EEP 225 : Electric Machines

Lecture 8
AC Machines IV

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1 Synchronous Generator Connected to Electrical Grids (Synchronization)

Generators don't supply load directly, they are first connected to the grid, the the grid supplies different loads

Electrical grids are characterized by their constant voltage and frequency from no load to full load conditions.[1]

It is not that simple to connect the generators directly to the grid, we must sync the following characteristics of the generator and the grid.

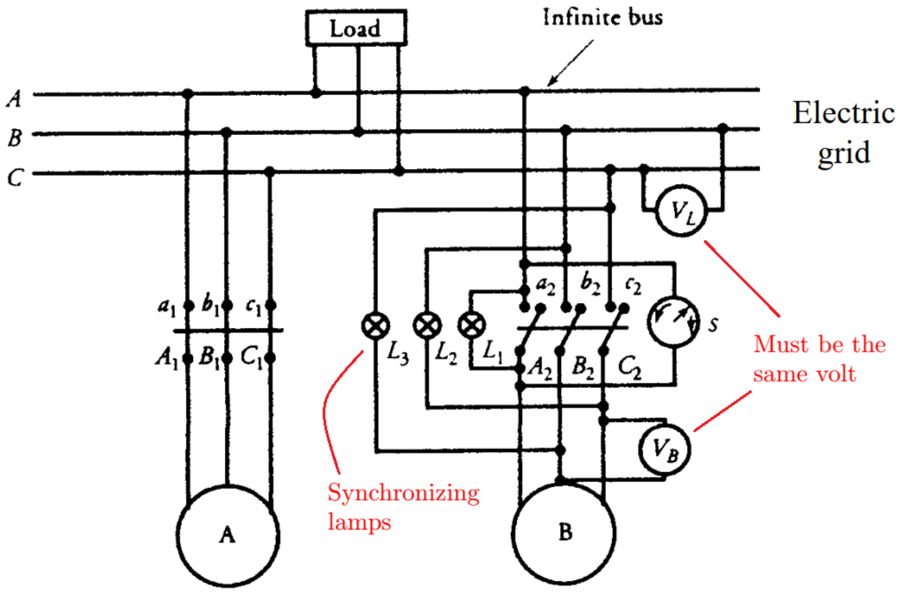

Figure 1

1. Same frequency, How?
   Control the speed of the prime mover.
2. Same Voltage, How?
   Control the field current of the alternator.
3. Same phase angle (a_2 and A_2), How?
   Use **synchronizing lamps** (low rating) or **Synchroscope** (high rating).
4. Same phase sequence[2] , How?
   Use **synchronizing lamps** or **Synchroscope.**

[1]There are two voltages in Egypt, 220Kv and 500Kv

[2]Remember from circuits 1, in any 3 phase system
Positive sequence $\rightarrow a, b, c$
Negative sequence $\rightarrow a, c, b$

Figure 2: Synchroscope

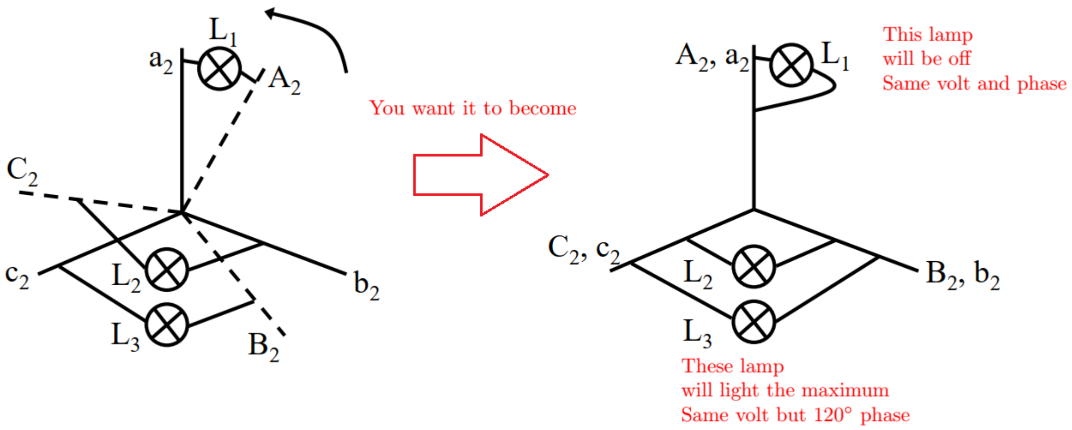

Figure 3: Two bright one dark lamp method

If the generator and the grid don't have the same phase angle, synchronization lamps will be on and off one after each other (like ↻).

When the phase angle get closer, speed of being of and off will decrease.

When phase angles become the same, 1st lamp will be off, 2nd and 3rd lamp will be one, when so, we close the switches and connect to the grid.

What if generator and grid don't have the same phase sequence? lamps will flash synchronously(with each other).

This is called two bright one dark lamp method.

There are three dark lamp method, in this method a lamp is connected between a_2 and A_2, between b_2 and B_2 and between c_2 and C_2.

When generator and grid have the same phase angle, all three lamps go off (same voltage difference and phase).

When the generator is connected to the grid, it gets the characteristics of the grid (its voltage and frequency are constant).

What if I tried to increase the speed of the prime mover by increasing the pressure of the steam?

Speed will not increase because of the constant frequency and voltage, but input torque will increase, which increases the power.

2 Electrical Load Diagram

Electrical load diagram is the **locus** diagram for constant electrical power and constant excitation (E) after the machine has been connected to infinite bus bars, i.e. for constant voltage and constant frequency operation.

For simplicity, electrical load diagram will be illustrated for large machines, in that case armature resistance is neglected.

$$R_a \approx 0 \qquad \therefore Z_s \approx X_s$$

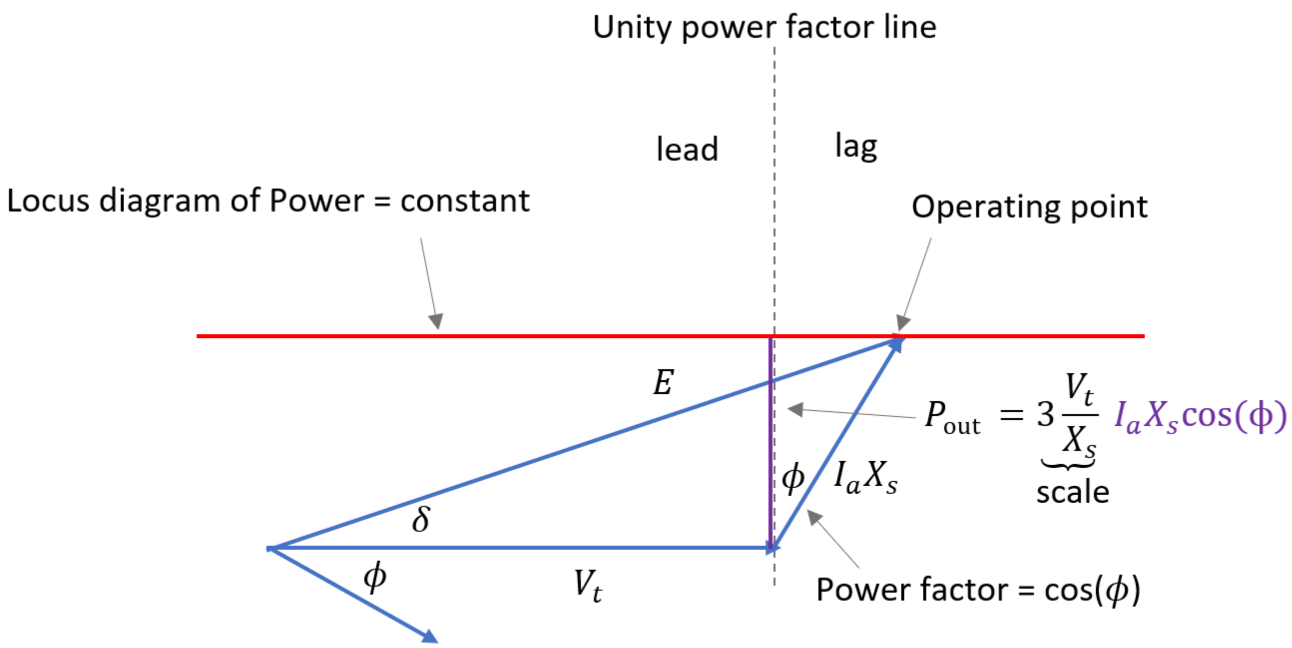

Figure 4: Operating point, how to measure power and locus diagram of constant power

How can we find power graphically?

$$P_{\text{out}} = 3V_t I_a \cos(\phi)$$

$$P_{\text{out}} = \underbrace{3\frac{V_t}{X_s}}_{\text{scale}} \underbrace{I_a X_s \cos(\phi)}_{\text{length}}$$

The projection of $I_a X_s$ on the unity power factor line is the power, but need to be multiplied by its scale

What are the scales?

$$\begin{aligned} 1\,\text{cm} &= \clubsuit && \text{Volts} \\ 1\,\text{cm} &= 3\frac{V_t}{X_s}\clubsuit && \text{Watt} \\ 1\,\text{cm} &= \frac{\clubsuit}{X_s} && \text{Amp} \end{aligned}$$

$\clubsuit$ will be given in the exam

What is the locus of constant output power?

The horizontal parallel red lines

What is the locus of constant constant excitation (E)?

The green circles with radius = excitation (E)

What is the locus of constant power factor line?

The gold lines with angle = ϕ lead or lag the vertical unity power factor line

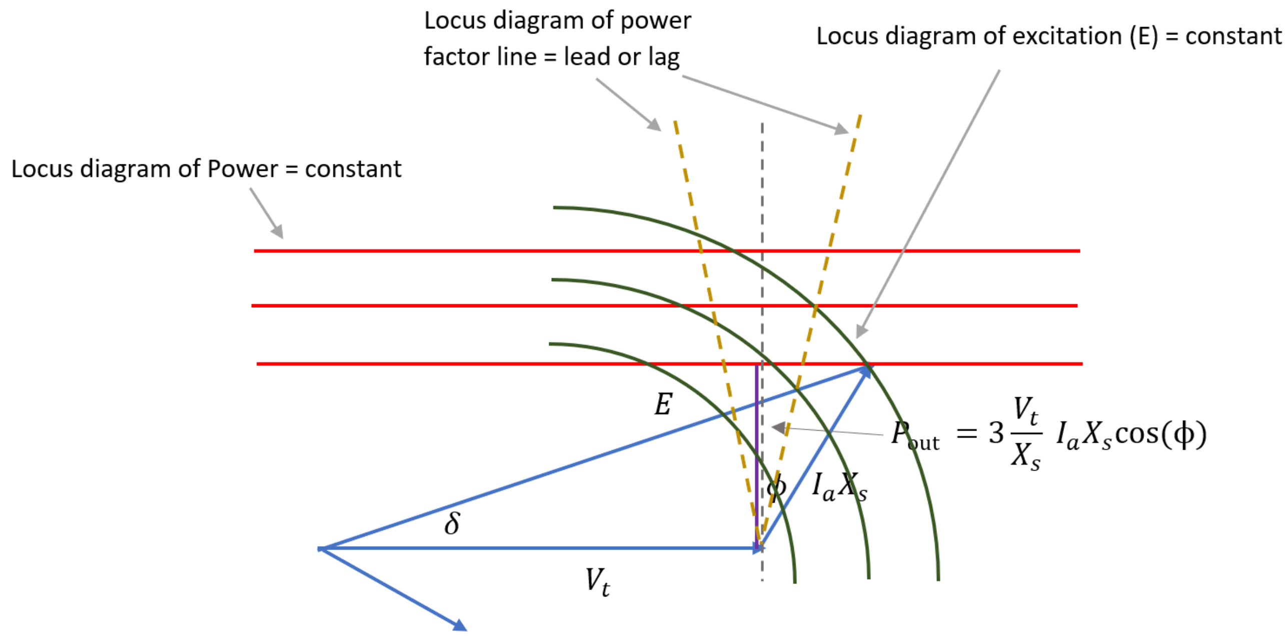

Figure 5: Locus diagram of constant power, constant excitation (E) and constant power factor line

How to get the maximum output power? Remember from lecture 7 : The **maximum output power** occurs at $\delta = \frac{\pi}{2}$ and is given by :

$$\boxed{P_{\text{out},\delta=0.5\pi} = 3\frac{|E||V_t|}{X_s}}$$

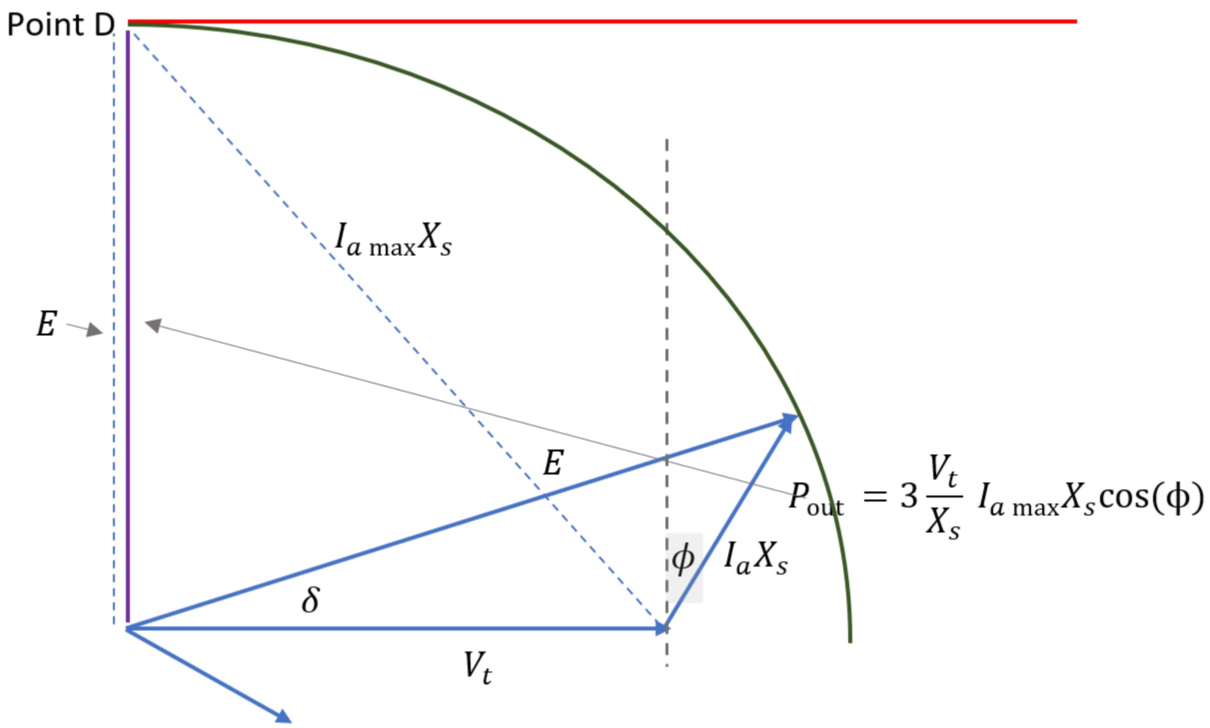

Figure 6: Maximum output power, in this figure, length of power = length of E, but value of power ≠ value of E, because each has its own scale

If the excitation is kept constant, and the operating point is allowed to move upwards on the circle, the output power is gradually increased ↑ until it reaches point D where the output power becomes maximum.

This is a limiting point after which the generator goes out of step and breaks out of synchronism.

In that case

$$\delta = 90^\circ$$

Note : There are 5 parameters

$$P \quad E \quad I_a \quad \delta \quad \phi$$

To determine the operating point, you only need **any two points**.

$\boxed{1.\ Q}$ — A 3-phase, Y connected alternator (= AC generator) is connected to 11000 V, 50 Hz infinite bus bars, it has to supply 3000 kW at 0.8 pf lagging. It has a synchronous reactance per phase of 15Ω. Find the value of the machine emf and power angle.

Find also the value of the emf at which the machine would supply the same power at unity pf.

For this value of the emf, find the maximum power and the corresponding current and pf which the machine would deliver before it breaks out of synchronism.

A —

Given Line voltage, we want to get phase voltage.

$$V_{t\text{phase}} = \frac{11000}{\sqrt{3}} = 6350 \text{ V}$$

Let's know the scale:

$$\begin{aligned} 1\,\text{cm} &= 1000 \text{ Volts} \\ 1\,\text{cm} &= 3 \times \frac{6350}{15} \times 1000 = 1270 \text{ KW} \\ 1\,\text{cm} &= \frac{1000}{15} \text{ Amp} \end{aligned}$$

Operating point (1) :

height of locus of power =

$$\frac{\text{power}}{\text{scale}} = \frac{3000}{1270} = 2.4\text{cm}$$

length of $V_{t\text{phase}} = \frac{6350}{1000} = 6.35\text{cm}$

we will draw $V_t = 6.35cm$

angle of power factor line $= \cos^{-1}(0.8) = 36.86°$ lagging

we will draw $\phi = 36.86°$ lagging

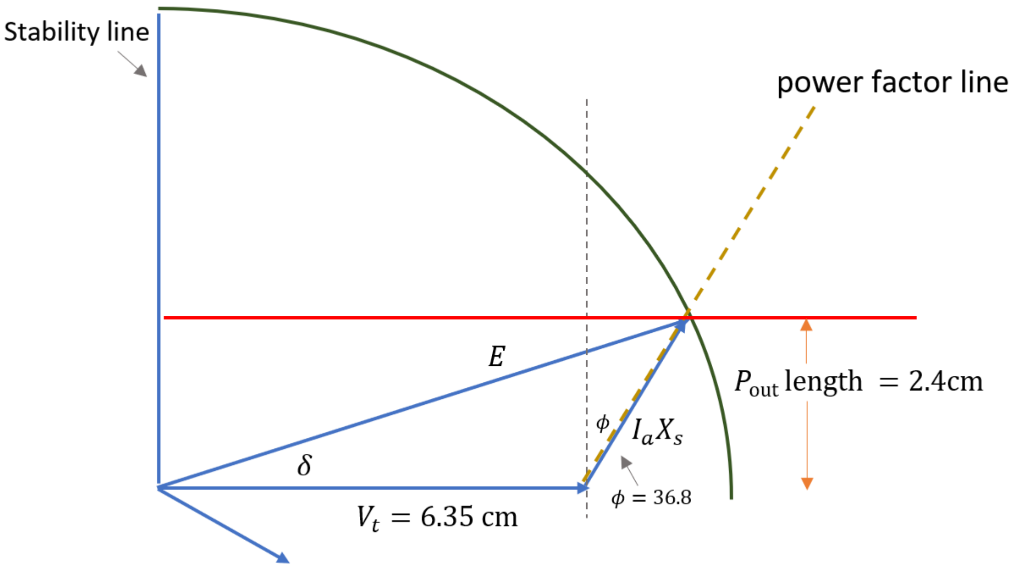

Figure 7

After drawing, we measure the length of E, we will find it 8.4 cm, which means that $E = 8.4 \times 1000 = 8400V$

Measure power angle, it equals 16°

Operating point (2) : Same power, unity power factor, what is E?:

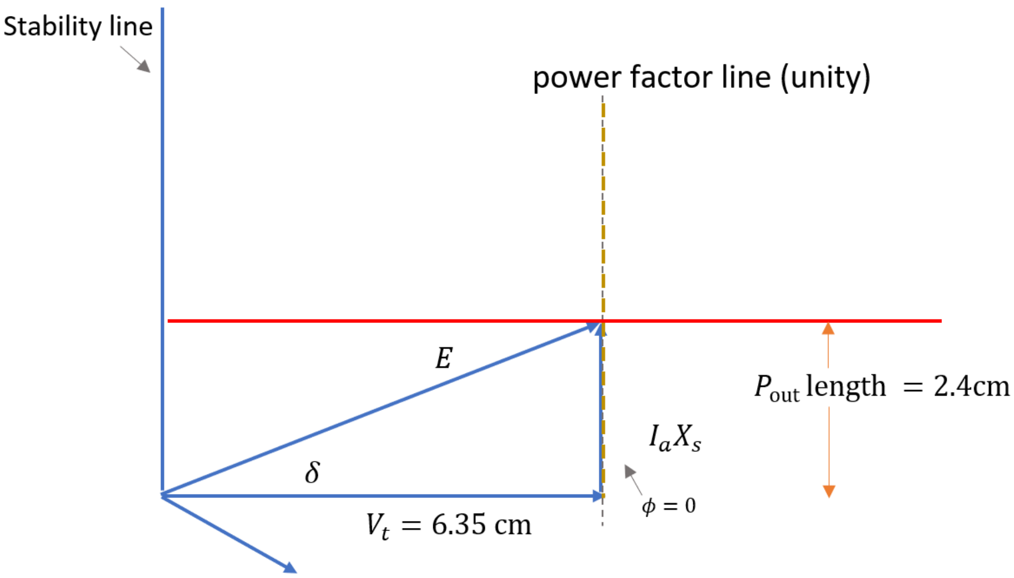

Figure 8

After drawing, we measure the length of E, we will find it 6.7 cm, which means that $E = 6.7 \times 1000 = 6700V$

Operating point (3) :

Same E, what is maximum power and power factor?:

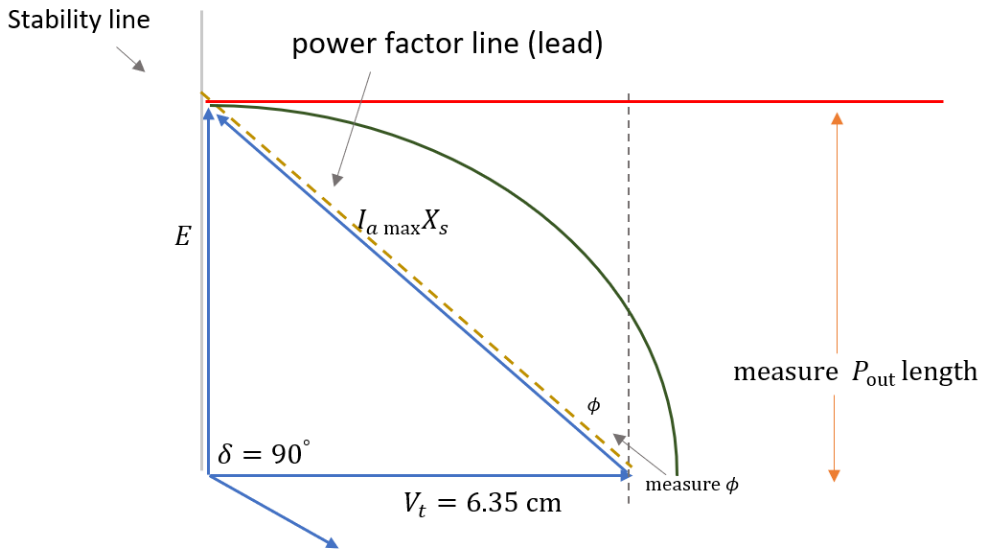

Figure 9

After drawing, we measure the height of P_{out}, we will find it 6.7 cm, which means that $P_{\max} = 6.7 \times 1270 = 8509\text{KW}$

Measure $I_{a\max}$, we will find it 9.2 cm, which means that $I_{a\max} = 9.2 \times 66.67 = 613.3A$.

Measure phase angle ϕ, we will find it 43°, which means that power factor $= \cos(43^{\circ}) = 0.73$ leading.

Note : At constant power, minimum current occurs at unity power factor.

Note : In real applications, generator supplies variable loads, so we deal with regions not single point e.g.(from unity power factor to 0.8 lag, and from $E = E_1$ and $E = E_2$):

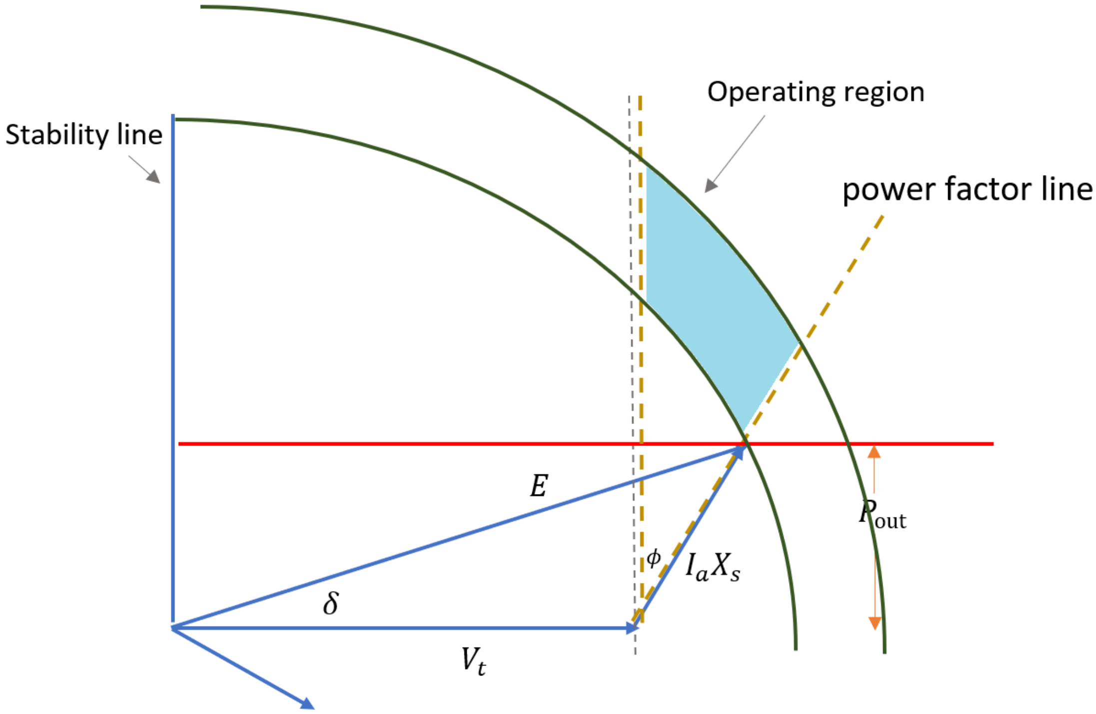

Figure 10: Operating region

In the case of operating region, graphical solution is much easier than analytical solution.

3 Synchronous Motors

One of the disadvantages of the synchronous motor is that its cost is higher than the cost of other motors at the same rating.

$$\text{Synchronous motors} > \text{Dc motors} > \text{Induction motors}$$

Another disadvantage is that it needs two types of supplies, AC supply and DC supply for the field circuit.

Equivalent Circuit of Synchronous Motor :

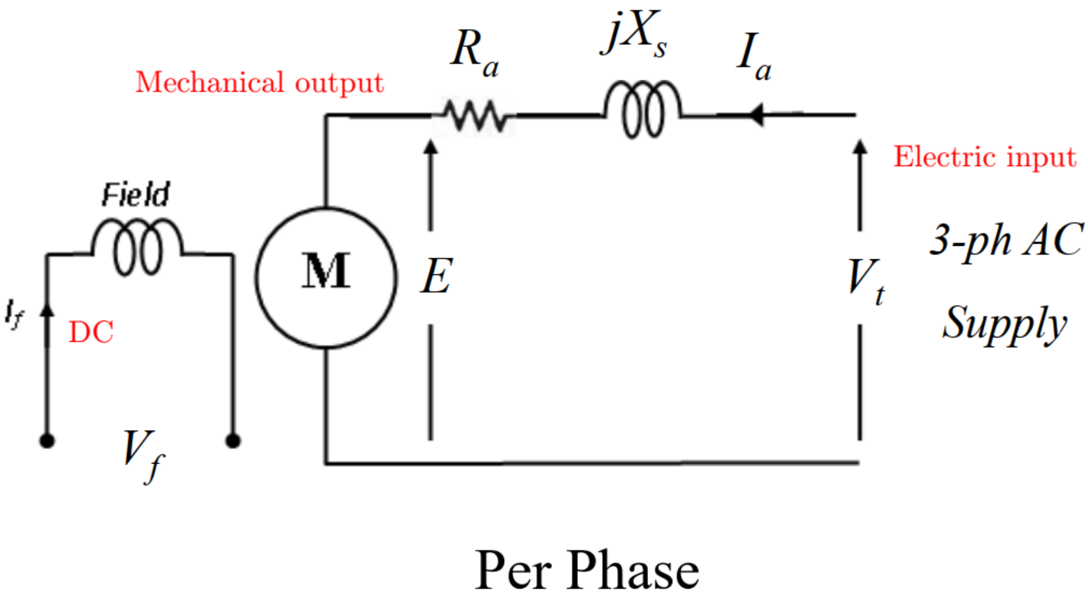

Figure 11: Equivalent Circuit of Synchronous Motor

$$\overline{E} = \overline{V_t} - \overline{I_a} \times \overline{Z_s}$$

$$E\underline{/\delta} = V_t\underline{/0} - I_a\underline{/\phi} \times Z_s\underline{/\theta}$$

3.1 Phasor Diagram of Synchronous Motors

$$E\underline{/\delta} = V_t\underline{/0} - I_a\underline{/\phi} \times Z_s\underline{/\theta}$$

$$E\underline{/\delta} = V_t\underline{/0} - I_a\underline{/\phi} \times (R_a + jX_s)$$

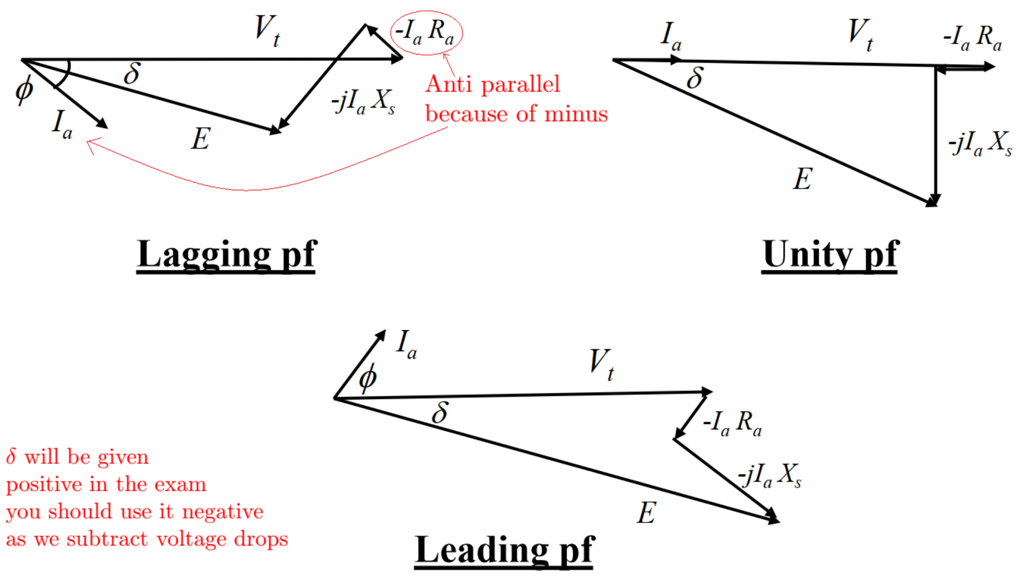

Figure 12: Phasor Diagram of Synchronous Motors

Instead of adding voltage drop as we did in generator, **we will subtract voltage drop.**

Synchronous motors are the **only** motors in which power factor can be controlled (by controlling excitation E), all other motors have lagging (inductive) power factor.

Therefore, synchronous motors can be over excited $E \uparrow\uparrow$ for power factor correction.

4 Power Flow, Losses and Efficiency

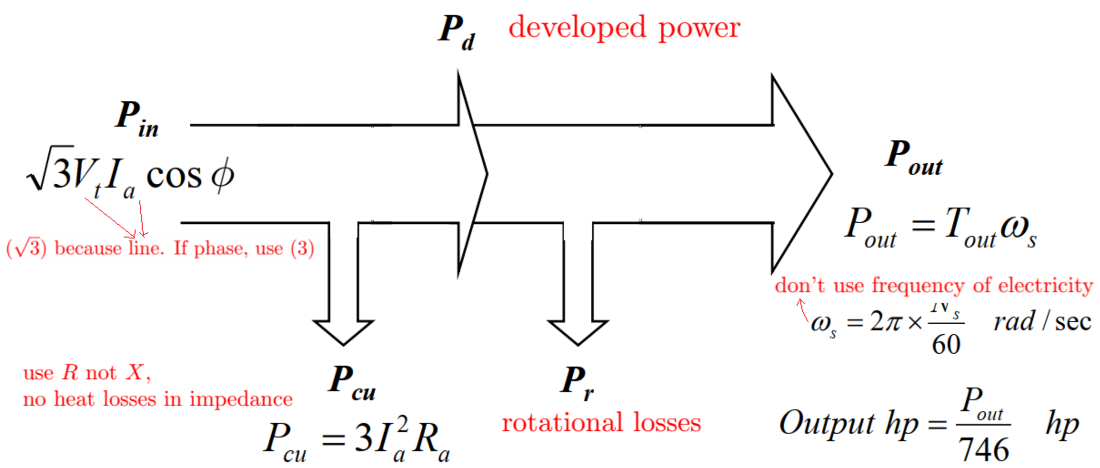

Figure 13: Phasor Diagram of Synchronous Motors

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_{\text{in}} - P_{\text{cu}} - P_{\text{r}}}{P_{\text{in}}}$$