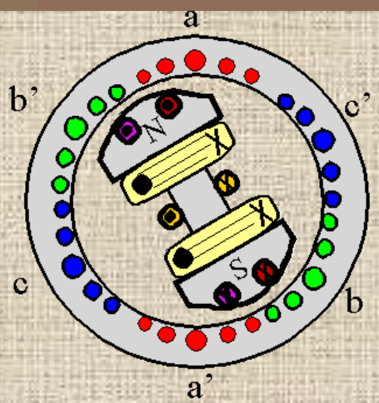
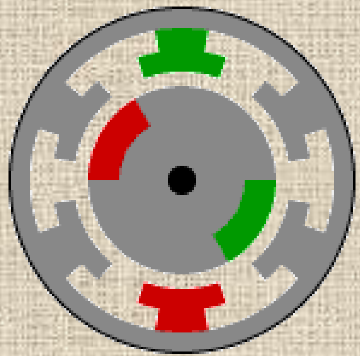
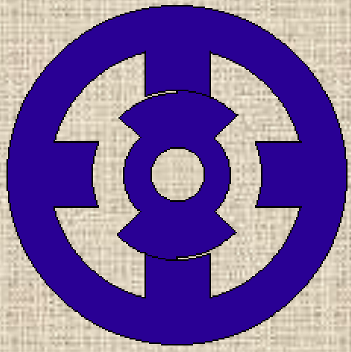
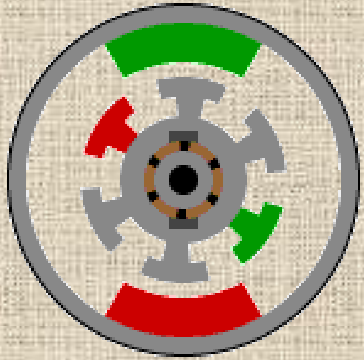
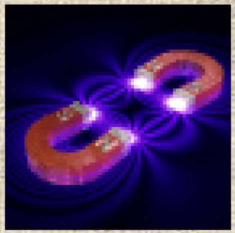


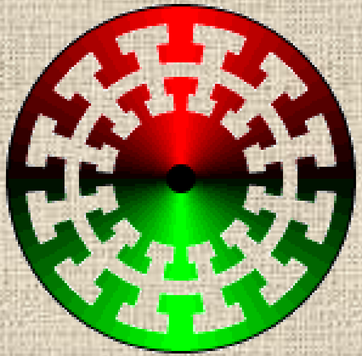




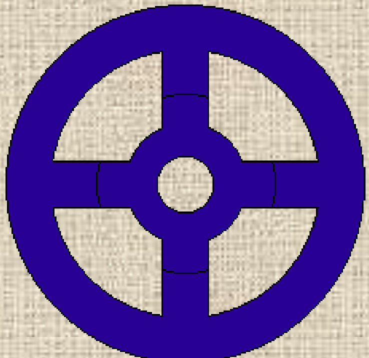


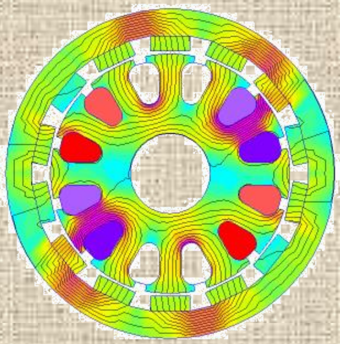


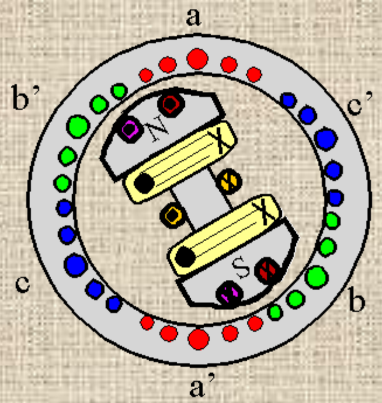
EE552 ELECTRICAL MACHINES III



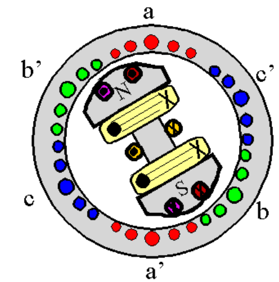
LECTURE 12







LECTURE NOTES

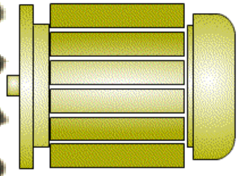


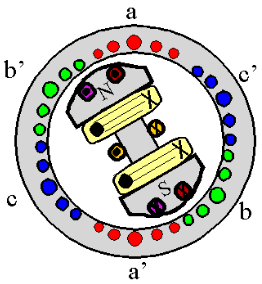
ELECTRICAL MACHINES III

EE552

SPRING 2018

Dr : MUSTAFA AL-REFAI

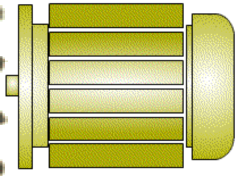


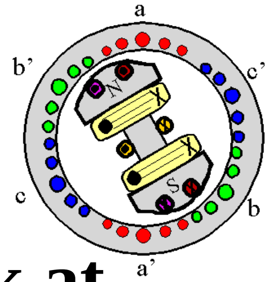


LECTURE 12

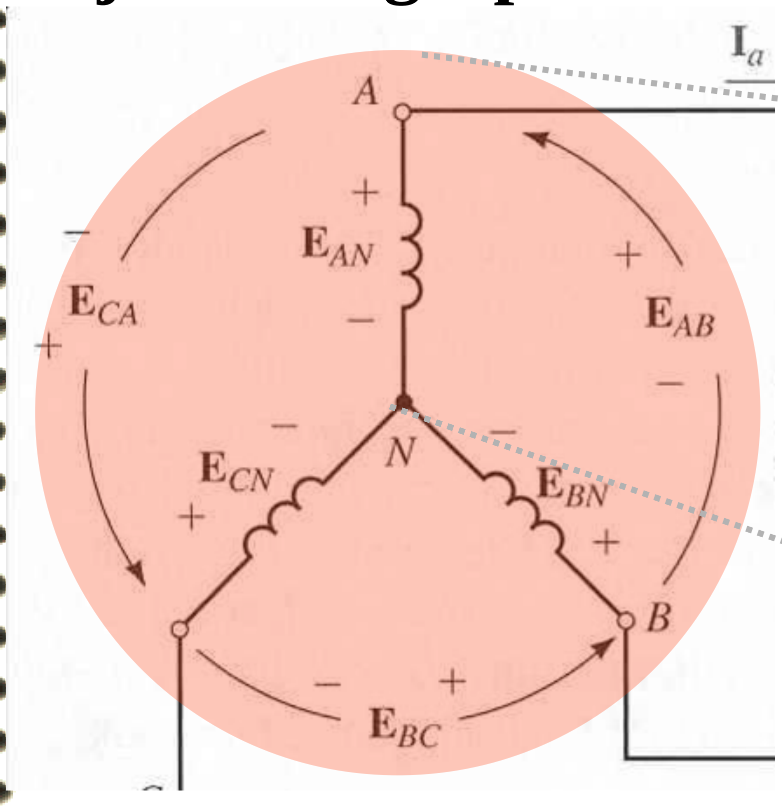
SYNCHRONOUS GENERATOR

Equivalent circuit of a synchronous generator

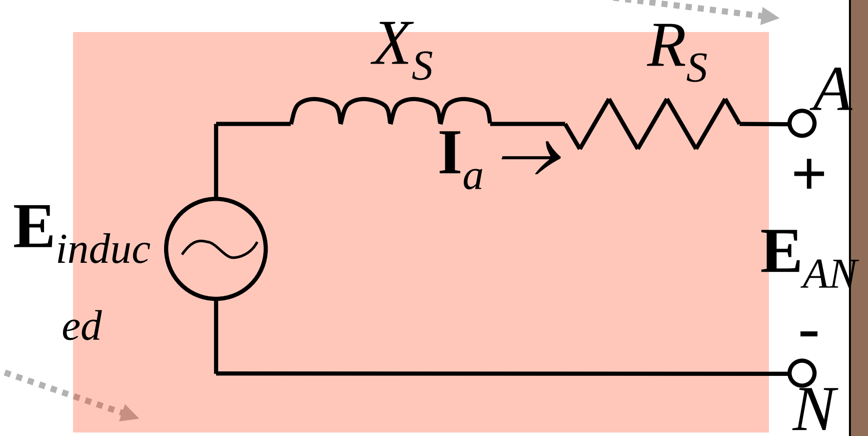




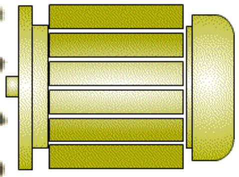
- Just like 3-phase loads, it is useful to look at just a single phase of the generator.



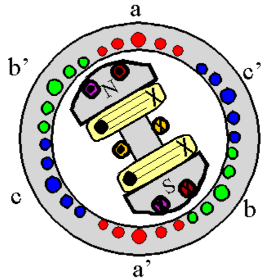
3-Phase Generator



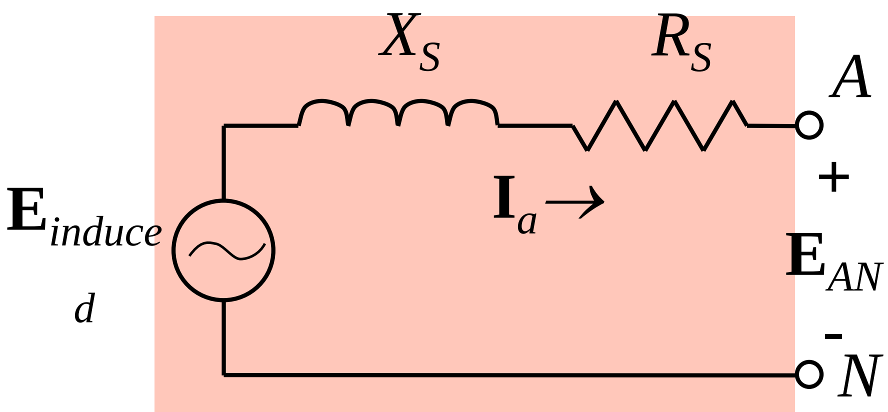
Single-phase equivalent

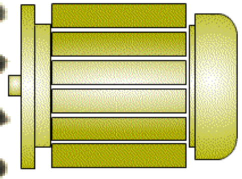


Equivalent circuit of a synchronous generator

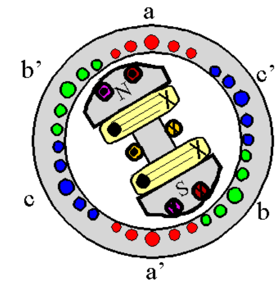


- $\mathbf{E}_{AN}$ is the phase voltage of the a-phase $\mathbf{I}_a$ is the line current
- $\mathbf{E}_{induced}$ is the induced armature voltage.
- R_S is the resistance of the generator's stator coil.
- X_S is the ***synchronous reactance*** of the stator coil.





Equivalent circuit of a synchronous generator



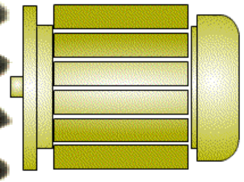
Assuming that the generator is connected to a lagging load, the load current I_A will create a stator magnetic field B_S, which will produce the armature reaction voltage E_{stat}. Therefore, the phase voltage will be

$$V_\phi = E_A + E_{stat}$$

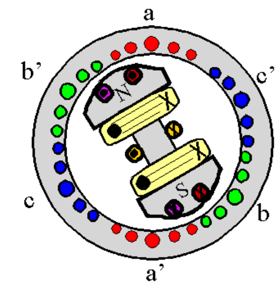
The net magnetic flux will be

$$B_{net} = \underbrace{B_R}_{\text{Rotor field}} + \underbrace{B_S}_{\text{Stator field}}$$

Note that the directions of the net magnetic flux and the phase voltage are the same.



Equivalent circuit of a synchronous generator



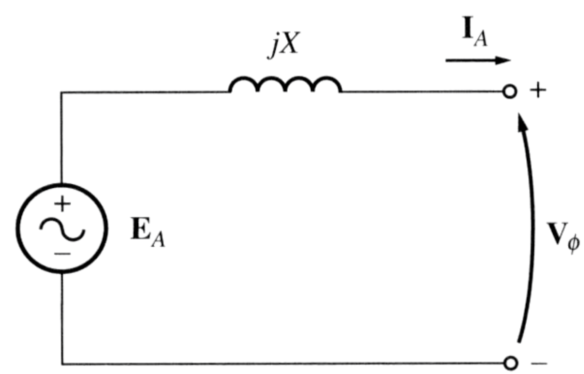
Assuming that the load reactance is X, the armature reaction voltage is

$$E_{stat} = -jXI_A$$

The phase voltage is then

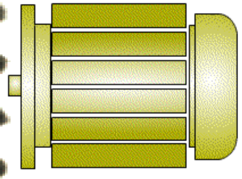
$$V_\phi = E_A - jXI_A$$

Armature reactance can be modeled by the following circuit…

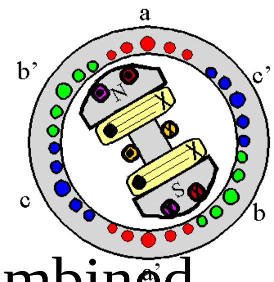


However, in addition to armature reactance effect, the stator coil has a self-inductance L_A (X_A is the corresponding reactance) and the stator has resistance R_A. The phase voltage is thus

$$V_\phi = E_A - jXI_A - jX_AI_A - RI_A$$



Equivalent circuit of a synchronous generator

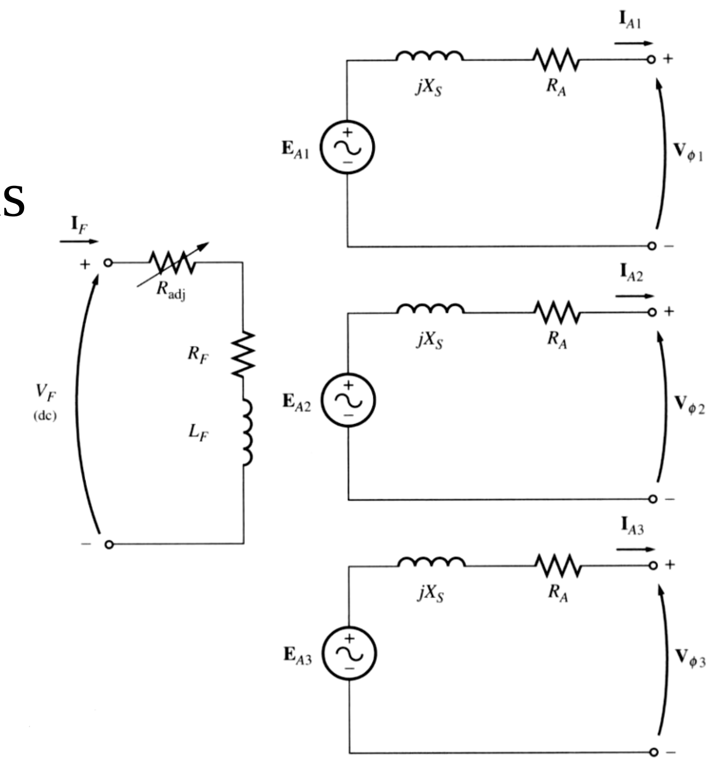


Often, armature reactance and self-inductance are combined into the synchronous reactance of the machine:

$$X_S = X + X_A$$

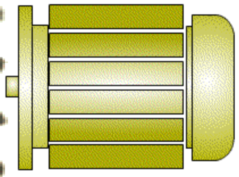
Therefore, the phase voltage is

$$V_\phi = E_A - jX_S I_A - R I_A$$

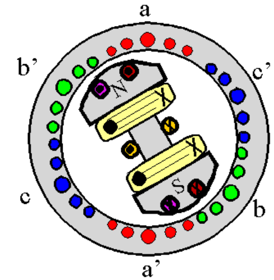


The equivalent circuit of a 3-phase synchronous generator is shown.

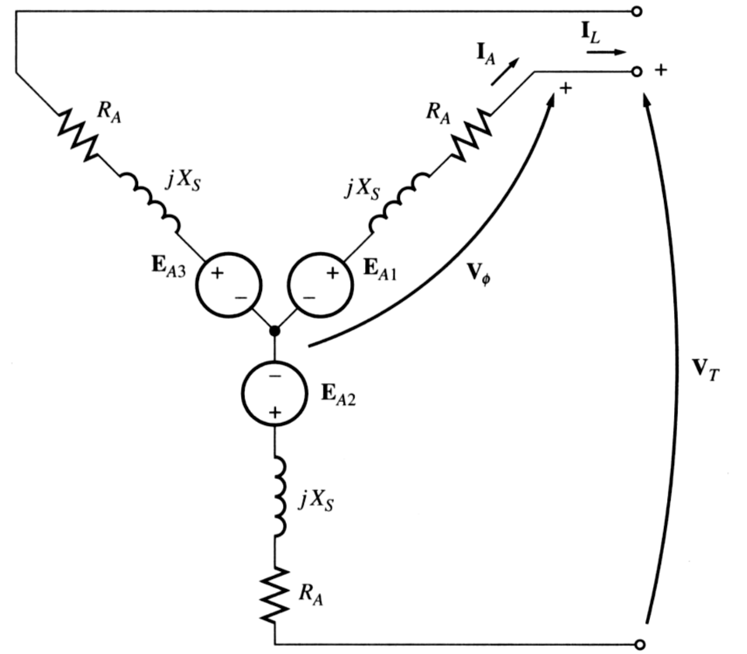
The adjustable resistor R_{adj} controls the field current and, therefore, the rotor magnetic field.

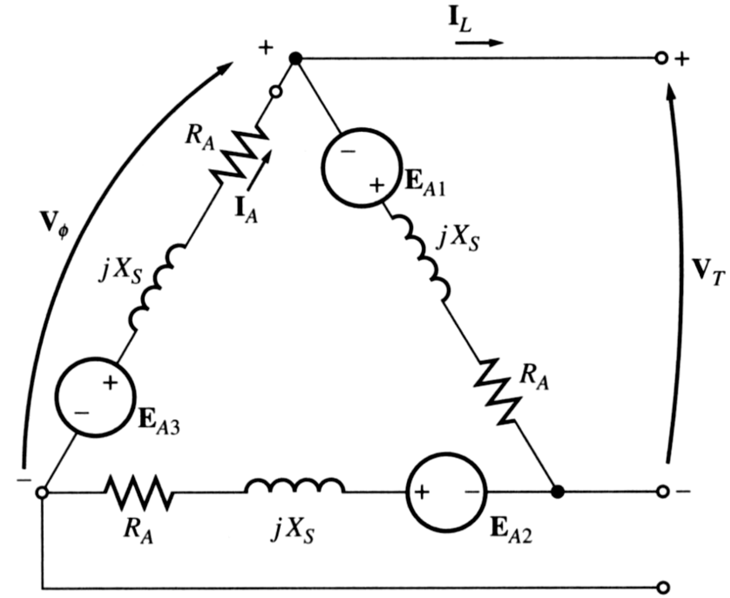


Equivalent circuit of a synchronous generator



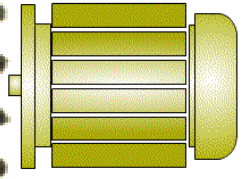
A synchronous generator can be Y- or Δ-connected:



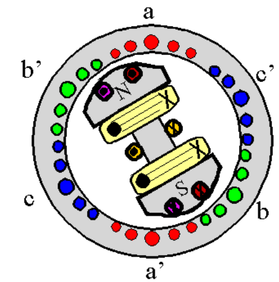


The terminal voltage will be

$$V_T = \sqrt{3}V_\phi \quad - \text{for } Y \qquad\qquad V_T = V_\phi \quad - \text{for } \Delta$$

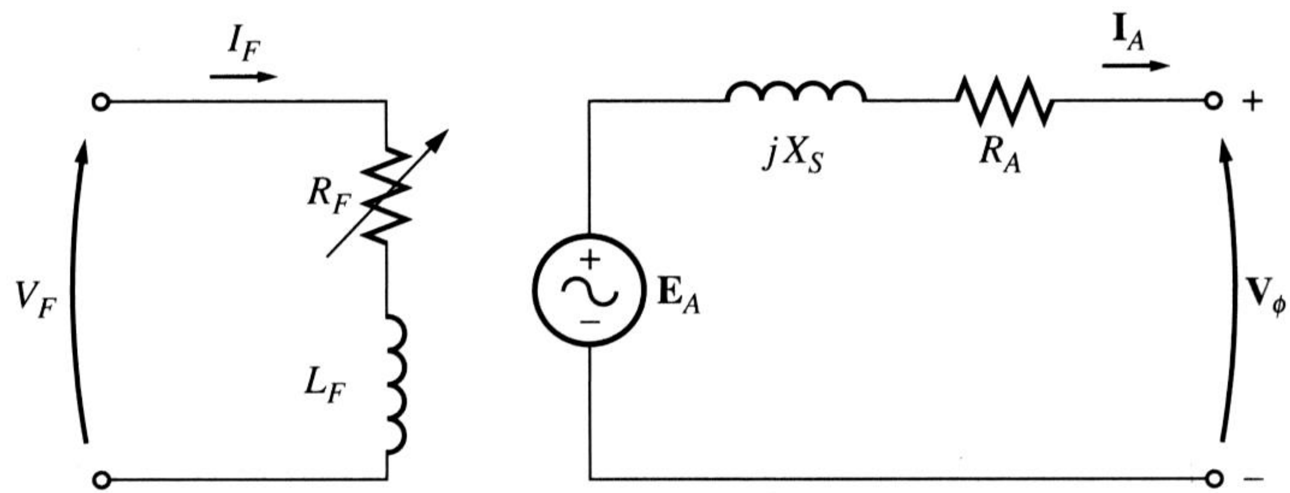


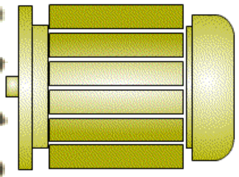
Equivalent circuit of a synchronous generator



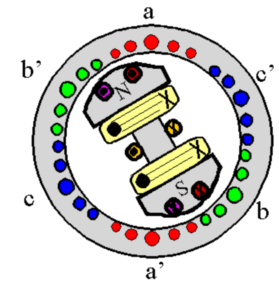
Note: the discussion above assumed a balanced load on the generator!

Since – for balanced loads – the three phases of a synchronous generator are identical except for phase angles, per-phase equivalent circuits are often used.



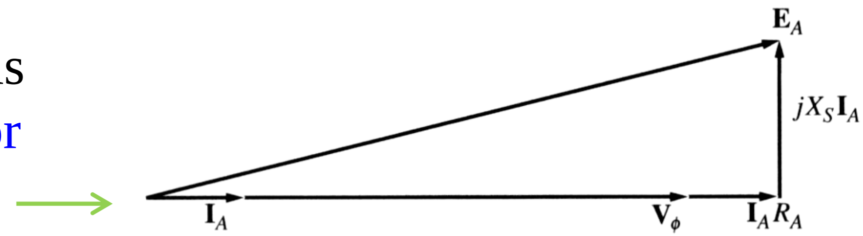


Phasor diagram of a synchronous generator

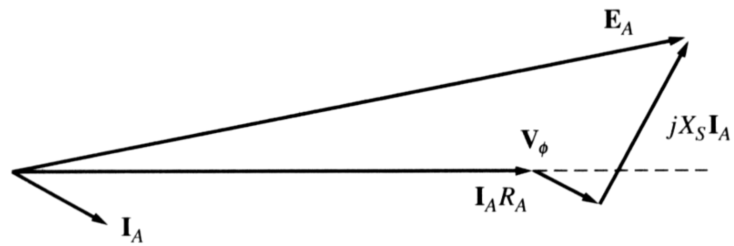


Since the voltages in a synchronous generator are AC voltages, they are usually expressed as phasors. A vector plot of voltages and currents within one phase is called a phasor diagram.

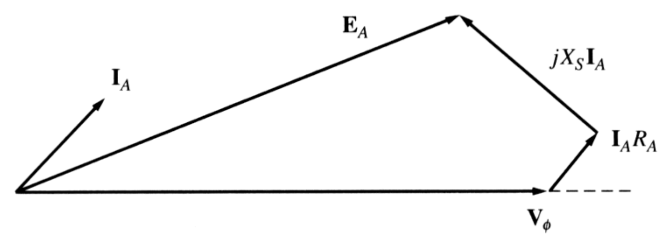
A phasor diagram of a synchronous generator with a unity power factor (resistive load)



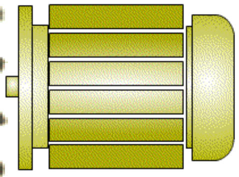
Lagging power factor (inductive load): a larger than for leading PF internal generated voltage E_A is needed to form the same phase voltage.



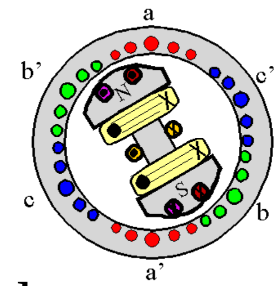
Leading power factor (capacitive load).



For a given field current and magnitude of load current, the terminal voltage is lower for lagging loads and higher for leading loads.



Phasor Diagram of Unsaturated Cylindrical Alternators

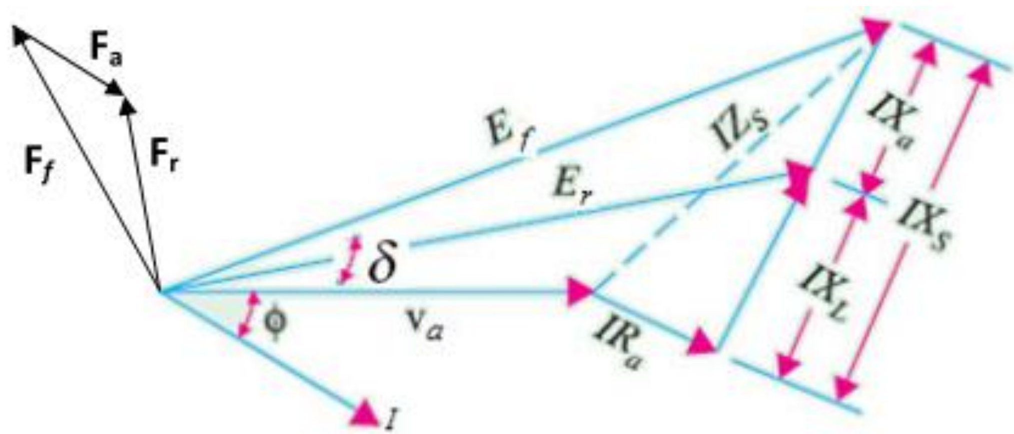


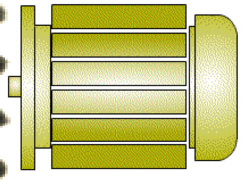
❑ Lagging power factor

Assume that the synchronous generator is loaded with a lagging power factor load.

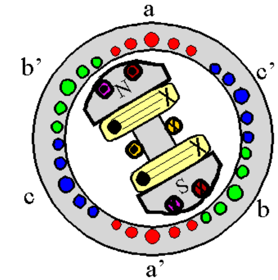
From the phasor diagram shown in next Fig, it is clear that the terminal voltage is decreased from its no-load value E_f to its loaded value V_a (for a lagging power factor). This is because of: Drop due to armature resistance, IR_a & drop due to leakage reactance, IX_L and drop due to armature reaction IX_a .

Phasor diagram for synchronous generator (p.f. Lag)





Phasor Diagram of Unsaturated Cylindrical Alternators cont…



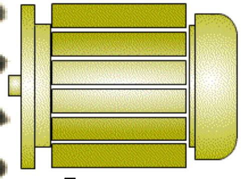
- **Lagging power factor**

The angle (δ) between the no-load voltage (E_f) and the terminal voltage (V_a) is called the load angle or (power angle) and it is positive value in case of alternators.

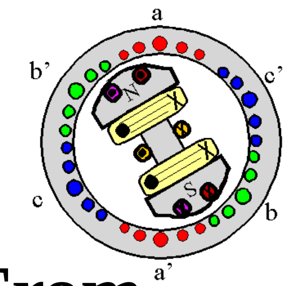
The DC voltage (Excitation voltage) produces a flux (Φ_f) or (field mmf F_f).

If the armature circuit is closed by an electric load, the armature reaction (Φ_a) or (armature mmf F_a) is produced. These two fluxes may support each other or oppose each other depend on the load power factor to produce the air-gap or resultant flux (Φ_r) or (resultant mmf F_r).

- From the phasor diagram shown in last Fig.
- Since $F_r < F_f$ this means that F_a oppose F_f
- Since $V_a < E_f$ this is called over-excited alternator



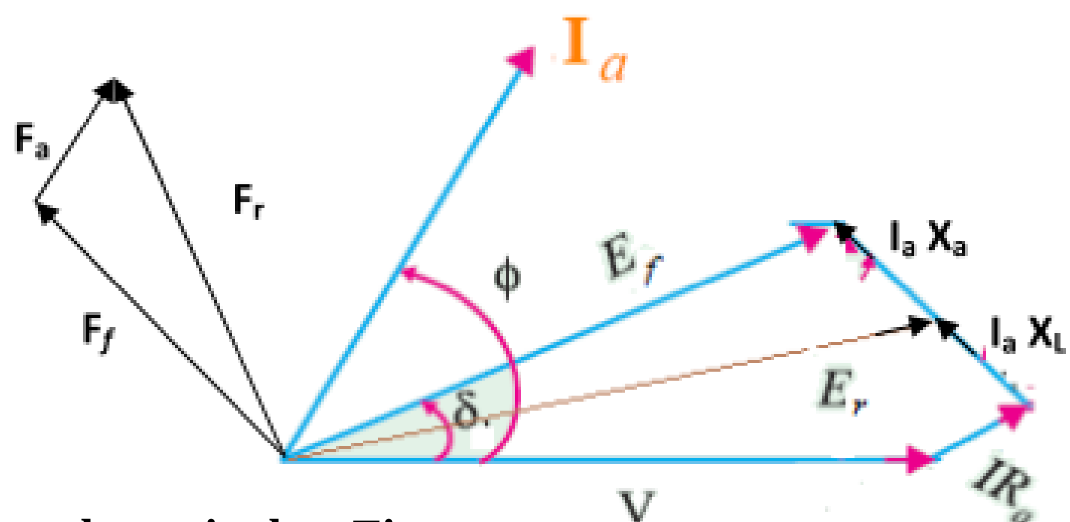
❑ Leading power factor



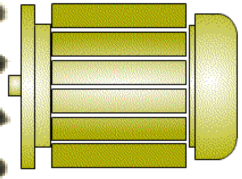
Assume that the synchronous generator is loaded with a leading power factor load. From the phasor diagram shown in next Fig. it is clear that the terminal voltage is increased from its no-load value **Ef**

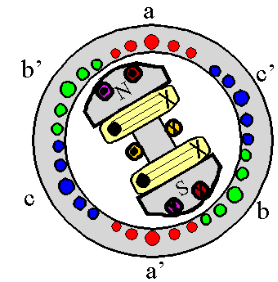
$$E_f = V + I_a(R_a + JX_s)$$

Phasor diagram for synchronous generator (p.f. Lead)



From the phasor diagram shown in last Fig.
Since Fr > Ff this means that Fa support Ff
Since Va > Ef this is called under-excited alternator

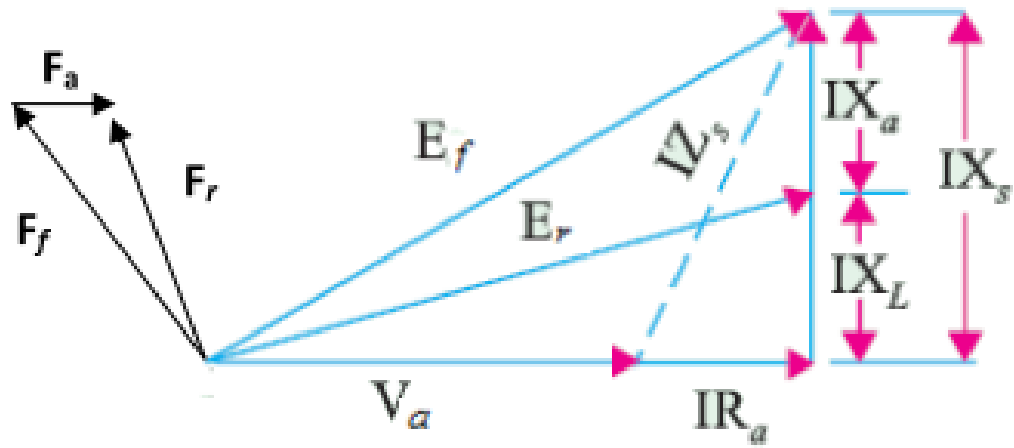




❑ Unity power factor

Assume that the synchronous generator is loaded with a unity power factor load. From the phasor diagram shown in next Fig. it is clear that the terminal voltage is decreased from its no-load value E_f (similar to lagging power factor)

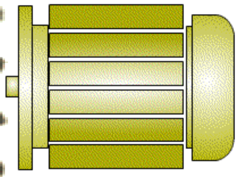
Phasor diagram for synchronous generator (p.f. unity)



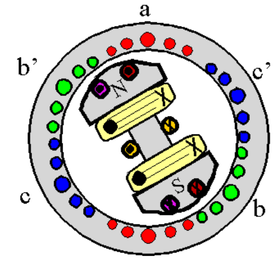
From the phasor diagram shown .

Since F_r < F_f this means that F_a oppose F_f

Since V_a < E_f this is called over-excited alternator

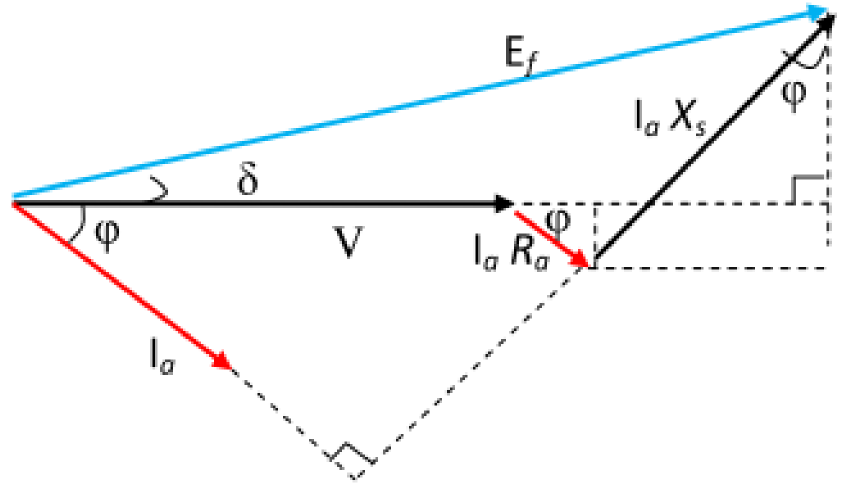


Analytical Representation of Phasor Diagram



Consider the phasor diagram of 3-phase alternator at lagging p.f. as shown.

We can describe this phasor diagram by two equations:



Alternator phasor diagram at lagging p.f

Horizontal Analysis:

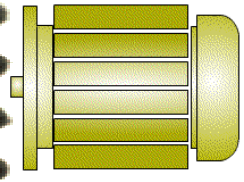
$$E_f \cos(\delta) = V + I_a R_a \cos(\varphi) + \ I_a X_s \sin(\varphi) \ldots (1)$$

Vertical Analysis:

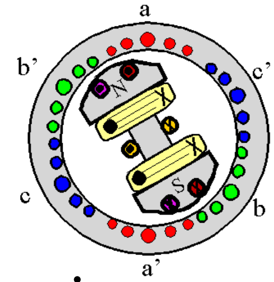
$$E_f \sin(\delta) = I_a X_s \cos(\varphi) - I_a R_a \sin(\varphi) \ldots (2)$$

By dividing (2) by (1), we obtain:

$$\tan(\delta) = \frac{I_a X_s \cos(\varphi) - I_a R_a \sin(\varphi)}{V + I_a R_a \cos(\varphi) + \ I_a X_s \sin(\varphi)}$$



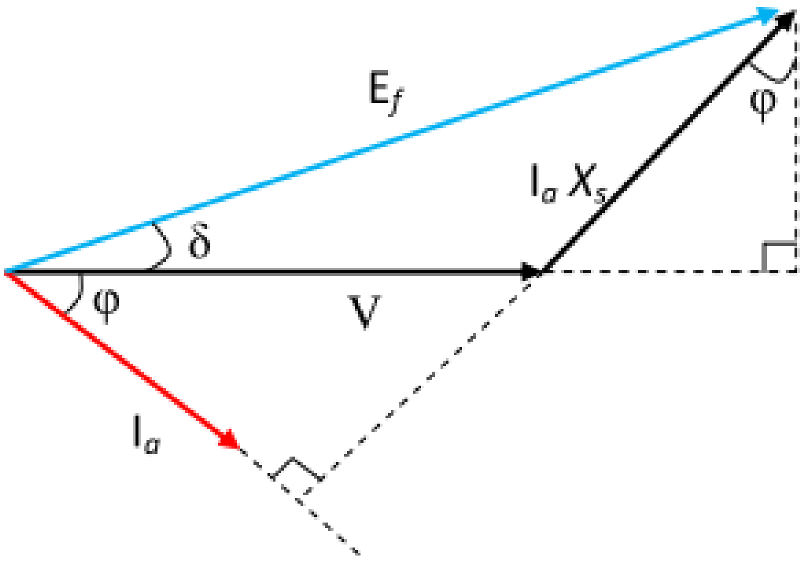
Analytical Representation of Phasor Diagram cont…



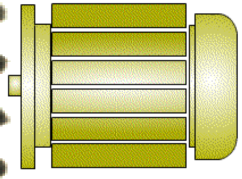
Once the angle (δ) is known, we can obtain the excitation voltage E_f .

Now, if R_a is neglected, the phasor diagram is shown in next fig

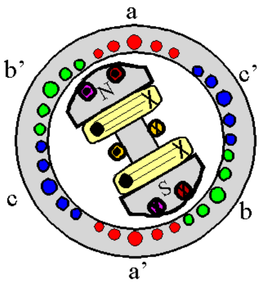
Equations (1) and (2) can be rewritten by replacing R_a =0 as:



Approximate phasor at lag p.f



Analytical Representation of Phasor Diagram cont…



Horizontal Analysis:

$$E_f \cos(\delta) = V + \; I_a X_s \sin(\varphi) \; \dots (3)$$

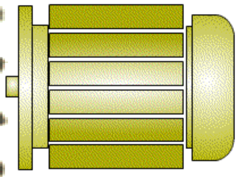
Vertical Analysis:

$$E_f \sin(\delta) = I_a X_s \cos(\varphi) \; \dots (4)$$

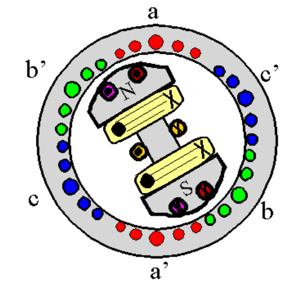
By dividing (4) over (3), we obtain:

$$\tan(\delta) = \frac{I_a X_s \cos(\varphi)}{V + \; I_a X_s \sin(\varphi)} \; \dots (5)$$

Once the angle (δ) is known, we can obtain the excitation voltage E_f .

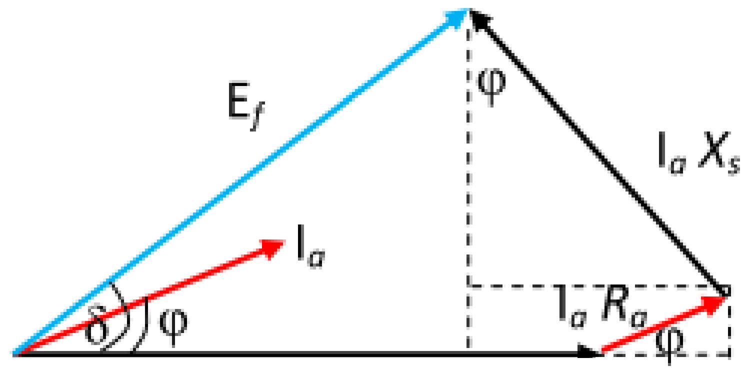


Analytical Representation of Phasor Diagram cont…



By the same way, we can describe the phasor diagram in case of leading power factor by two equations:

Alternator phasor diagram at leading p.f



Horizontal Analysis:

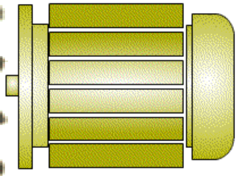
$$E_f\cos(\delta) = V + I_aR_a\cos(\varphi) - I_aX_s\sin(\varphi)\ \ldots(6)$$

Vertical Analysis:

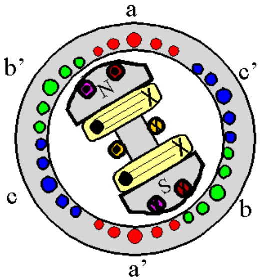
$$E_f\sin(\delta) = I_aX_s\cos(\varphi) + I_aR_a\sin(\varphi)\ \ldots(7)$$

By dividing (7) over (6), we obtain:

$$\tan(\delta) = \frac{I_aX_s\cos(\varphi) + I_aR_a\sin(\varphi)}{V + I_aR_a\cos(\varphi) - I_aX_s\sin(\varphi)}$$



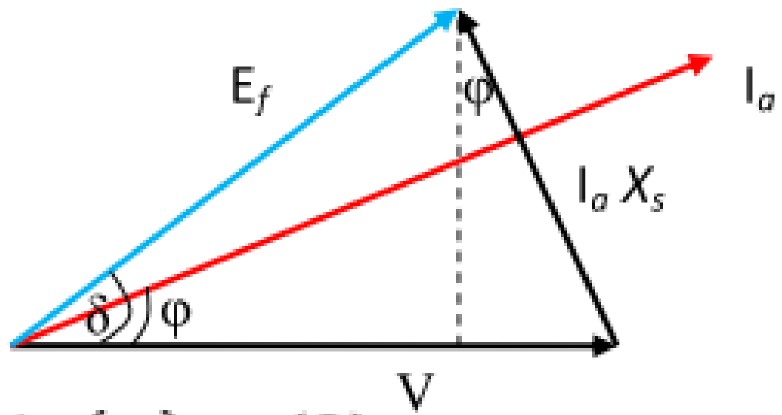
Analytical Representation of Phasor Diagram cont…



Once the angle (δ) is known, we can obtain the excitation voltage Ef .

Now, if R a is neglected, the phasor diagram is shown in next Fig. .

Approximate phasor at leading p.f



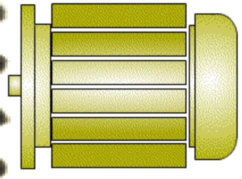
Horizontal Analysis:

$$E_f \cos(\delta) = V - I_a X_s \sin(\varphi) \ldots (8)$$

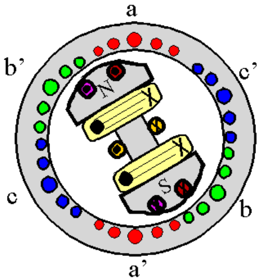
Vertical Analysis: $E_f \sin(\delta) = I_a X_s \cos(\varphi) \ldots (9)$

By dividing (9) by (8), we obtain: $\tan(\delta) = \dfrac{I_a X_s \cos(\varphi)}{V - I_a X_s \sin(\varphi)}$

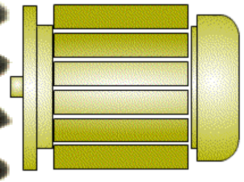
Once the angle (δ) is known, we can obtain the excitation voltage Ef .



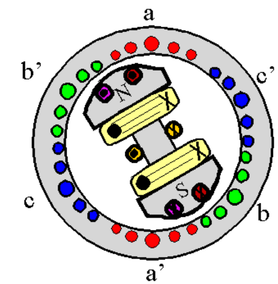
Analytical Representation of Phasor Diagram cont…



From the explained phasor diagrams given in above , we notice that V is always behind E_f , this means the power angle (δ) is always positive, and this is the remarkable notice on the phasor diagram of synchronous generators.



Power and torque in synchronous generators



A synchronous generator needs to be connected to a prime mover whose speed is reasonably constant (to ensure constant frequency of the generated voltage) for various loads.

The applied mechanical power

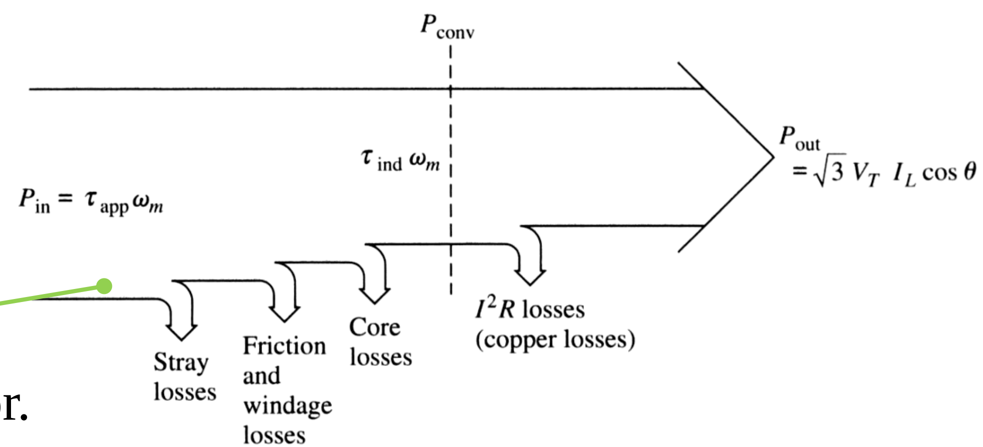
$$P_{in} = \tau_{app}\omega_m$$

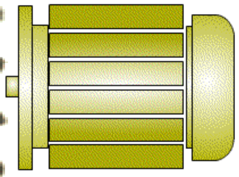
is partially converted to electricity

$$P_{conv} = \tau_{ind}\omega_m = 3E_A I_A \cos\gamma$$

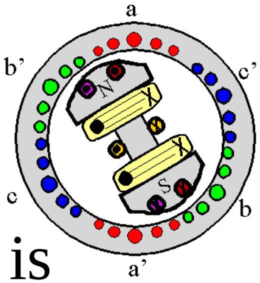
Where γ is the angle between E_A and I_A.

The power-flow diagram of a synchronous generator.





Power and torque in synchronous generators



The real output power of the synchronous generator is

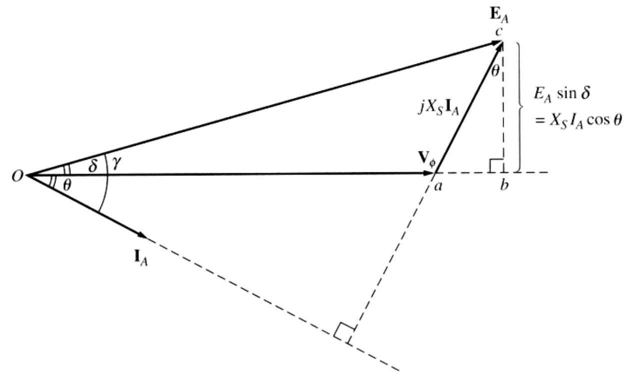
$$P_{out} = \sqrt{3} V_T I_L \cos\theta = 3 V_\phi I_A \cos\theta$$

The reactive output power of the synchronous generator is

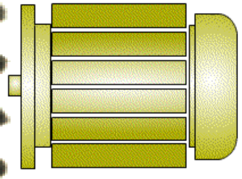
$$Q_{out} = \sqrt{3} V_T I_L \sin\theta = 3 V_\phi I_A \sin\theta$$

Recall that the power factor angle θ is the angle between V_ϕ and I_A and **not** the angle between V_T and I_L.

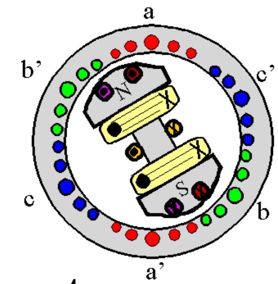
In real synchronous machines of any size, the armature resistance $R_A << X_S$ and, therefore, the armature resistance can be ignored. Thus, a simplified phasor diagram indicates that



$$I_A \cos\theta = \frac{E_A \sin\delta}{X_S}$$



Power and torque in synchronous generators



Then the real output power of the synchronous generator can be approximated as

$$\boxed{P_{out} \approx \frac{3V_\phi E_A \sin\delta}{X_S}}$$

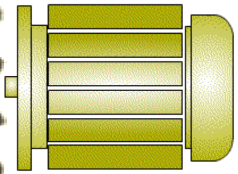
We observe that electrical losses are assumed to be zero since the resistance is neglected. Therefore:

$$\boxed{P_{conv} \approx P_{out}}$$

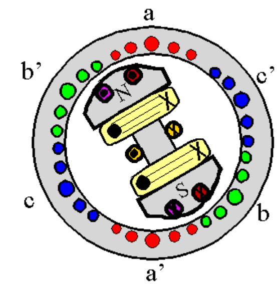
Here δ is the torque angle of the machine – the angle between V_ϕ and E_A.

The maximum power can be supplied by the generator when $\delta = 90^0$:

$$\boxed{P_{max} = \frac{3V_\phi E_A}{X_S}}$$



Power and torque in synchronous generators



The maximum power specified by last equation is called the static stability limit of the generator. Normally, real generators do not approach this limit: full-load torque angles are usually between 15^0 and 20^0.

The induced torque is

$$\tau_{ind} = kB_R \times B_S = kB_R \times B_{net} = kB_R B_{net} \sin\delta$$

Notice that the torque angle δ is also the angle between the rotor magnetic field B_R and the net magnetic field B_{net}.

Alternatively, the induced torque is

$$\tau_{ind} = \frac{3V_\phi E_A \sin\delta}{\omega_m X_S}$$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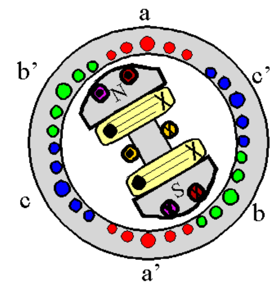
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END OF LECTURE 12