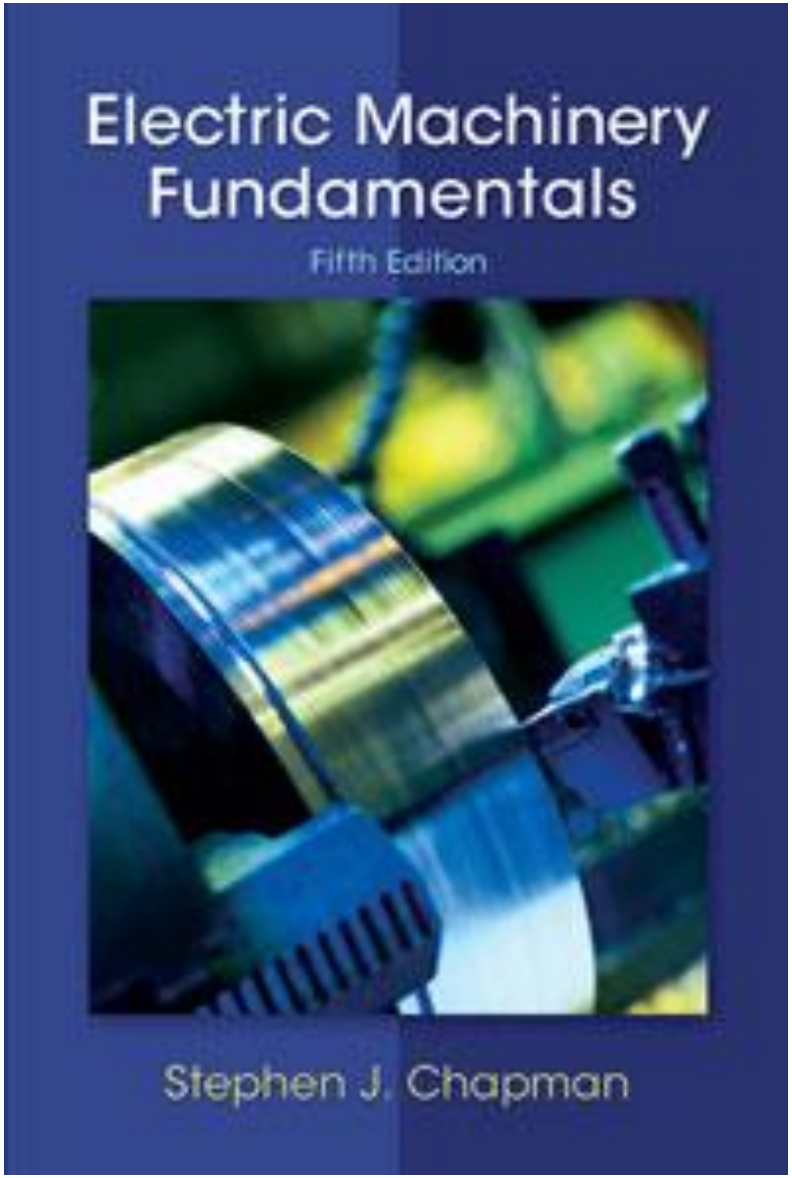


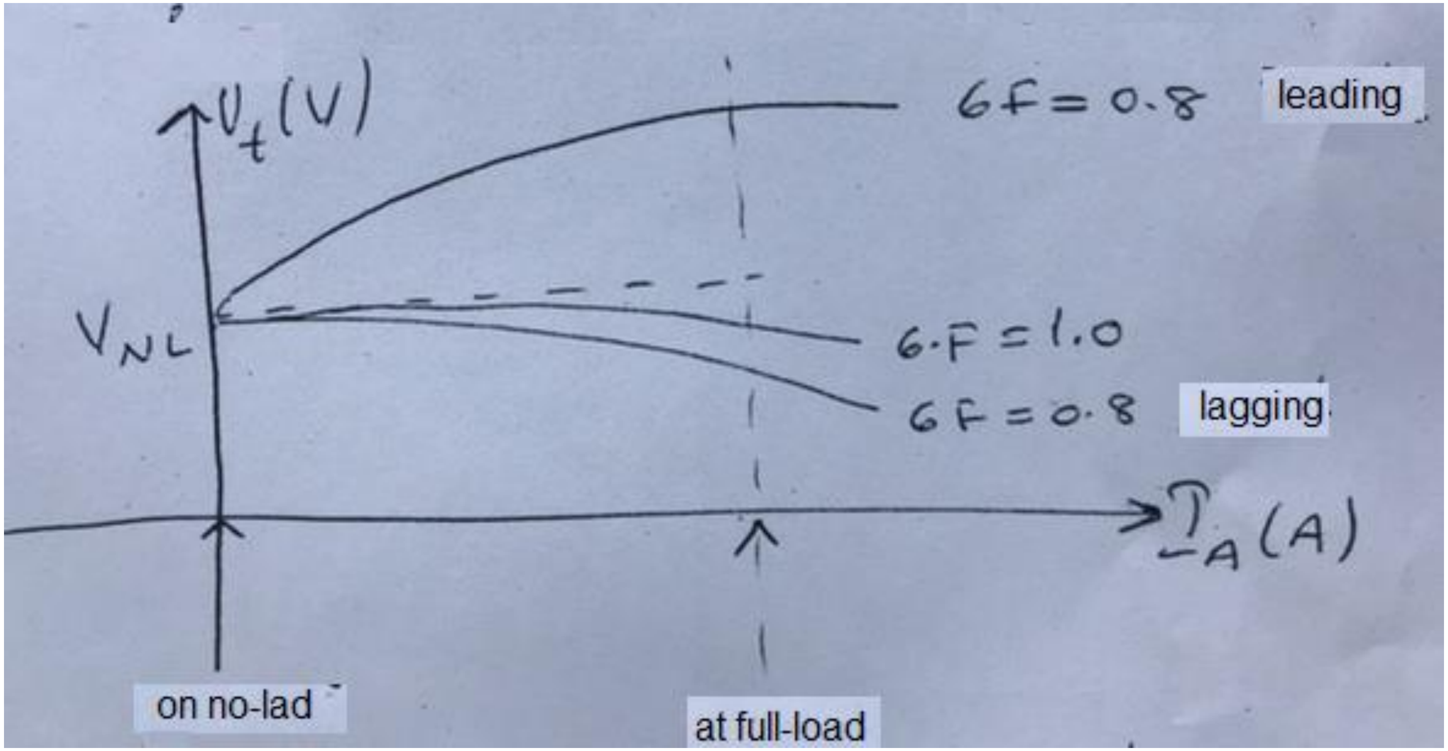
Synchronous Generators

Voltage Regulation

- The synchronous generator must provide the conditions listed below before feeding a load.

1. Since pole number of the machine is constant, the machine must be operated at right speed (synchronous speed) in order to generate voltage at required frequency.
2. A DC field excitation is required in the rotor.
3. The output voltage must be at desired level by adjusting the field current.

By providing these conditions, if the generator is loaded, the output voltage of the generator will be affected even the DC field excitation is constant. The voltage change of the generator depends on the load (i.e. load power factor). The output voltage will drop with resistive and inductive load increase, and it will increase with capacitive load increase.



- **Figure 6:** The output voltage vs load current for various load power factor.

- As we know before, factors such as voltage drop in the armature resistance and flux change due to the armature reaction affect the output voltage. The third factor affecting the output voltage of the synchronous generator is the voltage drop in the armature reactance. This is because of the armature inductance, L_A.
- $X_A = 2\pi f L_A \ (\Omega)$
- Where;
- L_A : armature winding inductance per phase (H)
- $\omega = 2\pi f$: Angular frequency in rad/s.

$$voltage\ regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} . 100$$

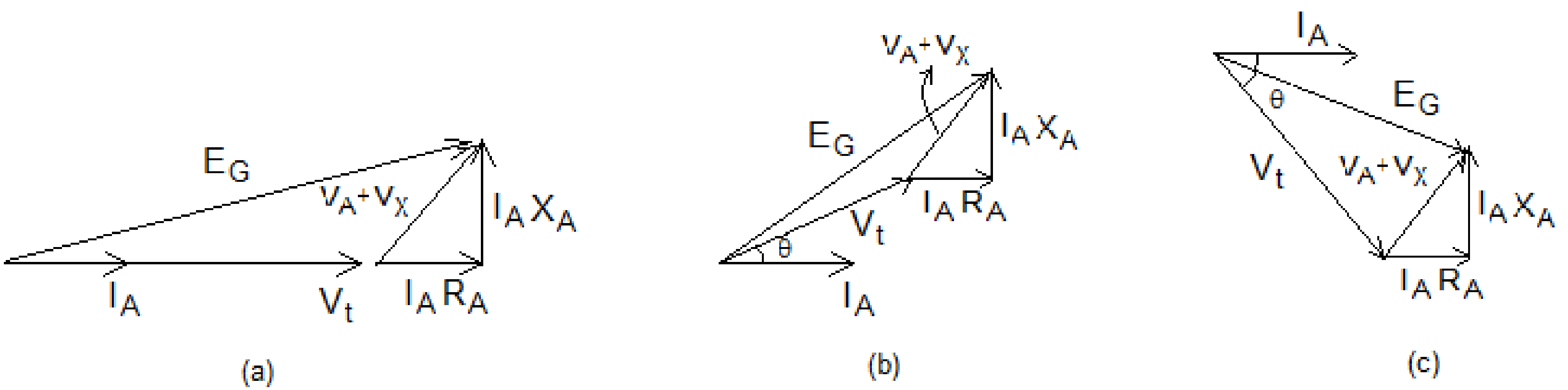
- V_{NL}: Voltage on no-load (V)
- V_{FL}: Voltage at full-load (V).

- In case the power factor is leading, the voltage regulation will be negative, which means that the voltage increases with the increase of the load.
- In general, the output voltage increases considerably when the load is extracted in AC generators. For this reason, voltage regulators are used together with synchronous generators.
- The voltage change in synchronous generators because of the armature reaction and reactance is much bigger than that of DC machines. The generators normally feeds long transmission lines having transformers resulting in extra voltage drops. All these negative factors result in unacceptable voltage changes with load changes in power delivery systems. For this reason, by using special designed regulators, the voltage drop is compensated by increasing DC field excitation current.

Voltage Drop in The Generator

- For example as a load, if a three-phase motor is supplied by the generator, a current in the armature winding of the generator will start to flow. The armature winding has a resistance, R_A per phase. Therefore, a voltage drop occurs in that resistance as;
- $$V_A = I_A.R_A \text{ (Volt/Phase)}$$
- Since three-phase is symmetrical, the voltage drop and therefore phase currents are same in all phases.
- The voltage drop does not only consist of the voltage on the resistance. In addition, a reactive voltage drop occurs because of the armature winding inductance.
- $$V_X = I_A.X_A \text{ (Volt/Phase)}$$
- X_A: Reactance per phase (Ω/Phase)

- It is not enough to know these voltage drops to determine the generated voltage. These voltages are added in vector to the output voltage to find the generated voltage. Therefore, it is required to know the character of the load and power factor.



- **Figure 7:** The effect of the power factor on the generated voltage by considering only the armature resistance and reactance. (a) PF=1.0; (b) PF=Lagging; (c) PF=Leading

- The relationship between the power factor and the generated voltage is shown in Fig.7. The generated voltage (E_G) is bigger than the output voltage (V_t) at unity and lagging power factors. However, the output voltage V_t is bigger than the generated voltage E_G at leading power factor. If the figure is examined carefully, E_G voltage is always leading the V_t voltage for all power factors.

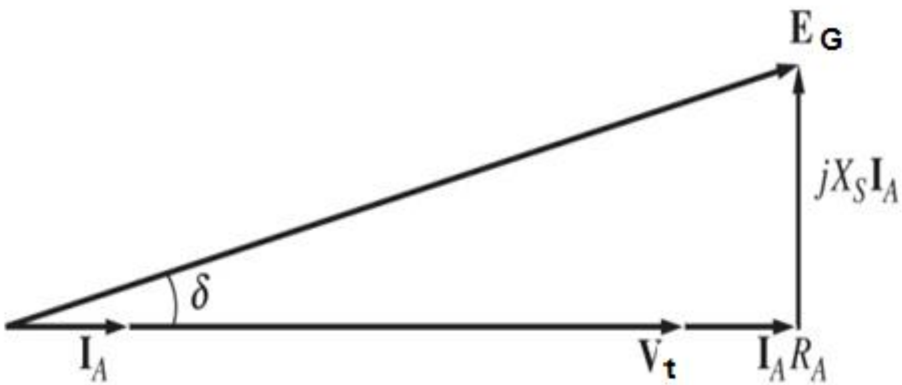
The Phasor Diagram of a Synchronous Generator

The Kirchhoff's voltage law equation for the armature circuit is;

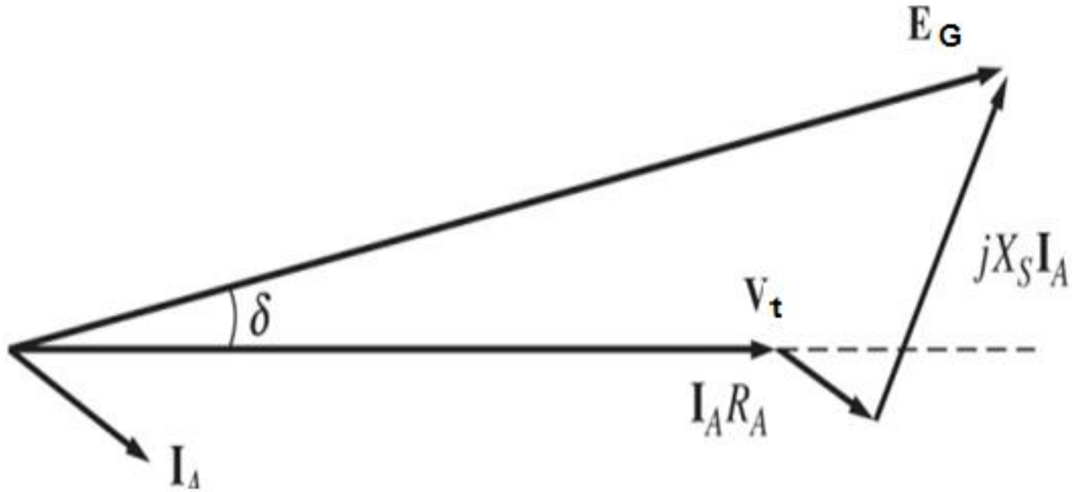
$$E_G = V_t + I_A(R_A + jX_S)$$

Where; $X_S = X_A + X_{AR}$

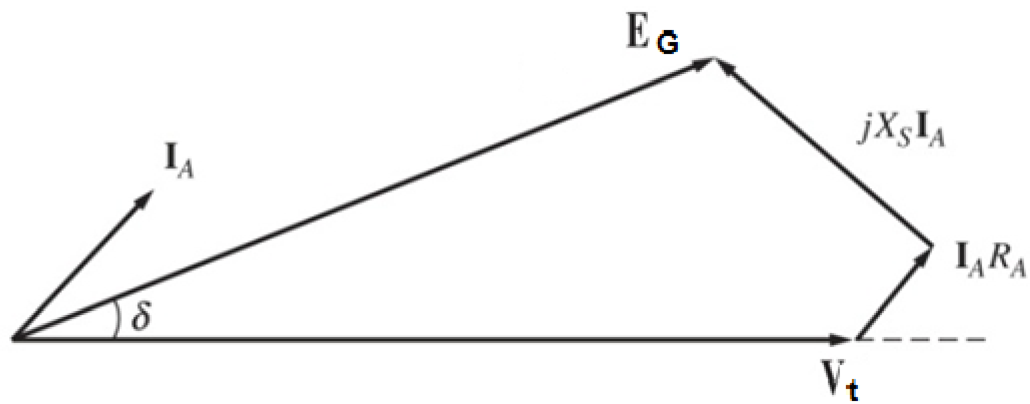
The phasor diagrams for unity, lagging, and leading power factors load are shown here:



(a) PF=1



(b) PF= Lagging



(c) PF= Leading

Figure 8:

- For unity power factor (Fig.8(a)), E_G voltage is bigger than V_t. For lagging power factor (Fig.8(b)), E_G is much bigger than V_t comparing to the unity power factor. However, for leading power factor (Fig.8(c)), V_t is bigger than E_G. That is; if the power factor is leading and the machine operates at full-load, the output voltage V_t is bigger than the voltage at no-load, E_G.
- $I_A.X_S$ voltage drop is known as synchronous reactance voltage and here, X_S is called as “synchronous reactance”. In Fig.8, the angle, δ between E_G and V_t is called as “power angle” or “torque angle”. This angle depends on the load and it is a measure of the airgap power.
- In the phasor diagrams drawn for pure inductive or capacitive loads, the angle δ is zero since there is no active power dissipated.

The Equivalent Circuit of a Synchronous Generator

- When generator is not loaded, the internal generated voltage E_A is the same as the voltage appearing at the terminals of the generator, V_t.

- When generator is loaded, a balanced 3-phase current will flow which results in the stator rotating magnetic field B_S. The net air gap flux density is the sum of the rotor and stator magnetic fields:

$$\boldsymbol{B}_{net} = \boldsymbol{B}_R + \boldsymbol{B}_S$$

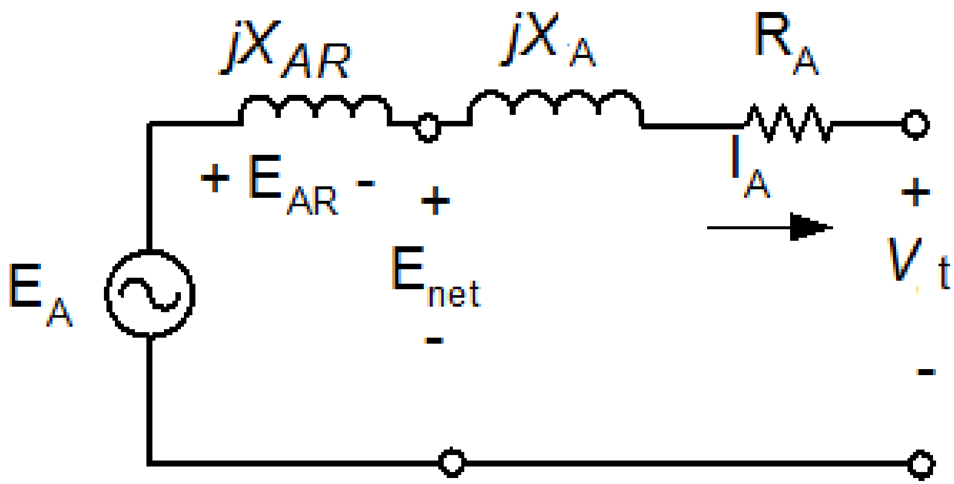
- The voltage induced in the armature would be the sum of the voltages induced by rotor field (E_A) and the voltage induced by the stator field (E_{AR}, or armature-reaction voltage).

$$\boldsymbol{E}_{net} = \boldsymbol{E}_A + \boldsymbol{E}_{AR}$$

Two other voltage drops must be considered:

- ○ Self (or leakage) inductance of the armature coils.
- ○ Resistance of the armature coils

- The armature-reaction voltage may be represented by an inductive voltage drop across an armature–reaction reactance X_{AR}, as shown here.



The two reactances may be combined into a single reactance called the synchronous reactance of the machine:

$$X_S = X_A + X_{AR}$$

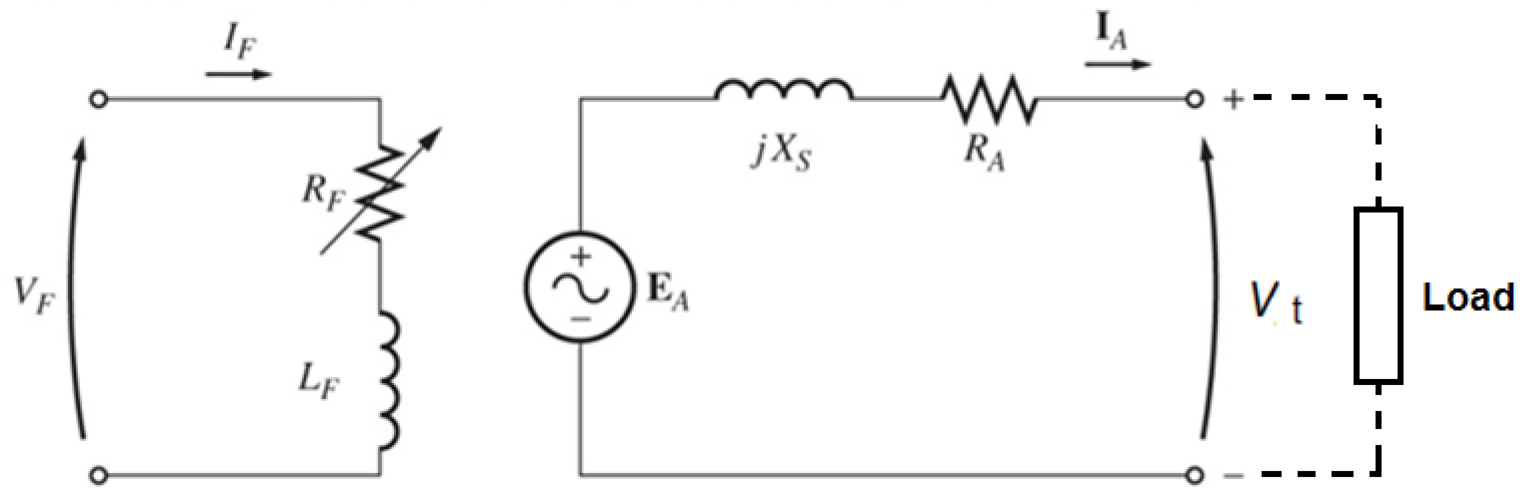


Figure 9:

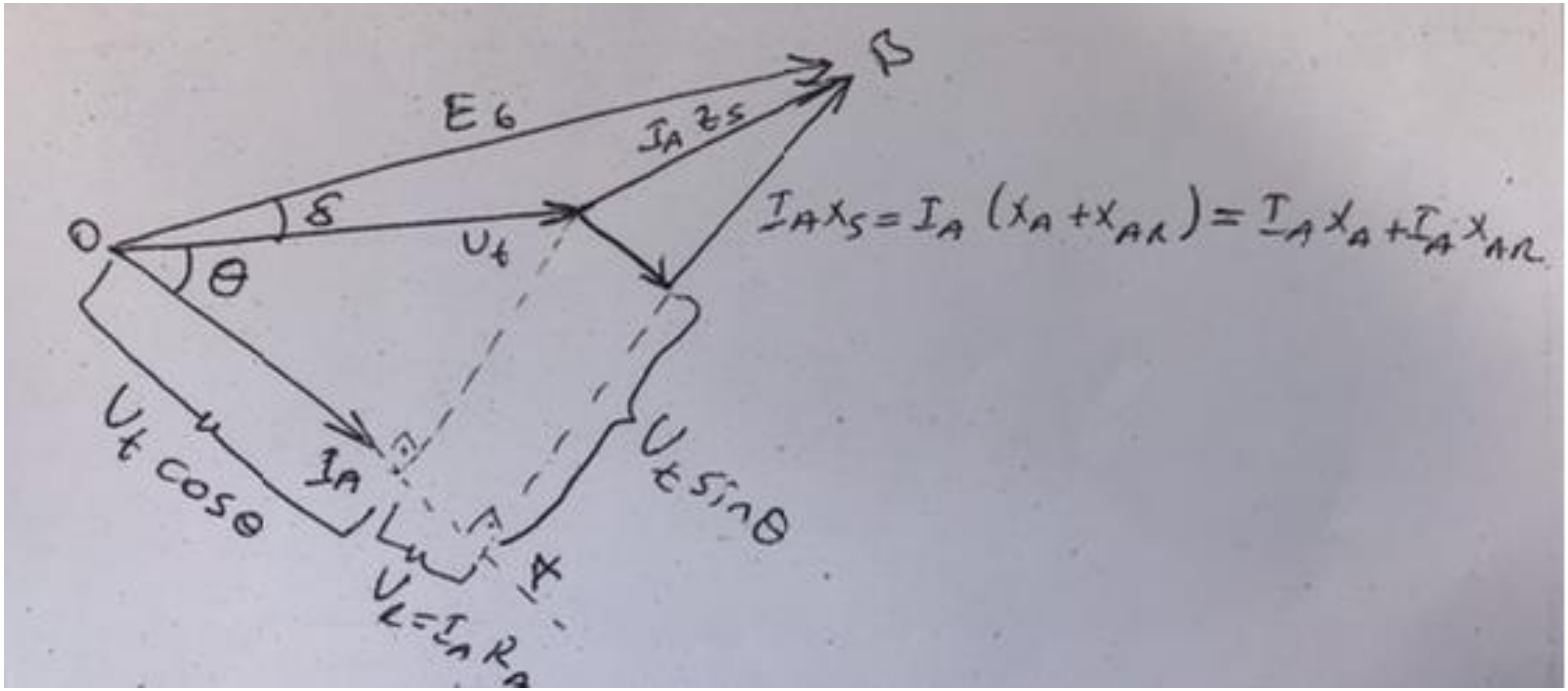
The per phase equivalent circuit of a synchronous generator.

$$\text{If} \quad X_S = X_A + X_{AR}$$

Then;

$$I_A.X_A + I_A.X_{AR} = I_A.X_S$$

Therefore , if V_t is taken as reference phasor, then the phasor diagram can be drawn as;



$$\bar{E}_G = \bar{I}_A \bar{Z}_S + \bar{V}_t$$

- Where Z_S is the armature impedance per phase.

$$Z_S = R_A + jX_S \quad \rightarrow \quad Z_S = \sqrt{R_A^2 + X_S^2}$$

- As can be seen from Fig.9, a synchronous generator can be modelled by an R-L circuit. In this circuit, R_A represents the armature resistance and X_S represents the synchronous reactance. The power factor angle, θ is determined by the load. The power dissipated on the load;
- $P_L = V_t.I_A.\cos\theta$ (Watt/Phase)
- Since the machine is a three-phase machine;
- $P_L = 3.V_t.I_A.\cos\theta$

- The power is usually represented by line current and line voltage. In this case, winding connection type must be known. If the armature windings are connected in star;

$$I_A = I_L \ \ and \ V_t = \frac{V_L}{\sqrt{3}}$$

$$P_L = 3\frac{V_L}{\sqrt{3}} I_L cos\theta = \sqrt{3} V_L I_L cos\theta$$

- This is a general expression of three-phase power and it is independent of armature or load connection type.

$$\bar{I}_A = I_A(cos\theta - jsin\theta)$$

$$\bar{Z}_S = R_A + jX_S$$

- For inductive load characteristic;

$$E_G = V_t + I_A(cos\theta - jsin\theta).(R_A + jX_S)$$

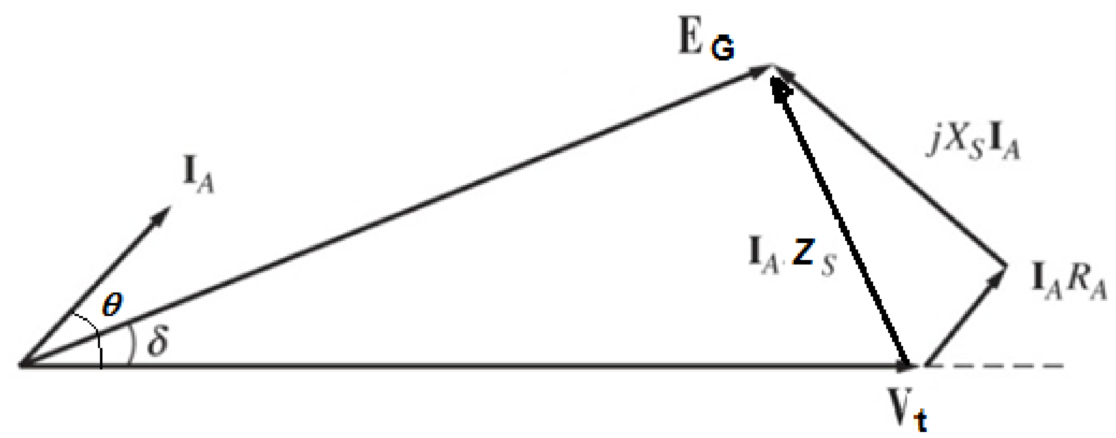
If $V_t = V_t$. 0 is taken as reference phasor and consider the phasor diagram;

OA = $V_t.cos\theta + V_R$ and AB = $V_t.sin\theta + V_S$

Since E_G = OB then;

$$E_G = [(V_t cos\theta + V_R)^2 + (V_t sin\theta + V_S)^2]^{1/2}$$

If the load is capacitive, the phasor diagram will be as;



- By the help of the phasor diagram it can be obtain that;

$$E_G = [(V_t cos\theta + V_R)^2 + (V_t sin\theta - V_S)^2]^{1/2}$$

- If the load is pure resistive load, then PF=cosθ=1 and sinθ=0. Then;

$$E_G = [(V_t + V_R)^2 + (V_S)^2]^{1/2}$$

- R_A is usually much smaller than X_S (specially at high rated machines). Therefore, V_R voltage can be neglected comparing to V_S.

- **Example:**
- Figure given below shows the equivalent circuit and phasor diagram of a 250 kVA, 660 V, 60 Hz, a three-phase and star connected synchronous generator. Armature resistance and synchronous reactance of the generator is 0.1 Ω/Phase and 1.4 Ω/Phase, respectively. A load with power factor of 0.866 (lagging) is connected to the output of the generator. Calculate the voltage regulation.
- **Solution:**

$$I_A = \frac{250000}{\sqrt{3}.\,660} = 219\,A$$

$$V_t = \frac{V_L}{\sqrt{3}} = \frac{660}{\sqrt{3}} = 381\,V$$

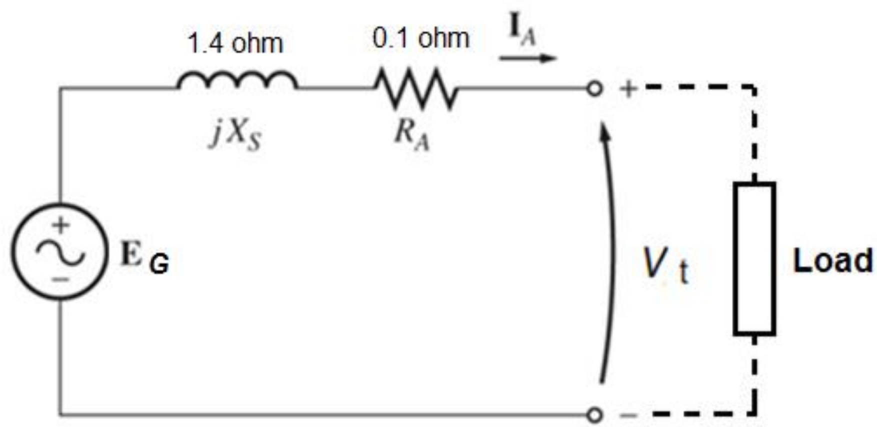
$$I_A R_A = 219 * 0.1 = 21.9\,V$$

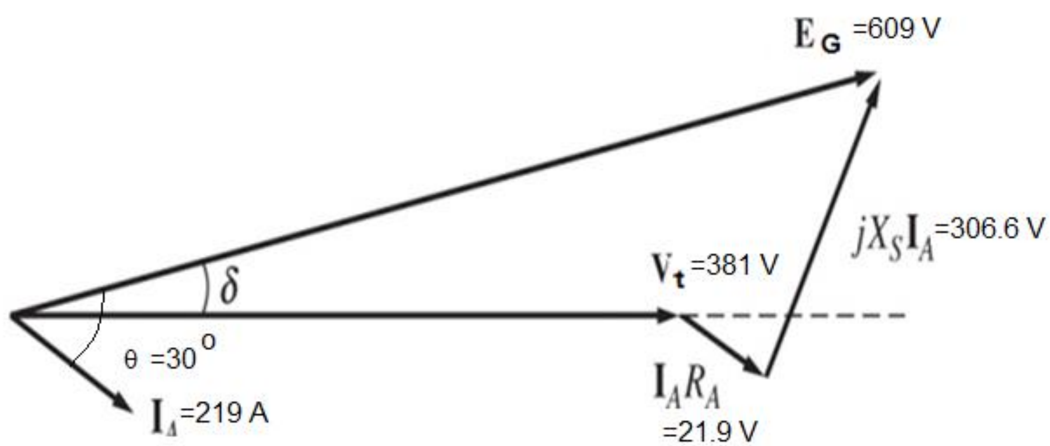
$$I_A X_S = 219 * 1.4 = 306.6\,V$$

$$cos\theta = 0.866 \;\; and \;\; sin\theta = 0.5\;(lagging)$$

$$E_G = [(381 * 0.866 + 21.9)^2 + (381 * 0.5 + 306.6)^2]^{\frac{1}{2}} = 609\,V$$

$$Voltage\,Regulation = \frac{609 - 381}{381} * 100 = 59.8\%$$


1.4 ohm
0.1 ohm
I_A
jX_S
R_A
+
–
E_G
V_t
Load


E_G =609 V
$jX_S I_A$=306.6 V
V_t =381 V
δ
θ =30 o
I_A=219 A
$I_A R_A$
=21.9 V