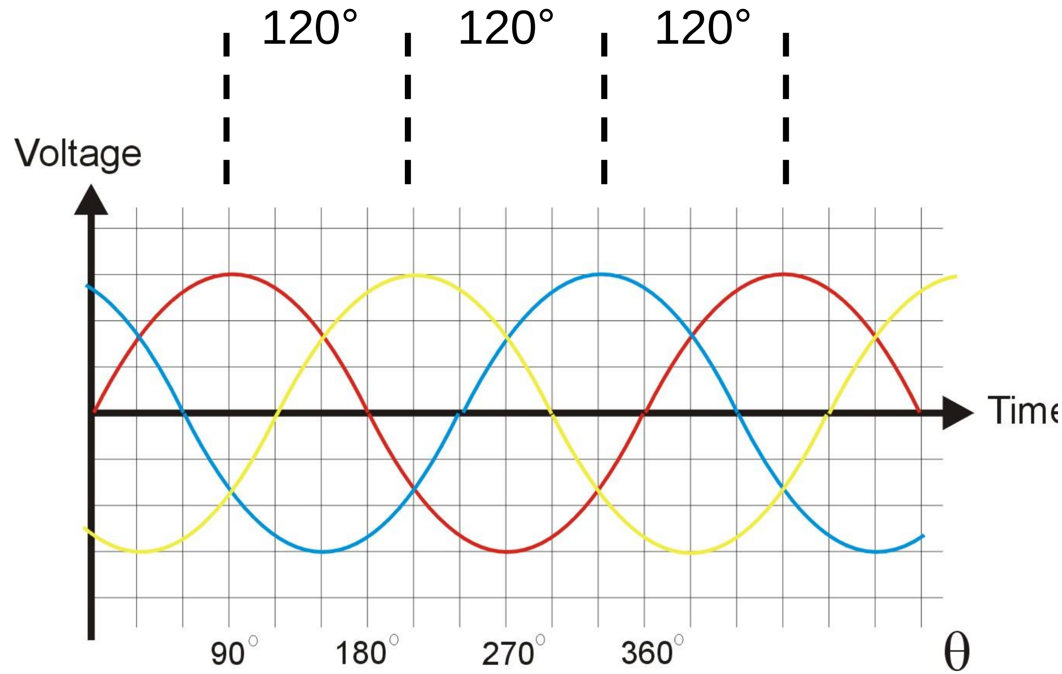


Voltage (V_{ph}) induced in Stator Winding Coils (1+, 1-) $= \dfrac{N.d\phi}{dt}$

Where N is the number of turns in the Stator coils and ϕ is the Rotor Magnet flux

3 Phase AC Generator



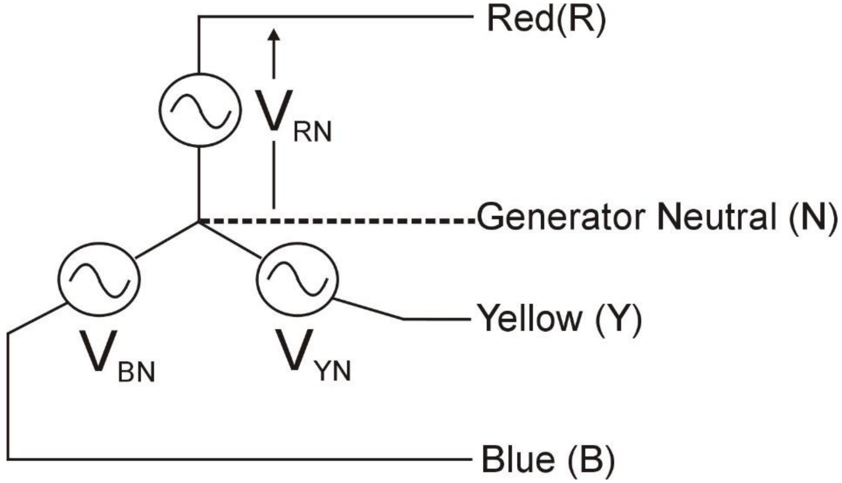


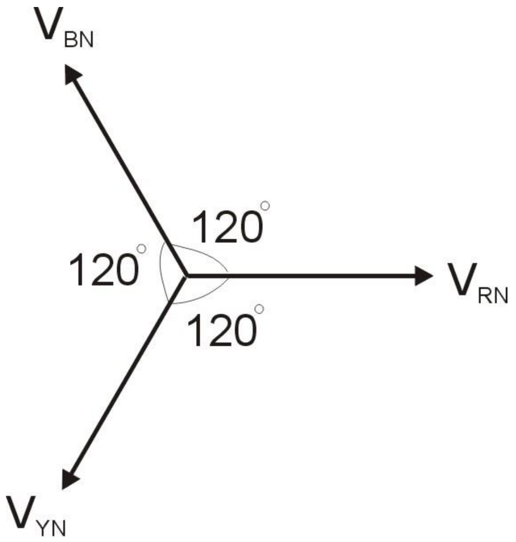
Now have 3 Phase windings on the Stator 120° apart

Countries use different conventions for naming the 3 PHASE voltages. We will adopt the (old!) UK convention of RED, YELLOW & BLUE PHASES

3 Phase Generator: Circuit Diagram & Phasor Diagram

3-phase 4-wire





$$V_{RN} = V_{pk} \cos\theta$$

$$V_{YN} = V_{pk} \cos\left(\theta - \frac{2\pi}{3}\right)$$

$$V_{BN} = V_{pk} \cos\left(\theta + \frac{2\pi}{3}\right)$$

Complex Form (Polar):

$$V_{RN} = V_{ph}\angle 0^o$$

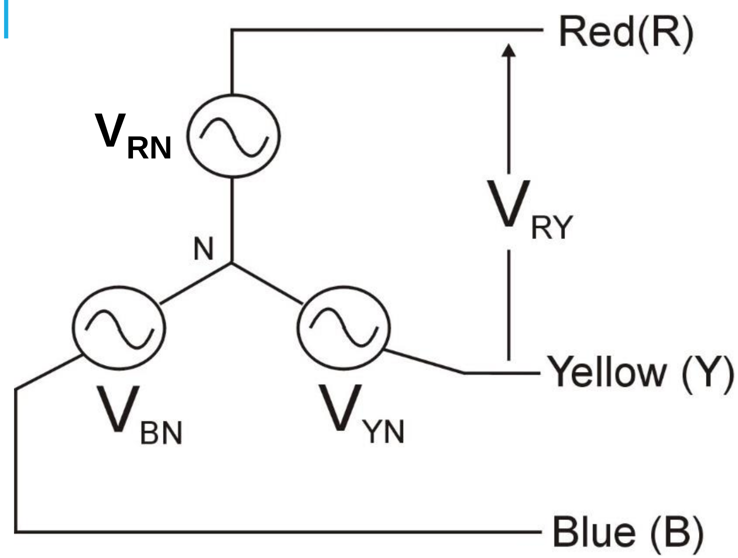
$$V_{YN} = V_{ph}\angle -120^o$$

$$V_{BN} = V_{ph}\angle 120^o$$

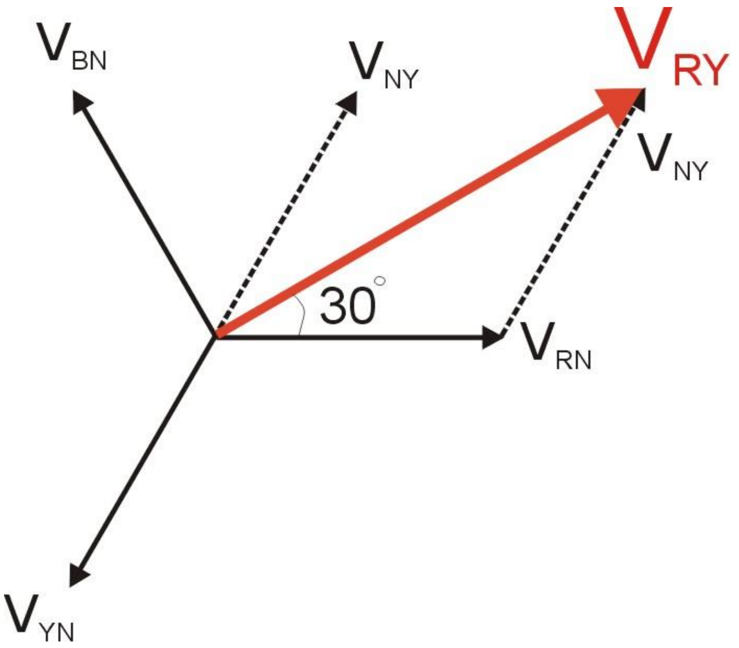
Note: all 3 Phase Voltages have the same rms magnitude V_{ph}

3 Phase Generator: Line Voltage V_{RY}

3-phase 3-wire



Phasor Diagram

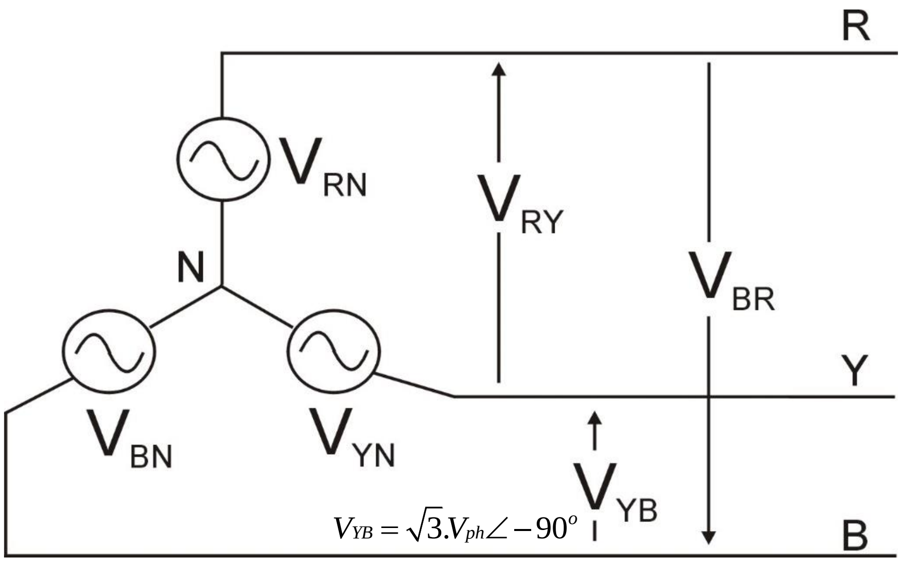


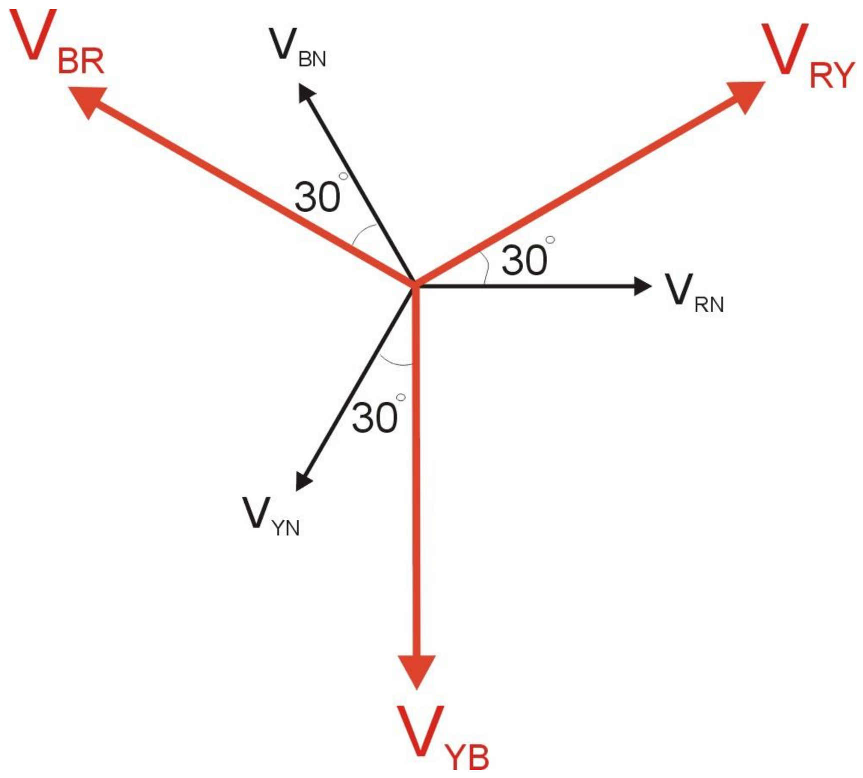
$$V_{RY} = V_{RN} + V_{NY} = V_{RN} - V_{YN}$$

$$\boxed{V_{RY} = \sqrt{3} \cdot V_{ph} \angle 30^0}$$

Proof: Convert V_{RN} and V_{NY} into Cartesian Form and ADD

3 Phase Generator: Line Voltages

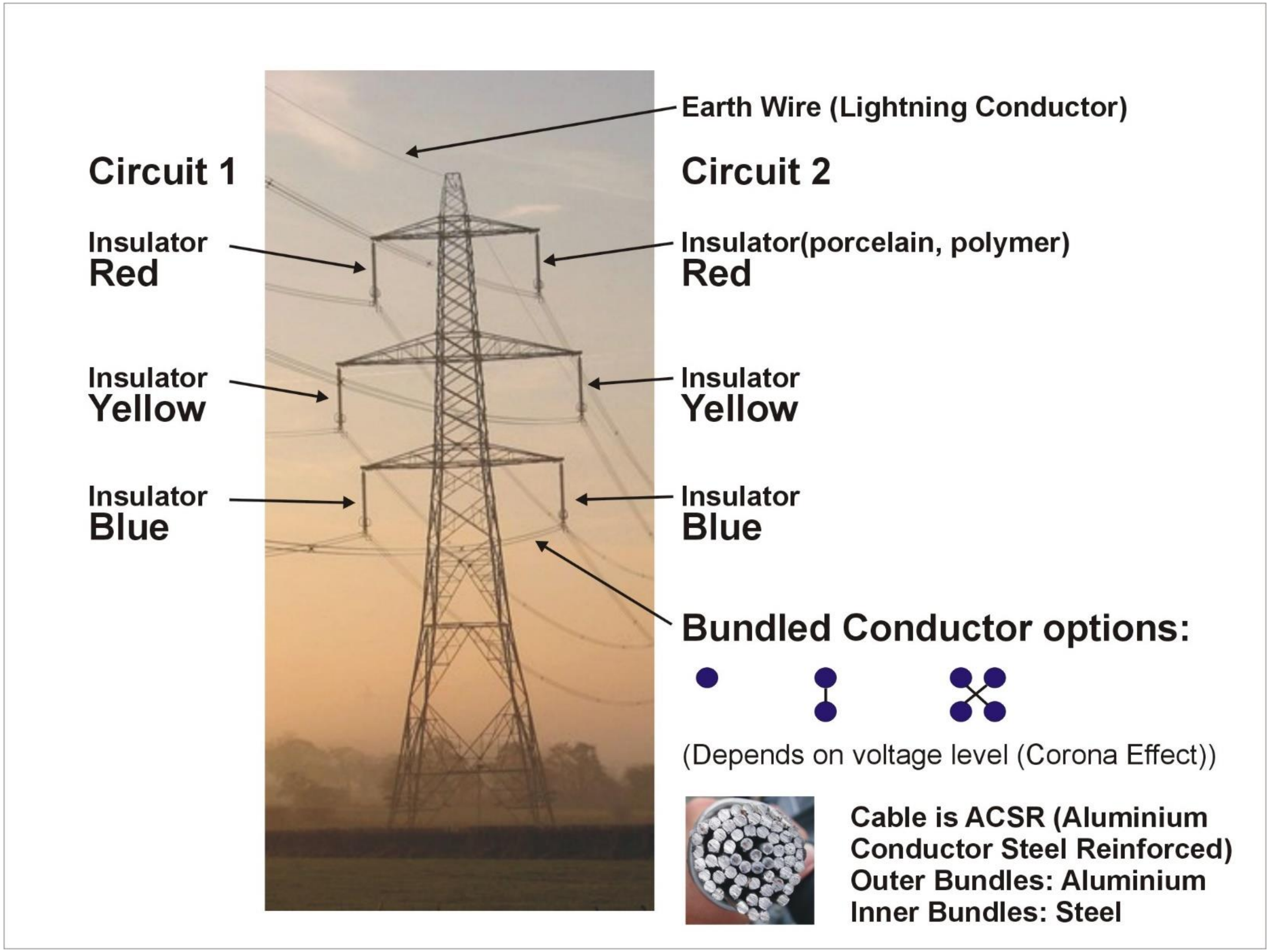




$$V_{RY} = \sqrt{3}.V_{ph}\angle 30^o \quad V_{BR} = \sqrt{3}\cdot V_{ph}\angle 150^o \quad V_{YB} = \sqrt{3}\cdot V_{ph}\angle -90^o$$

Note: V_{RN} has been chosen to be on Reference axis

3 Phase Transmission Lines: Anatomy of a pylon

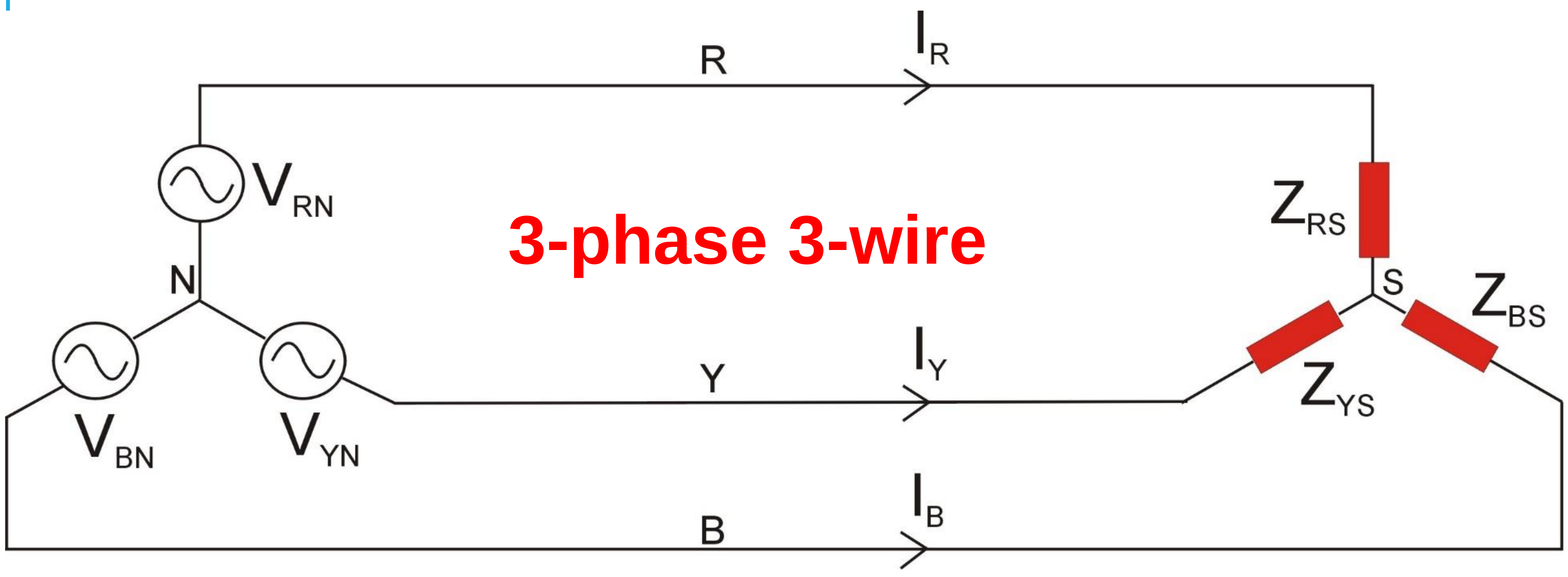


3 Phase Transmission Lines: some interesting facts!

If you want to find out more about pylons then check out the Pylon Appreciation Society at http://www.pylons.org/

- The ‘standard’ UK pylon was chosen by Sir Reginald Blomfield (a leading architect) in 1928
- The tallest pylon in the world is in China. The Yangtze River crossing pylon is 346.5m high
- The Beauly-Denny transmission line upgrade in Scotland consists of 600 towers with an average height of 53m
- The UK National Grid is made up of 440kV, 275kV, 132kV, 110kV, 33kV and 11kV transmission lines
- Q. Why do you never see birds standing on large transmission lines?

A (balanced) STAR connected 3 Phase Load



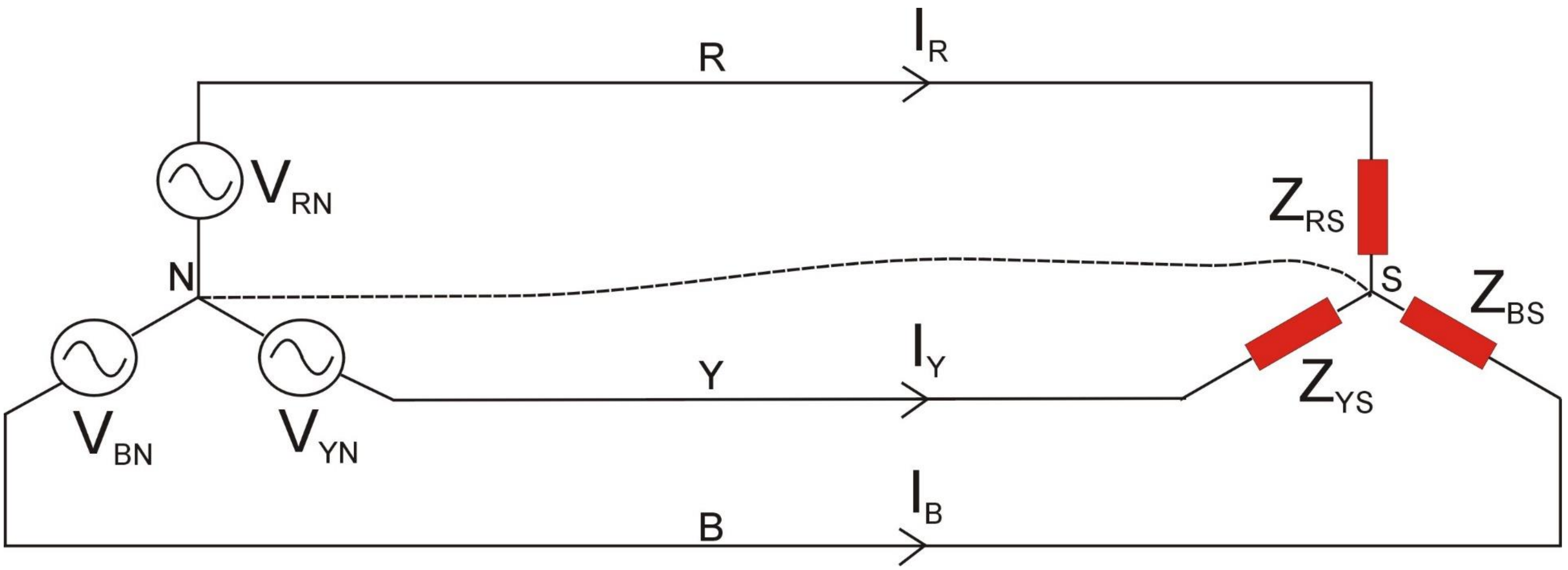
Notes:

1. 'Balanced' means that the load Impedances are equal: $Z_{RS} = Z_{YS} = Z_{BS}$

2. I_R, I_Y and I_B are termed the LINE currents

3. If the load is balanced then the load STAR point (S) is at the same voltage as the Generator Neutral (N): $V_{SN} = 0$

A (balanced) STAR connected 3 Phase Load



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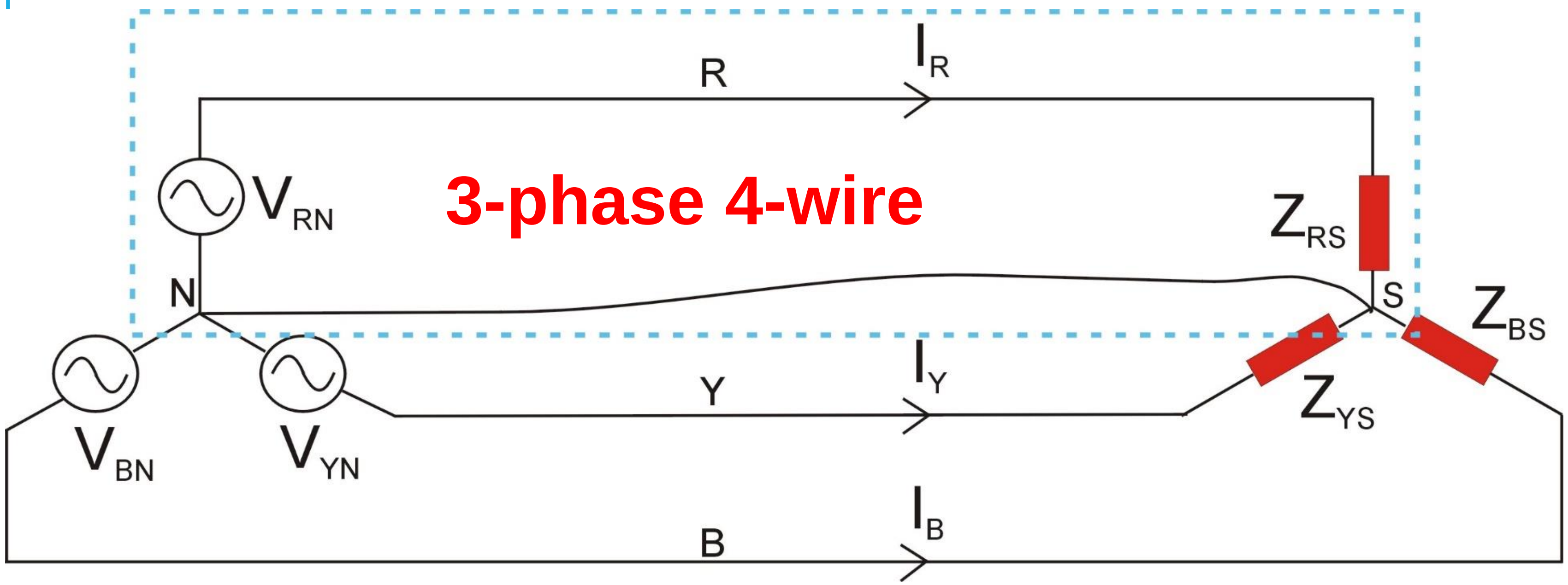
A (balanced) STAR connected 3 Phase Load

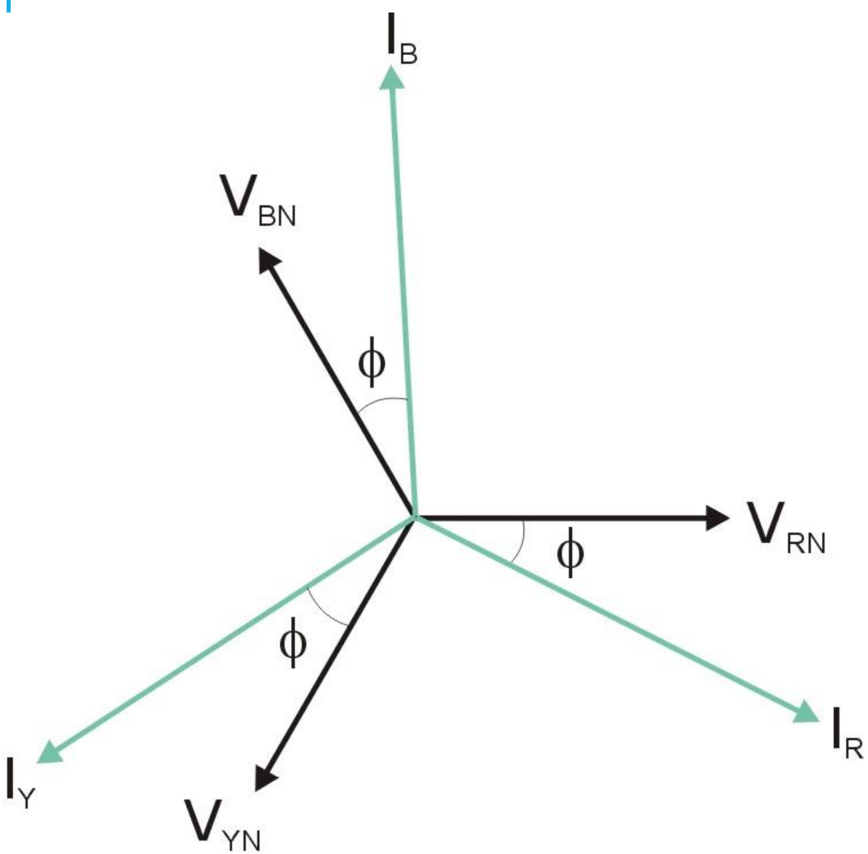


Observing the circuit within the blue dotted line we can see the following very simple relationship:

$$V_{RN} = Z_{RS}.I_R$$

Therefore determining line currents (and subsequently power quantities) is relatively straight-forward for a given magnitude of phase voltage and load Impedance, the result being equal magnitude line currents 120° out of phase with one another.

Balanced STAR connected load: Line Currents



Note: Load Impedances shown here are Resistive + Inductive

Notes:

1. Line Currents are 120° apart and equal in magnitude.

2. $$V_{RN} = Z_{RS}.I_R$$

$$V_{YN} = Z_{YS}.I_Y$$

$$V_{BN} = Z_{BS}.I_B$$

3. The power equations for any phase are:

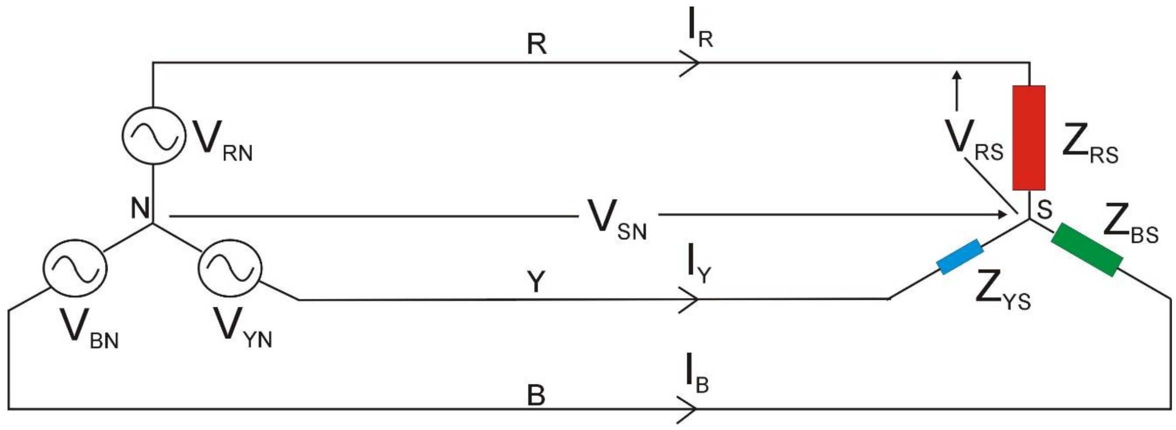
$$S = V_{ph}.I_L$$

$$P = V_{ph}.I_L.Cos\phi$$

$$Q = V_{ph}.I_L.Sin\phi$$

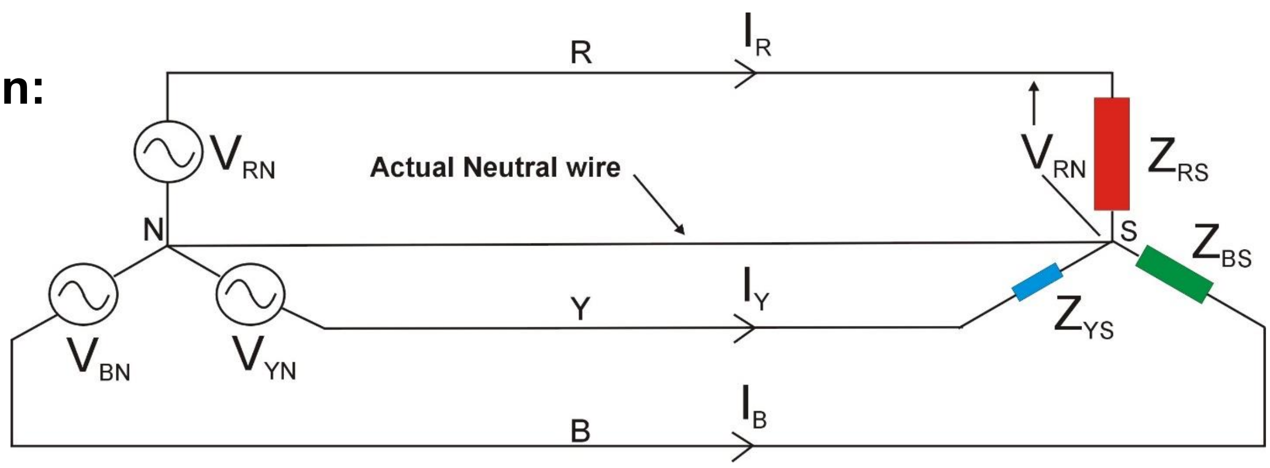
Where V_{ph} is the rms magnitude of the phase voltage, and I_L is the rms line current and Φ is the angle between them

The effects of an UNbalanced STAR connected 3 Phase Load:

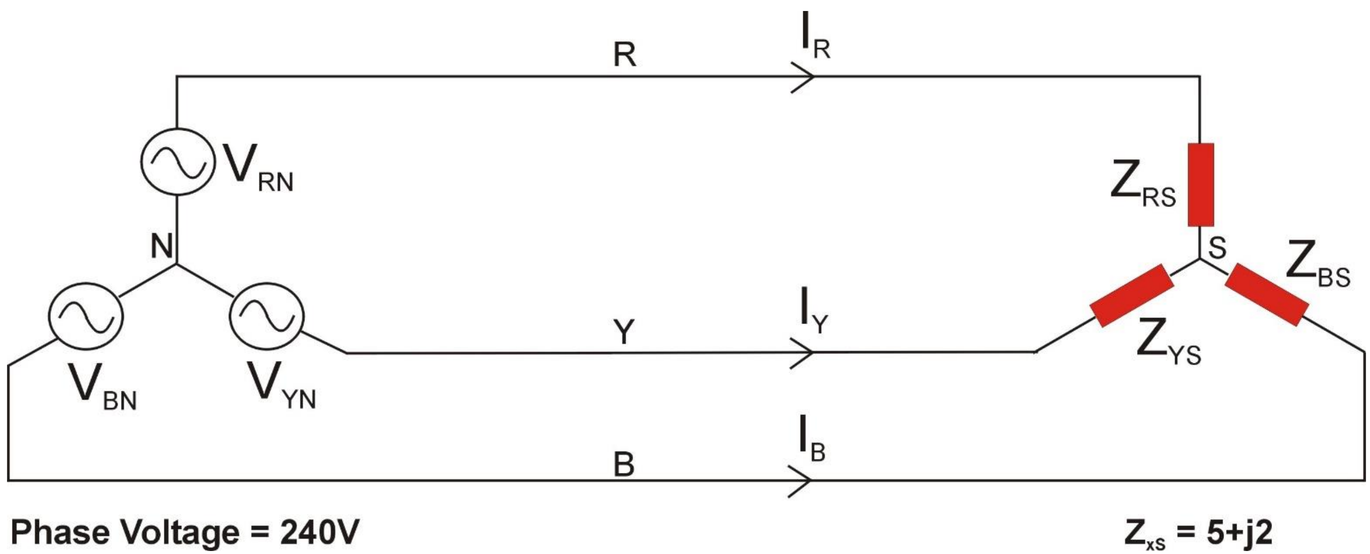


Now $V_{SN} \neq 0$, and therefore $V_{RS} \neq V_{RN}$, the result being potential over or under voltage conditions ie PROBLEMs for the end users.

'A' Solution:



Balanced STAR connected load EXAMPLE:

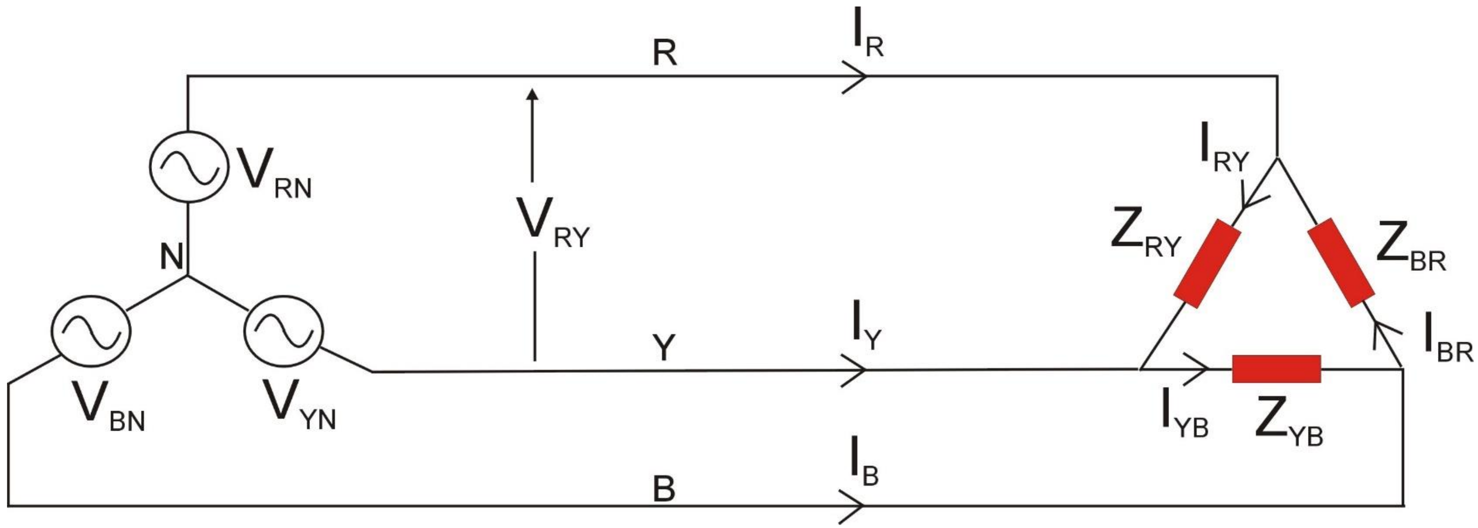


For the balanced 3 phase Star connected load determine the following:

1. The magnitude of the line voltages
2. The line currents I_R, I_Y and I_B
3. The phasor diagram showing all line currents and phase voltages
4. The TOTAL real power supplied by the 3 phase supply

Solution done on whiteboard during lecture

A (balanced) DELTA connected 3 Phase Load



For the balanced load:

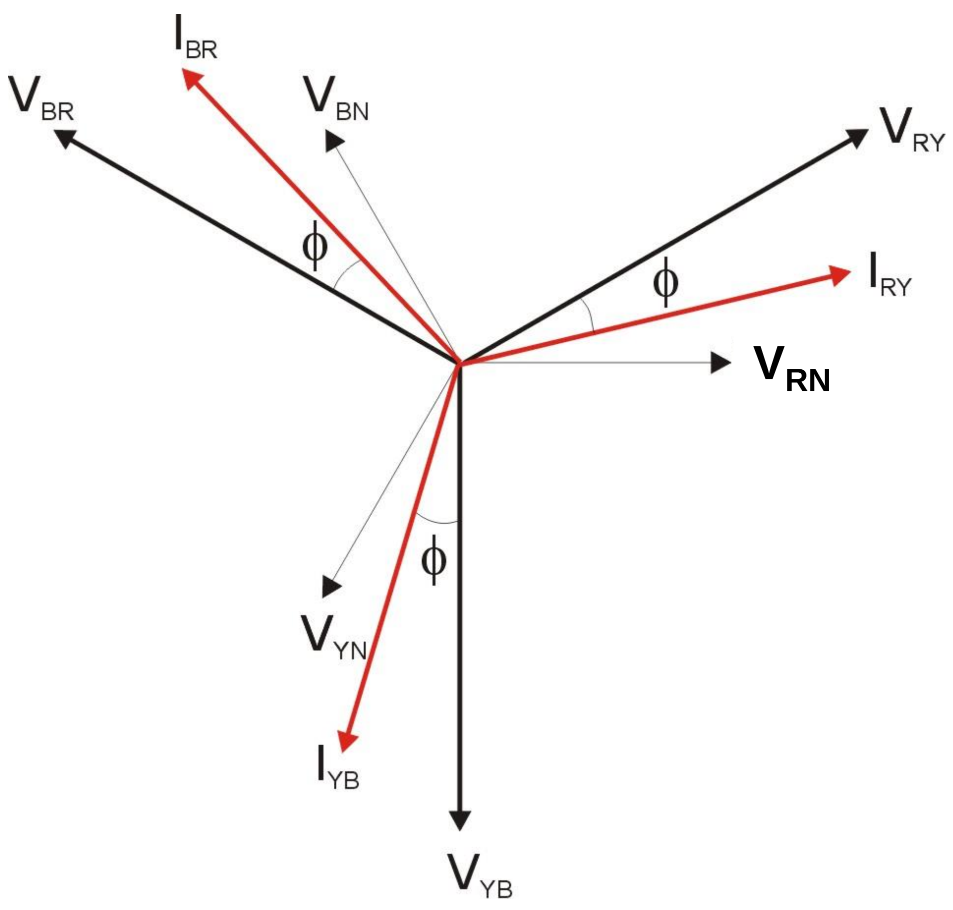
$$I_{RY} = \frac{V_{RY}}{Z_{RY}} = I_{ph}\angle\phi$$

Where Iph is rms magnitude of the load phase currents

$$I_{YB} = I_{ph}\angle(\phi - 120^o)$$

$$I_{BR} = I_{ph}\angle(\phi + 120^o)$$

Balanced DELTA connected load: Load Phase Currents (I_{RY}, I_{YB}, I_{BR})



Note Load Impedances shown here are Resistive + Inductive

Notes:

1. Load Phase Currents are 120° apart and equal in magnitude.

2. $$I_{RY} = \frac{V_{RY}}{Z_{RY}}$$

$$I_{YB} = \frac{V_{YB}}{Z_{YB}}$$

$$I_{BR} = \frac{V_{BR}}{Z_{BR}}$$

3. The power equations for any phase are:

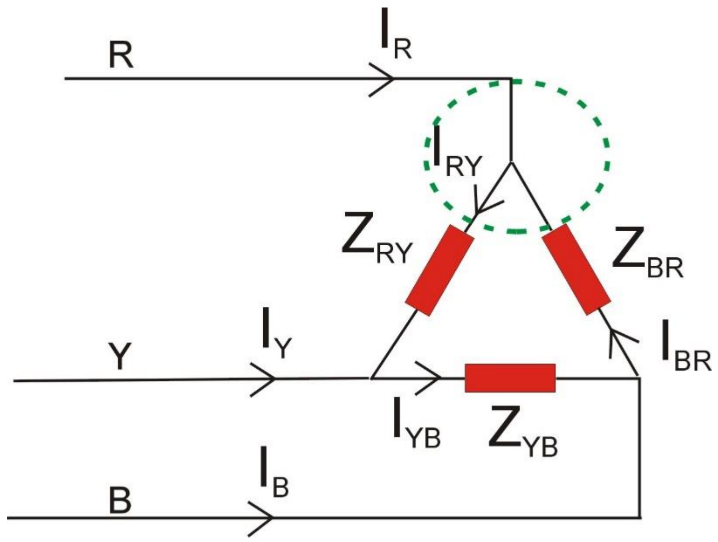
$$S = V_L.I_{ph}$$

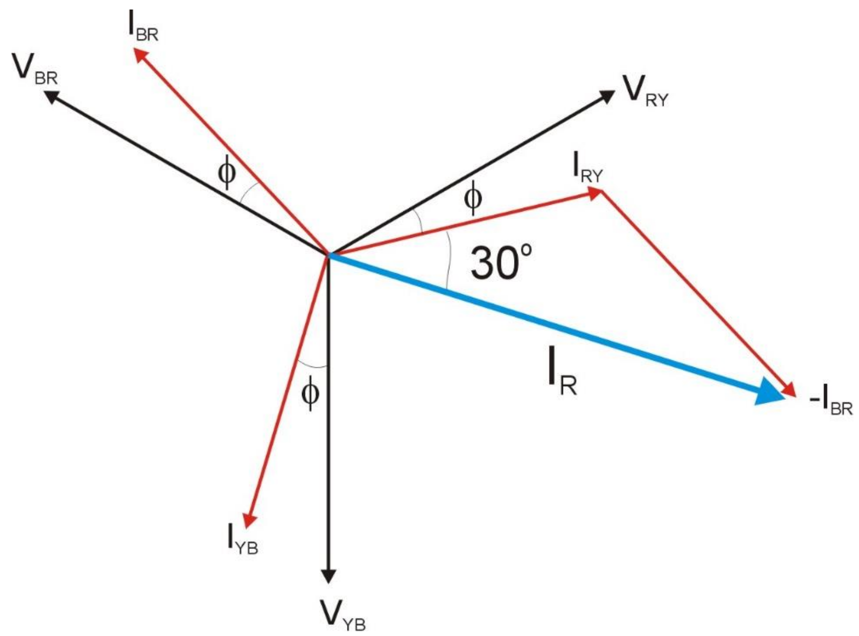
$$P = V_L.I_{ph}.Cos\phi$$

$$Q = V_L.I_{ph}.Sin\phi$$

Where V_L is the rms magnitude of the LINE voltage, I_{ph} is the rms load phase current and Φ is the angle between them

Balanced DELTA connected load: Line Currents (I_R, I_Y, I_B)





Currents in and out a junction must sum to zero:

$I_R - I_{RY} + I_{BR} = 0$

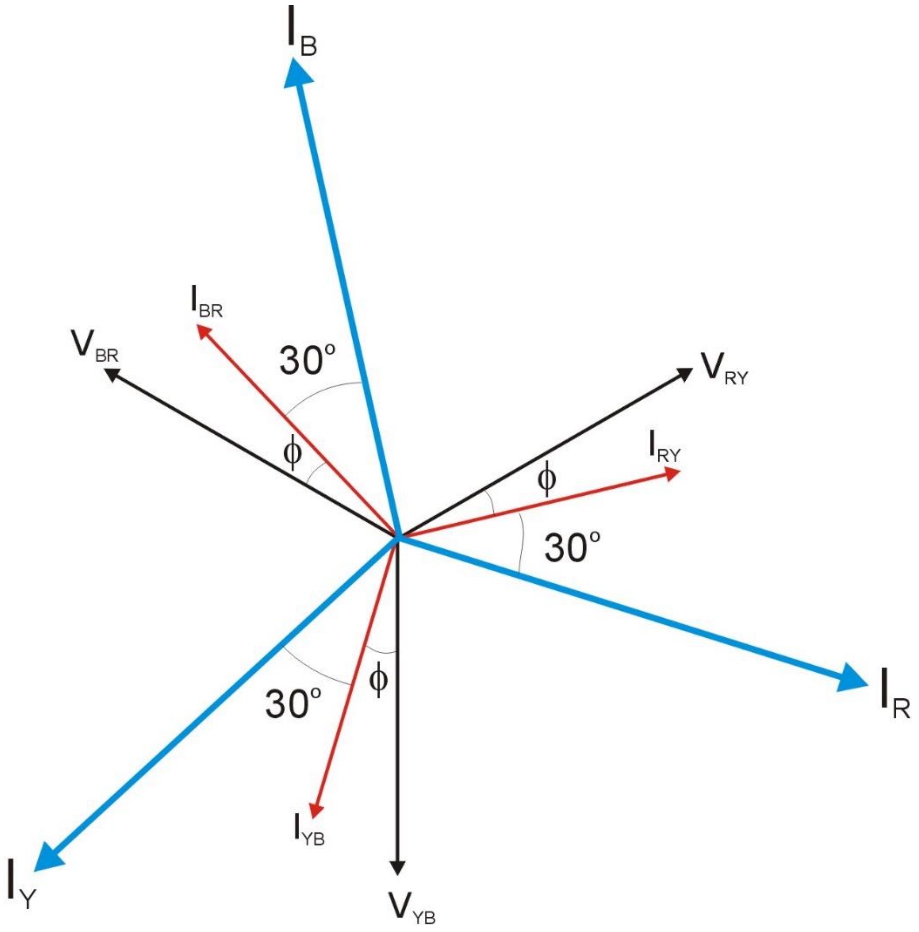
$I_R = I_{RY} - I_{BR}$

Where all the currents are phasors

Result:

The line current I_R LAGs I_{RY} by 30º and is $\sqrt{3}$ x magnitude of I_{RY}

Balanced DELTA connected load:
Line Currents (I_R, I_Y, I_B)



Notes:

1. Line Currents are 120° apart and equal in magnitude.

2. Line Currents are √3 x magnitude of load phase currents

2. Line Currents lag the load phase currents by 30º