POWER ENGINEERING
#16 SYNCHRONOUS GENERATOR (I)

2018

University of Glasgow

Plan for Today:

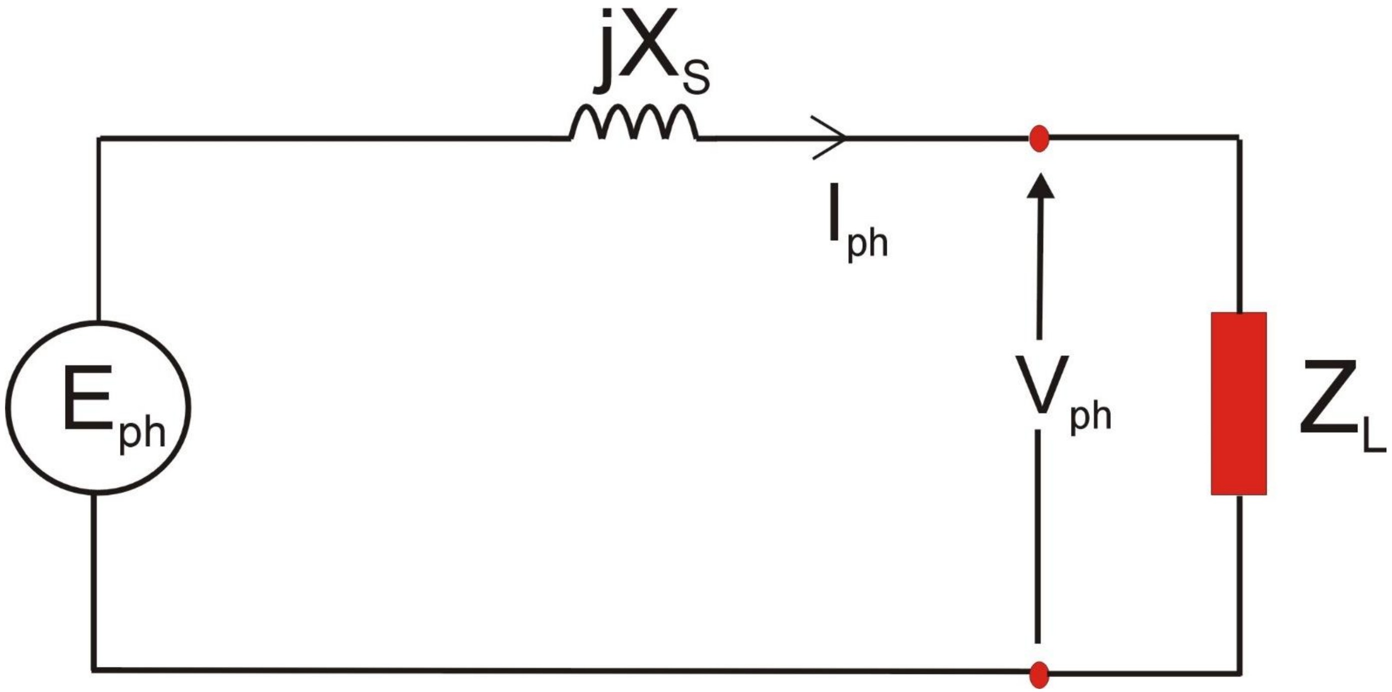
- Quick recap on the main results from the introductory lecture
- Unlocking the **POWER** of the phasor diagram #1
- Operating Modes:
  - Stand Alone Mode
  - Grid Connected Mode
- Stand Alone Mode Operation + Example
- Unlocking the **POWER** of the phasor diagram #2

Synchronous Generators

	PM Generator	Wound Field Generator
Rotor Flux	Fixed	Set by I_f
Excitation Voltage	Set by speed	Set by speed & I_f Typically FIXED speed
Voltage Frequency	Set by speed	Set by speed Typically FIXED speed

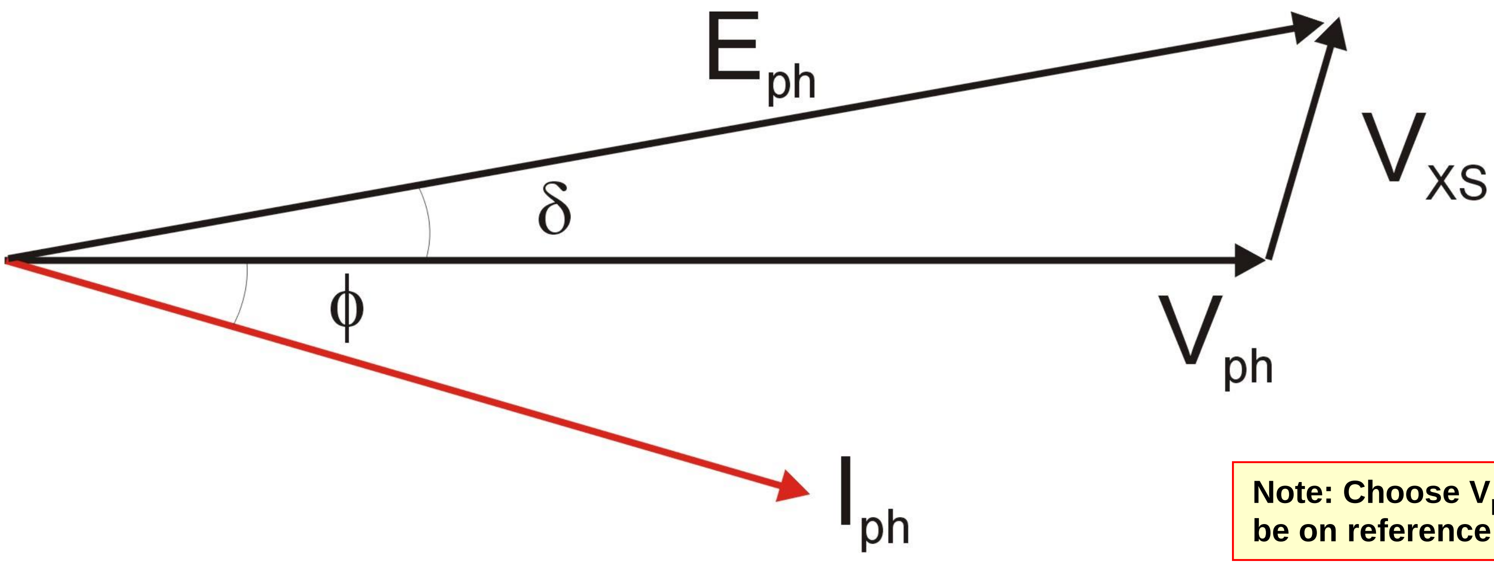
Note: from now on we will only consider fixed speed operation of a Wound Field Generator

Per Phase Equivalent Circuit with Load Impedance Z_L:



A Phase current I_{ph} will flow through load Z_L, the magnitude and phase of which is determined by E_{ph}, X_S and Z_L. The Terminal Voltage V_{ph} can the be determined once I_{ph} is known.

Typical (per phase) Phasor Diagram



Note: Choose V_{ph} to be on reference axis

Notes:

1. The angle Φ is the load **Power Factor Angle** (angle between V_{ph} and I_{ph})

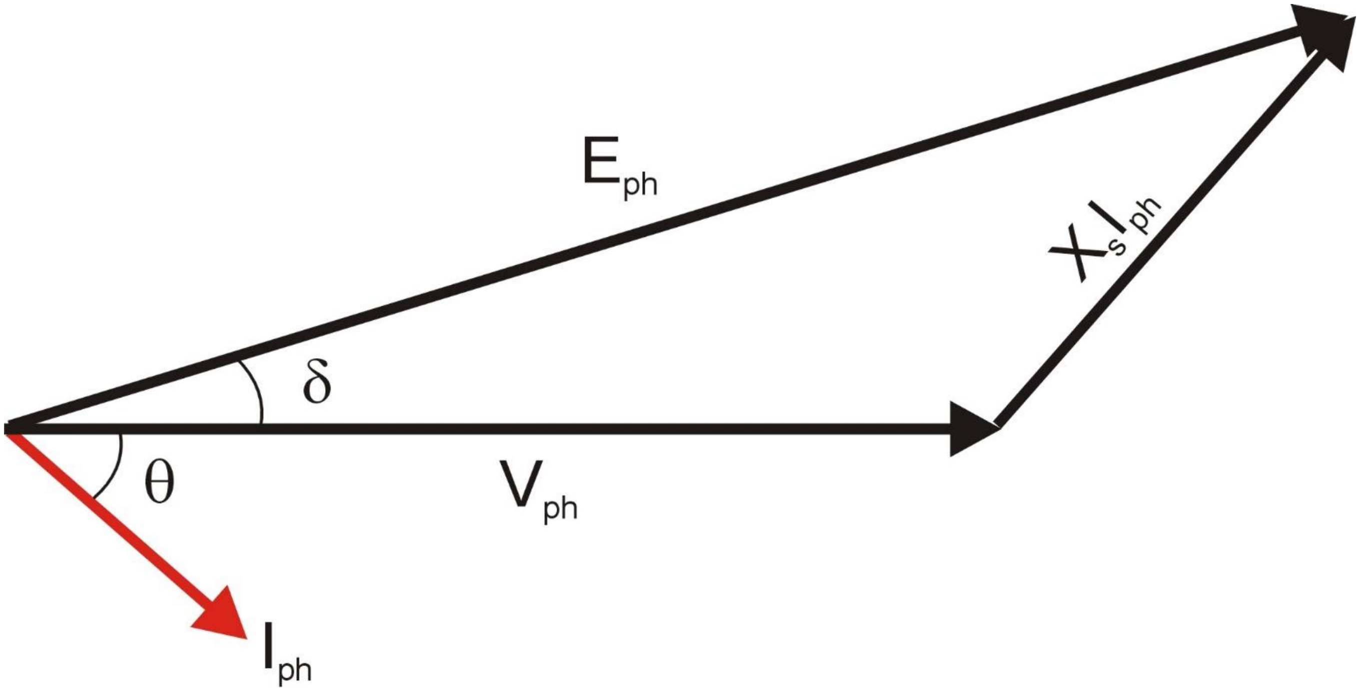
2. The Voltage across the Synchronous Reactance (V_{XS}) leads the phase current I_{ph} by 90º ($V_{XS} = I_{ph}.j_{XS}$)

3. $E_{ph} = V_{ph} + V_{XS}$ (phasor arithmetic)

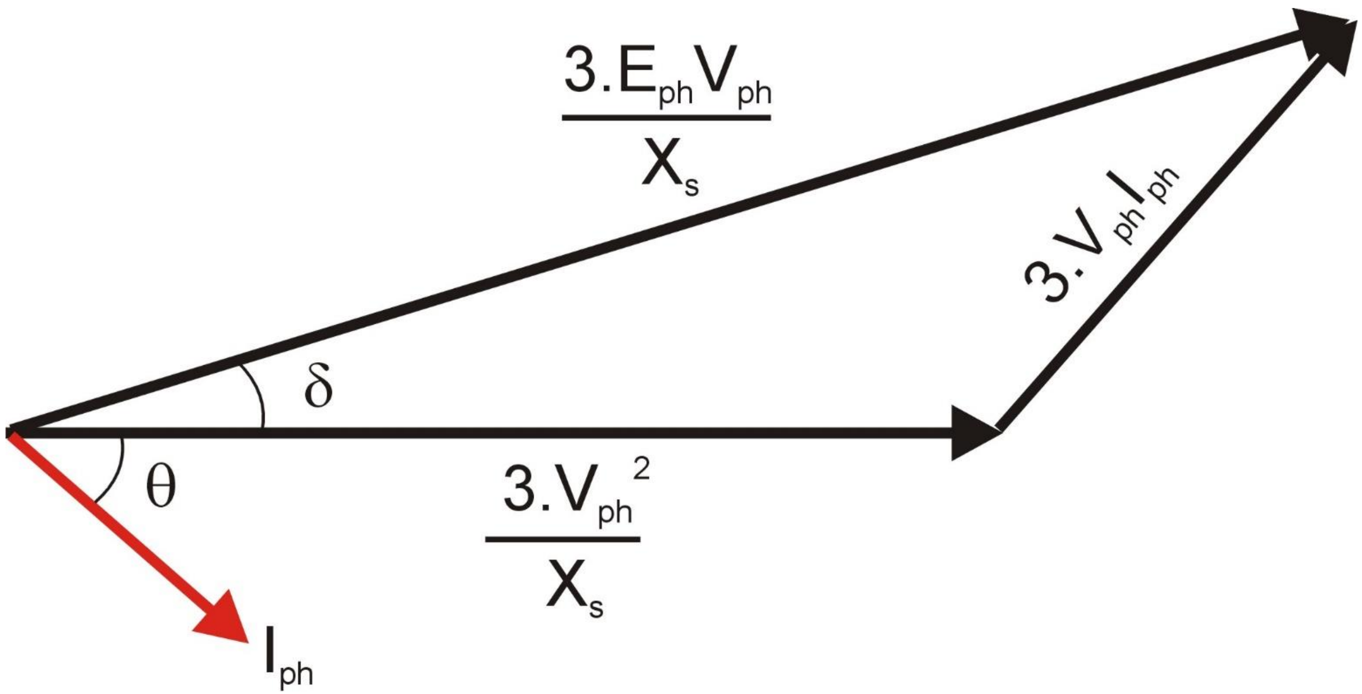
4. The Angle δ between V_{ph} and E_{ph} is termed the **LOAD ANGLE**

Unlocking the Power of the Phasor Diagram #1:

Typical Phasor Diagram:

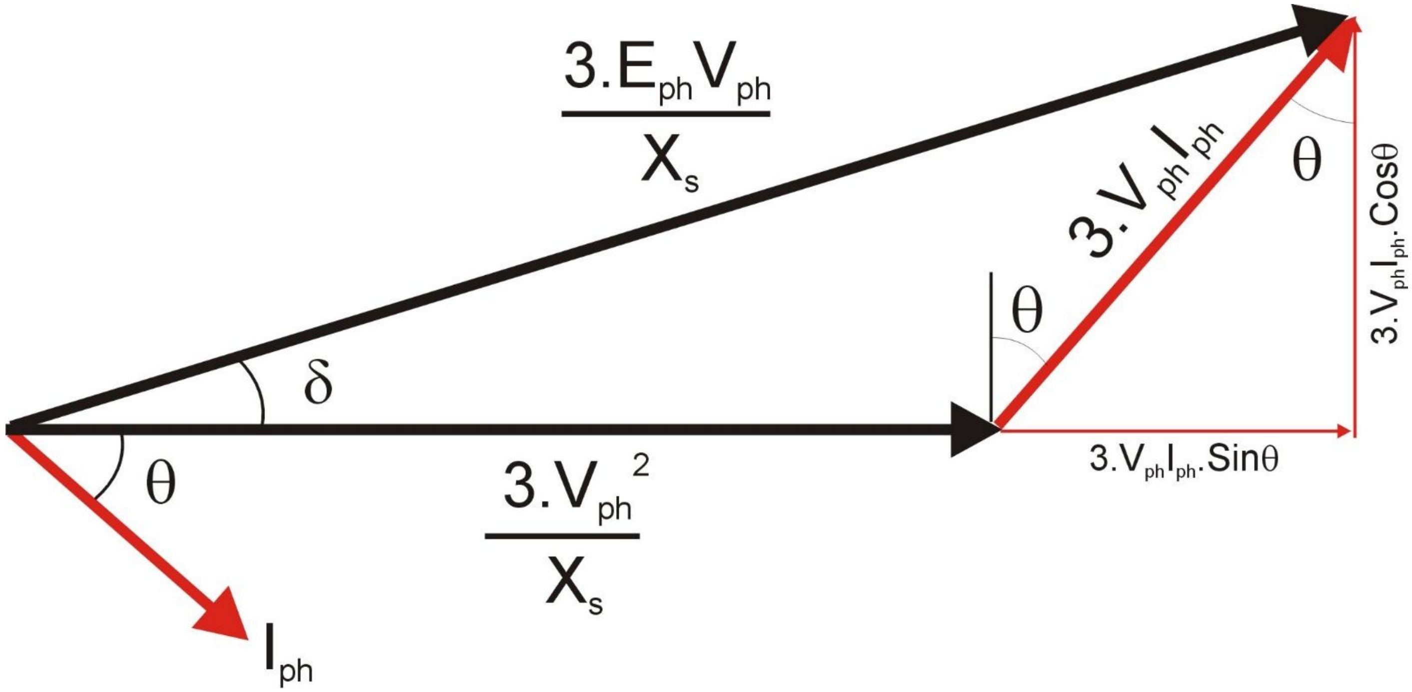


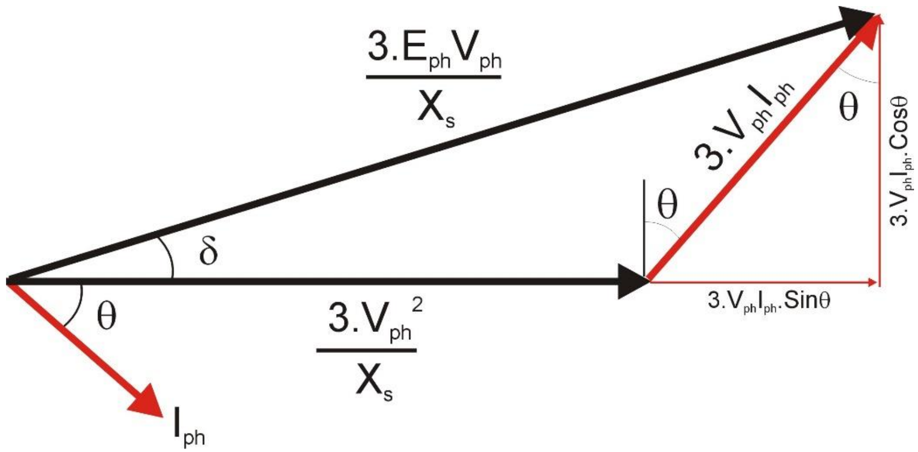
Multiply all Voltage Phasors by $\dfrac{3.|V_{ph}|}{X_s}$



Note: Vph is magnitude only

Output Power as a function of Load Angle (δ)





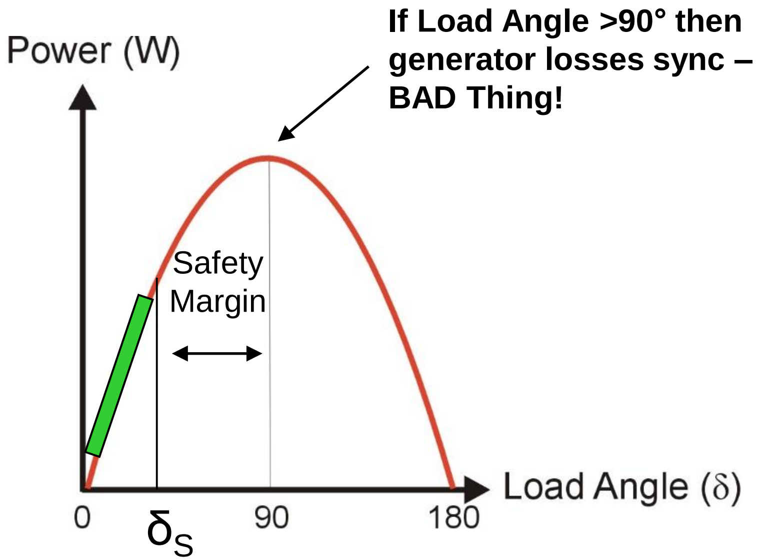
$$Sin(\delta) = \frac{O}{H}$$

Result: Load Angle is kept below δ_S to avoid stability problems

$$Sin(\delta) = \frac{O}{H} = \frac{3V_{ph}.I_{ph}Cos\theta}{\frac{3E_{ph}V_{ph}}{X_s}}$$

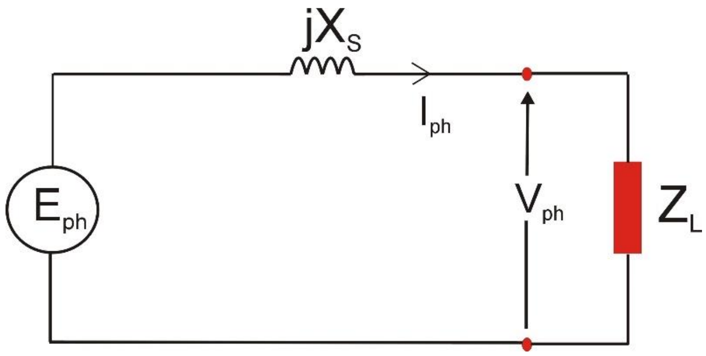
$$Sin(\delta) = \frac{X_s.Power(W)}{E_{ph}V_{ph}}$$

$$Power(W) = \frac{E_{ph}V_{ph}Sin(\delta)}{X_s}$$



Operating Modes

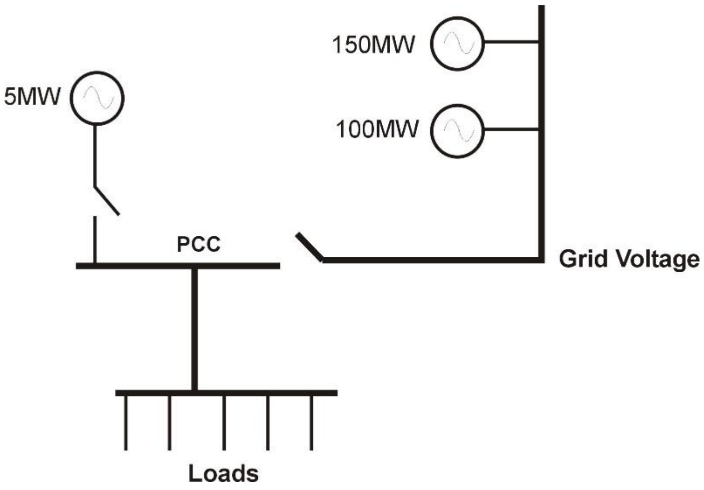
Stand Alone Mode



The Generator operates in isolation with a (variable) load connected across its terminals

The result is the terminal voltage (V_{ph}) varies as a function of Load (Z_L) and Excitation Voltage (E_{ph})

Grid Connected Mode



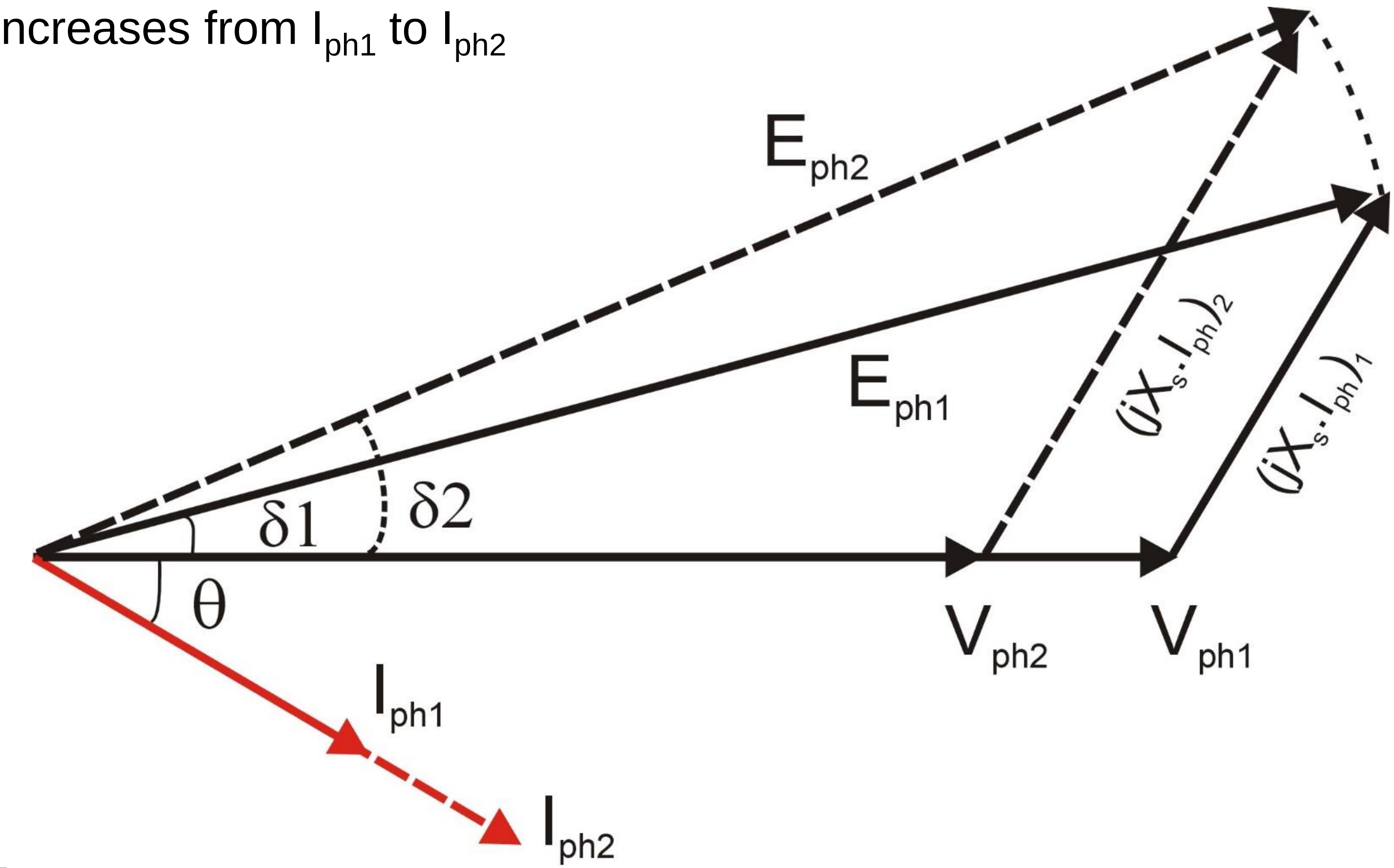
The Generator connects to a ‘network’ of large Generators

The result is the terminal voltage (Vph) is **FIXED**

Stand Alone Mode: Increase in Load with no change to Excitation (E_{ph})

1] Power Factor Angle θ is set by load and stays constant (approximation)

2] Current Increases from I_{ph1} to I_{ph2}



Results:

Stand Alone Mode: Example

A star connected, 398V, 25kVA rated, stand alone micro-hydro 3 phase synchronous generator is operating near Galway in Ireland. It has a Synchronous Reactance of 3.5Ω. Considering an operating point of 18kW at rated current with a lagging power factor and rated terminal voltage, calculate:

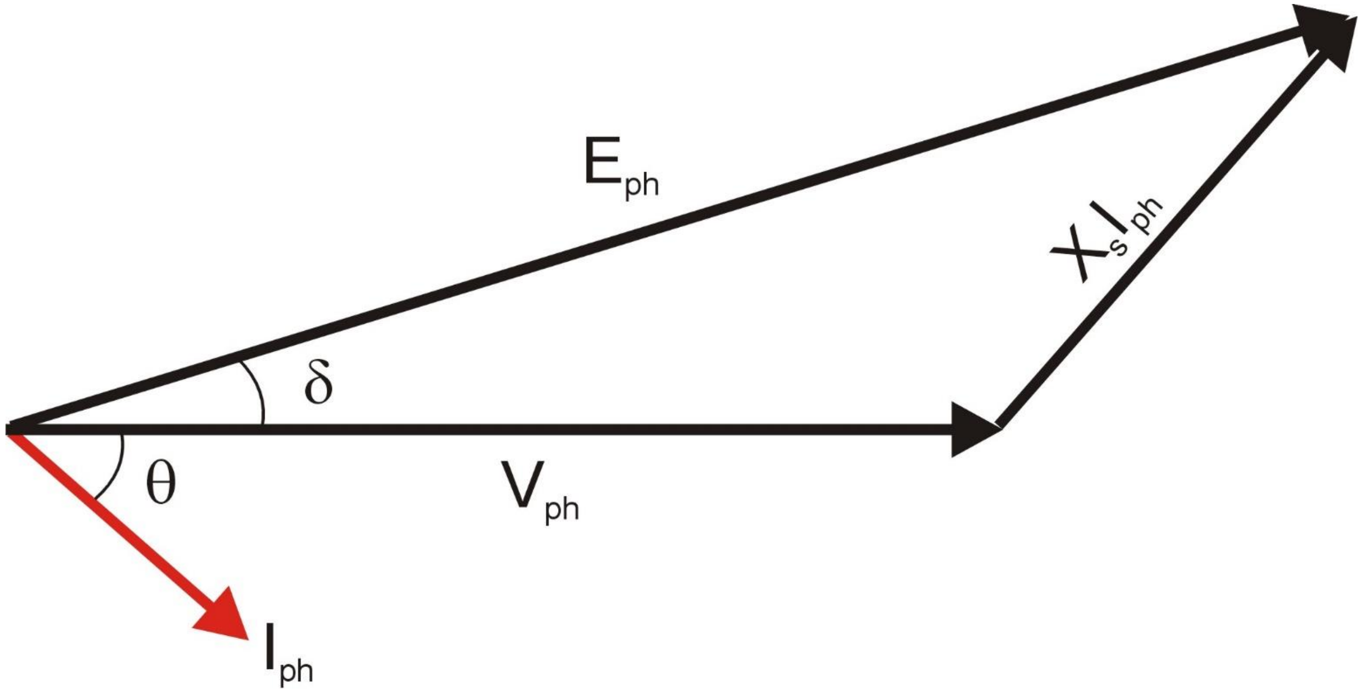
(i) Phase Current
(ii) Reactive Power
(iii) Power Factor
(iv) Required Excitation Voltage (E_{ph})
(v) Load Angle (δ)

Also sketch a phasor diagram (to scale) indicating V_{ph}, V_{xs}, E_{ph}, I_{ph} and load angle.

Solution done on whiteboard during lecture

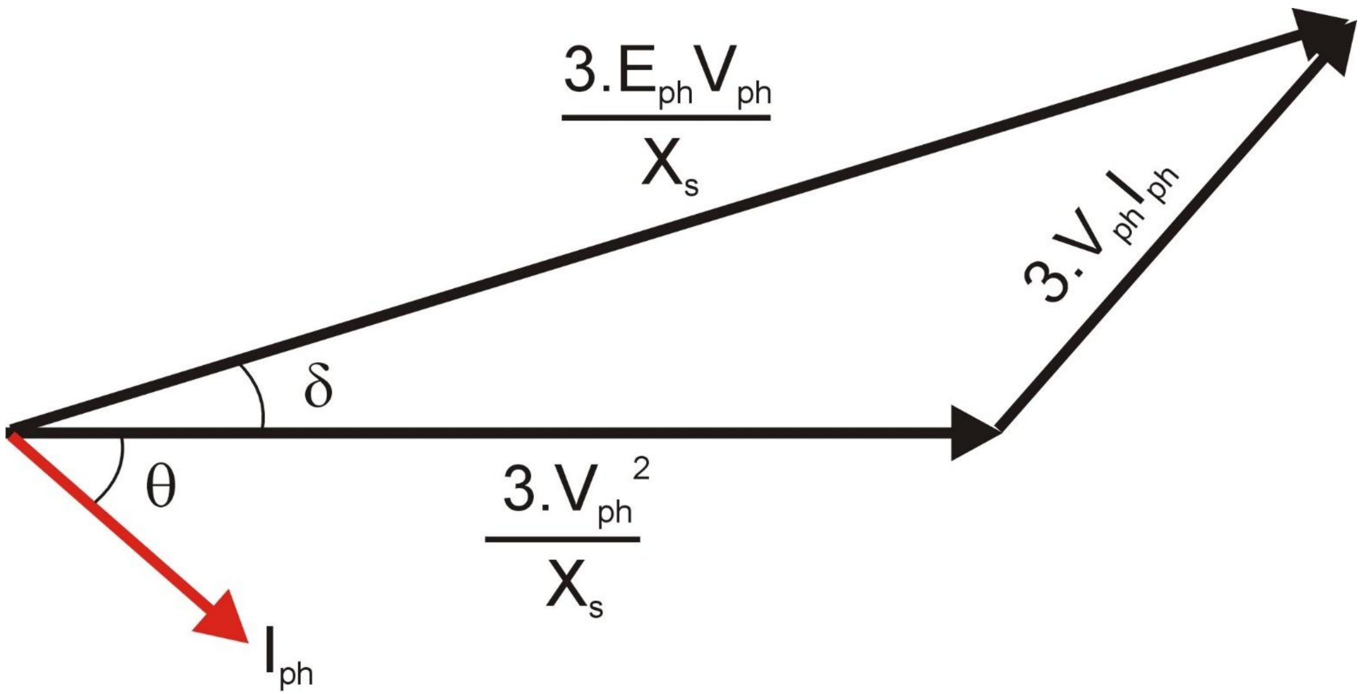
Unlocking the Power of the Phasor Diagram #2:

Typical Phasor Diagram:



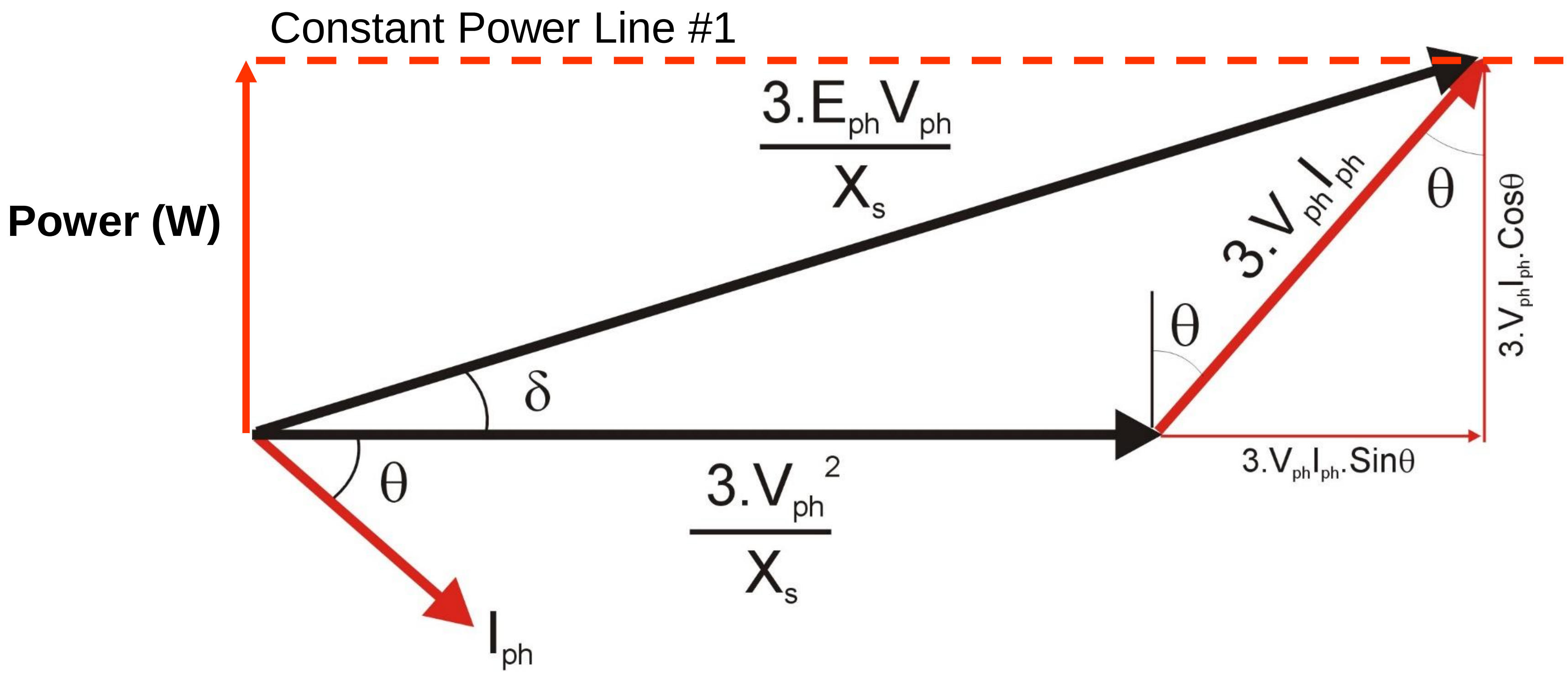
NOTE: for Grid Connected Mode the Terminal Voltage (V_{ph}) is **FIXED**

Multiply all Voltage Phasors by <u>CONSTANT</u> $\dfrac{3.V_{ph}}{X_s}$



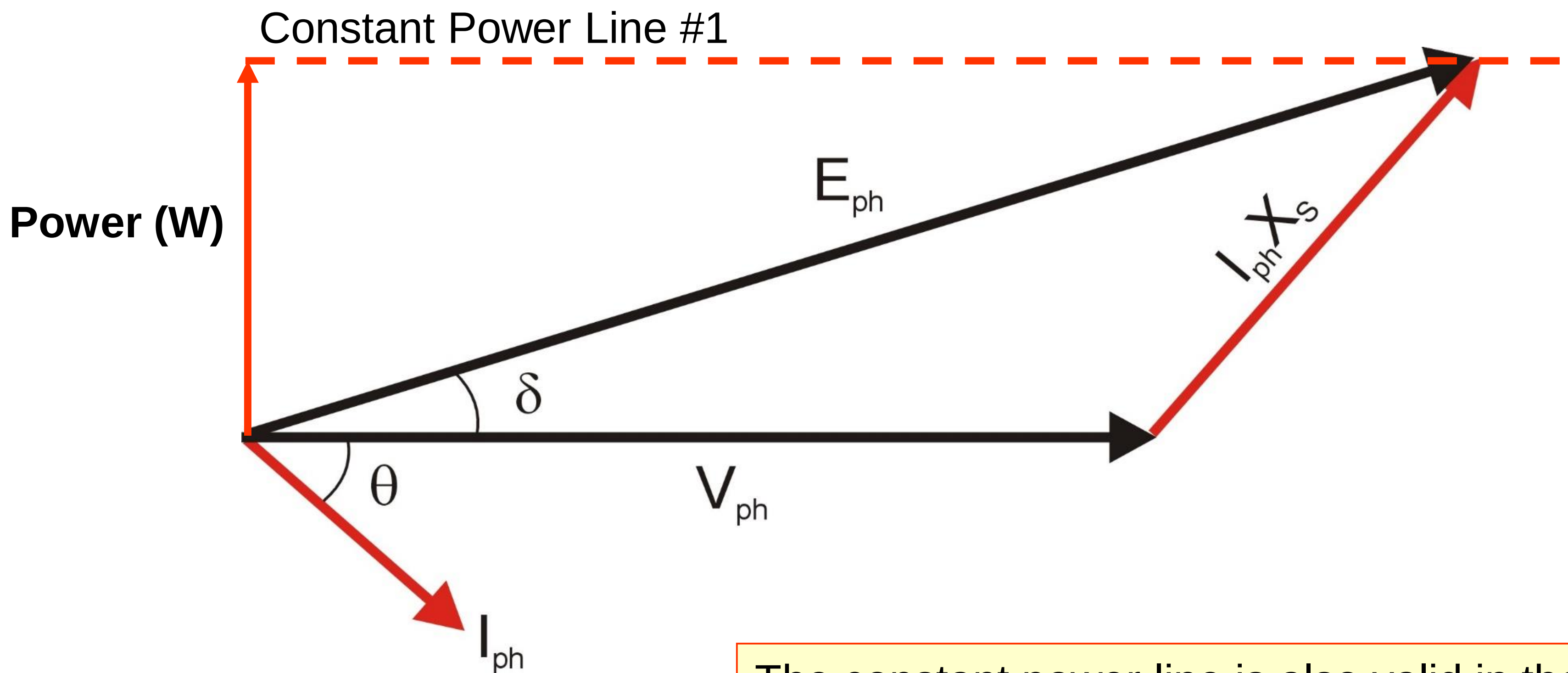
Note: V_{ph} is magnitude only

Constant Power Line #1



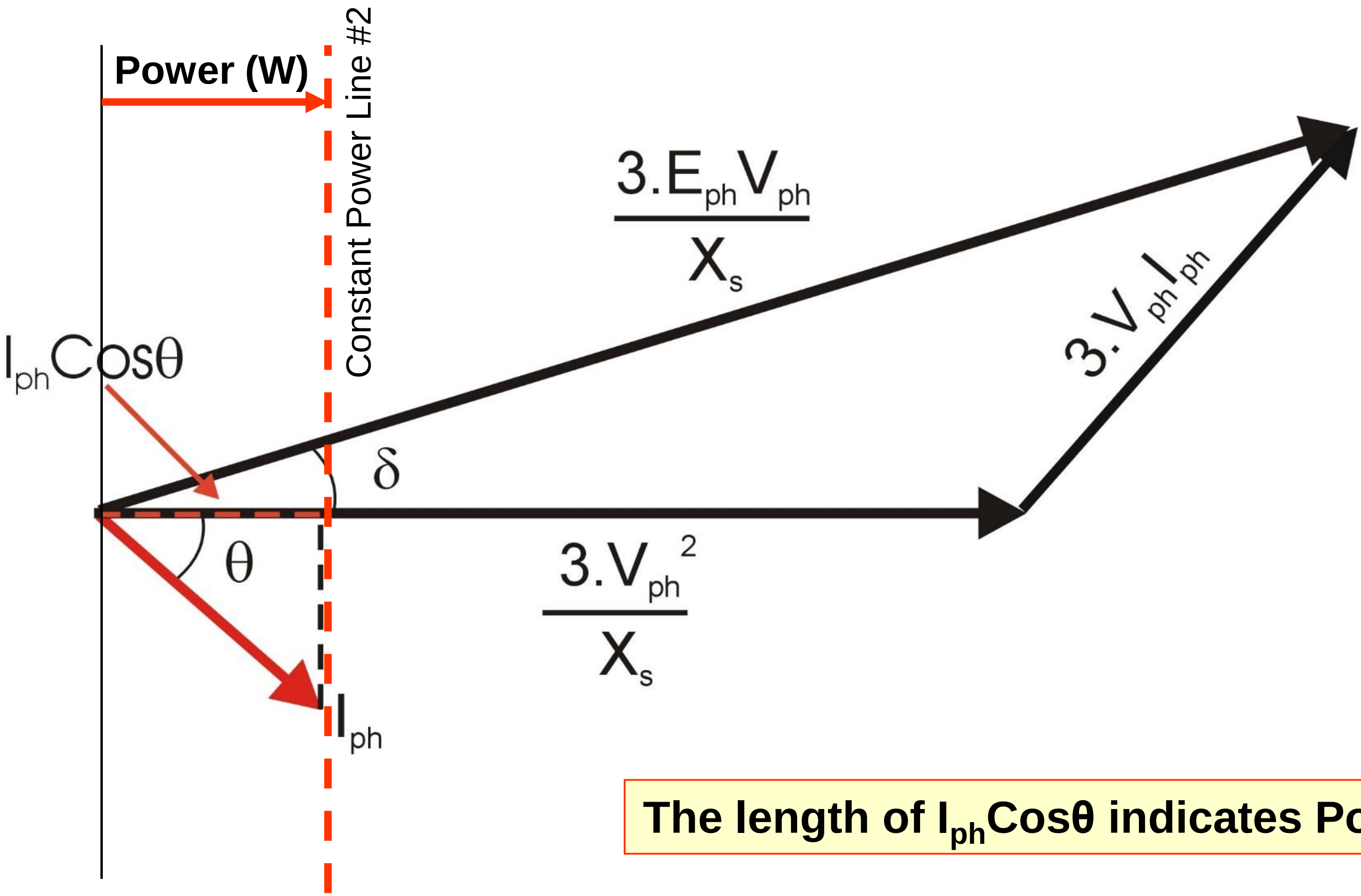
The length of $3.V_{ph}.I_{ph}Cos\theta$ indicates Power

Constant Power Line #1



The constant power line is also valid in the standard phasor diagram as $3Vph/X_S$ is a CONSTANT

Constant Power Line #2

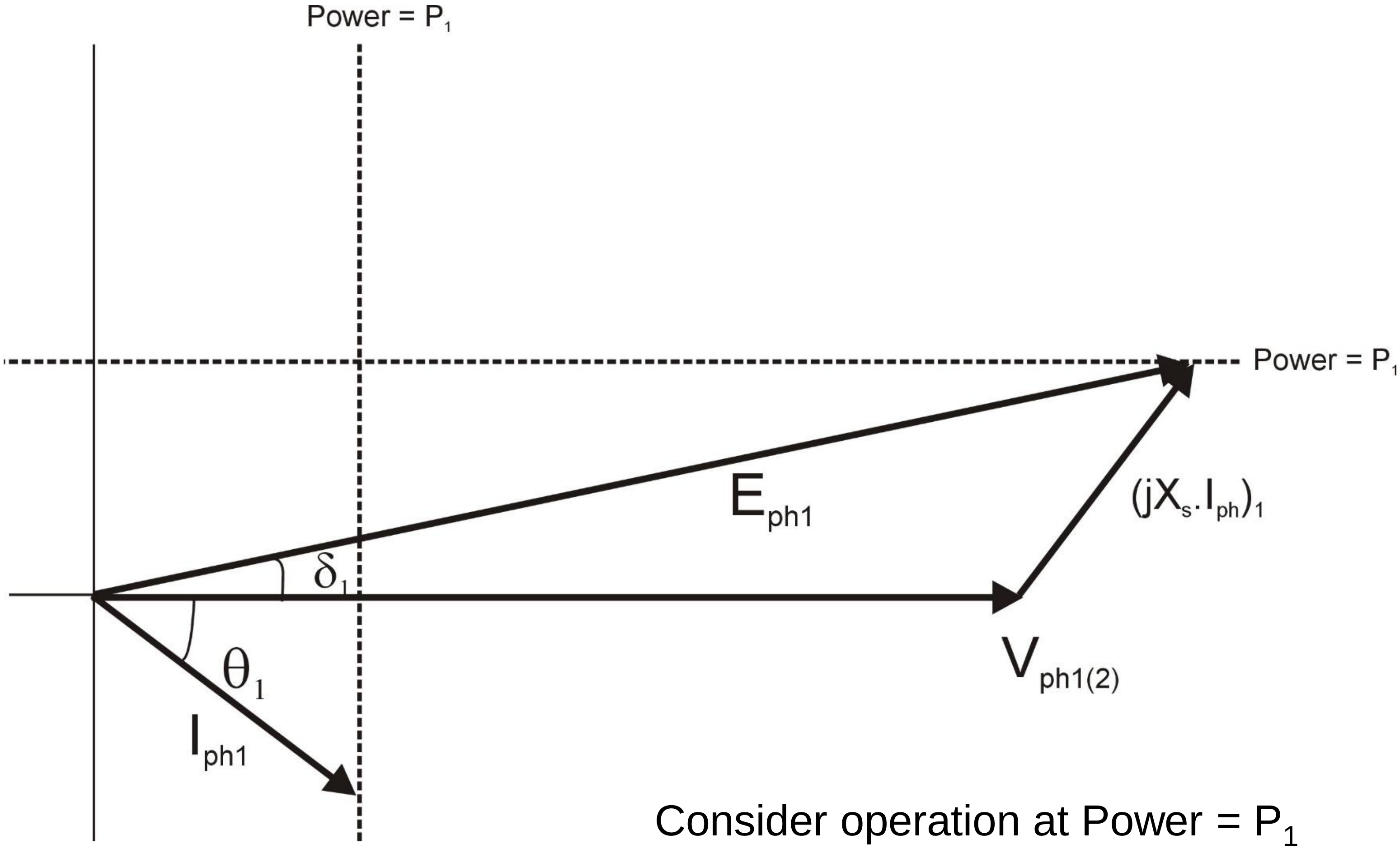


The length of $I_{ph}Cos\theta$ indicates Power

Remember V_{ph} is CONSTANT

Grid Connected Generator: Example

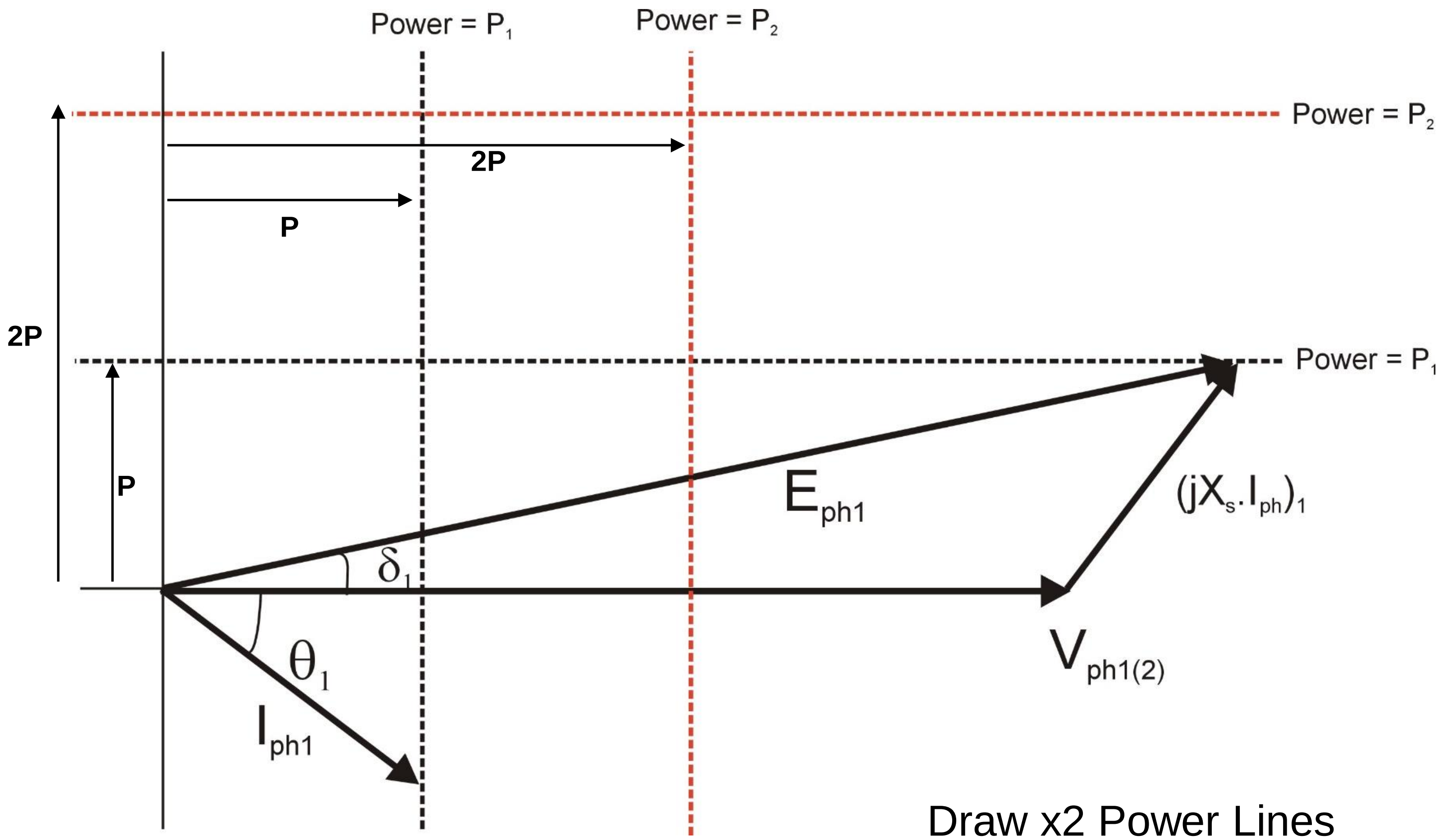
Determine the changes to the Phasor Diagram for a x2 increase in Output Power (W) and no change to the Excitation Voltage (E_{ph})



Consider operation at Power = P_1

Grid Connected Generator: Example

Now consider a x2 increase in Output Power (W):



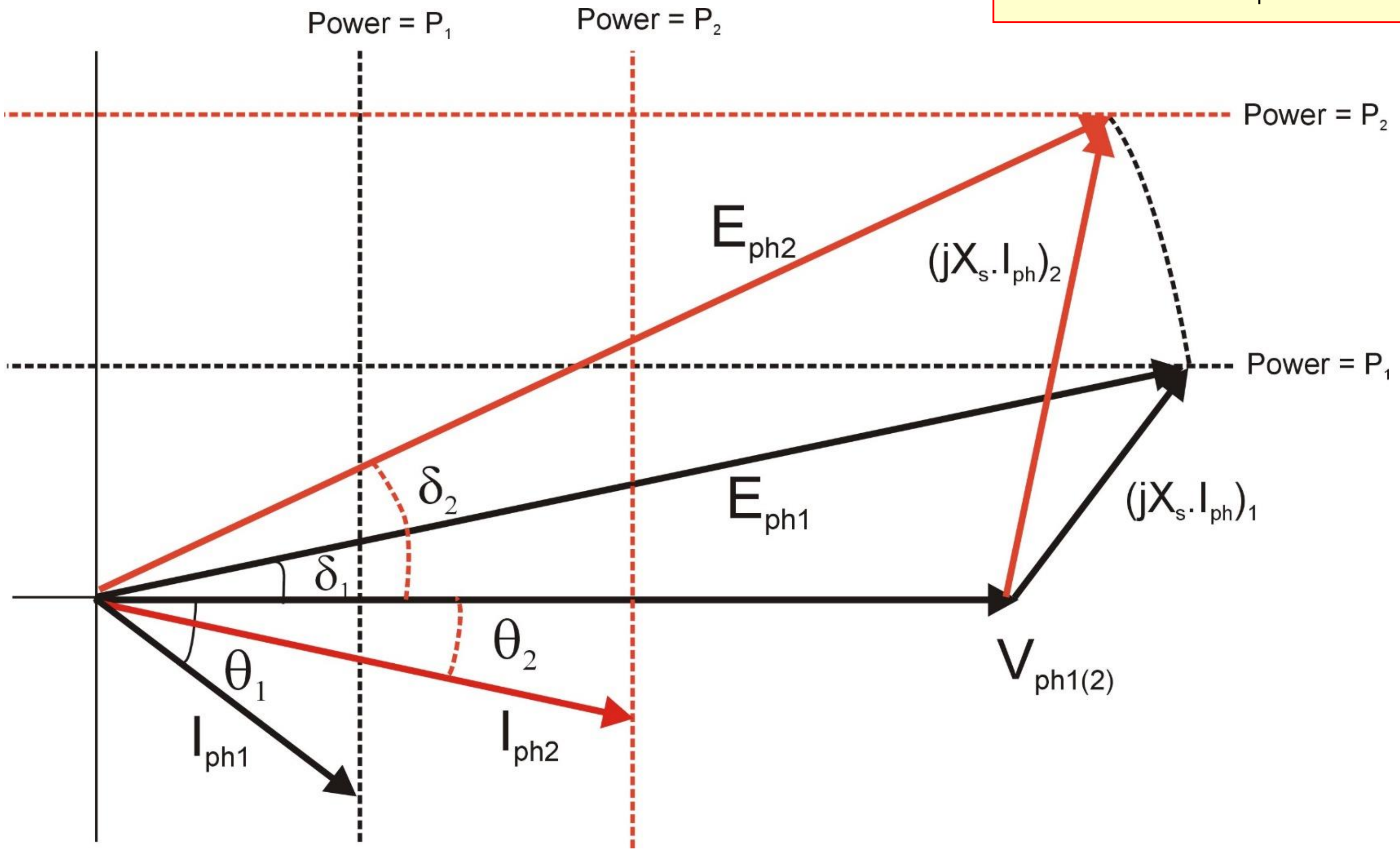
Draw x2 Power Lines

Grid Connected Generator: **Example**

Now consider a x2 increase in Output Power (W):

Procedure:

1. Rotate E_{ph} CCW to P_2 line
2. Calculate V_{xs}
3. Calculate I_{ph}



Example:

Part A

A 3 phase Synchronous Generator with a Synchronous Reactance of 25Ω is connected to an 10kV (Phase Voltage) grid and supplies 1MW at a 0.819 lagging Power Factor at its terminals. Calculate the phase current and resultant V_{XS}, and from the phasor diagram graphically determine the required Excitation Voltage (E_{ph}) and Load Angle (δ)

Part B

The load is increased to 3MW, calculate the resultant changes to the phase current, power factor and load angle for constant Excitation Voltage.

Solution done on whiteboard during lecture