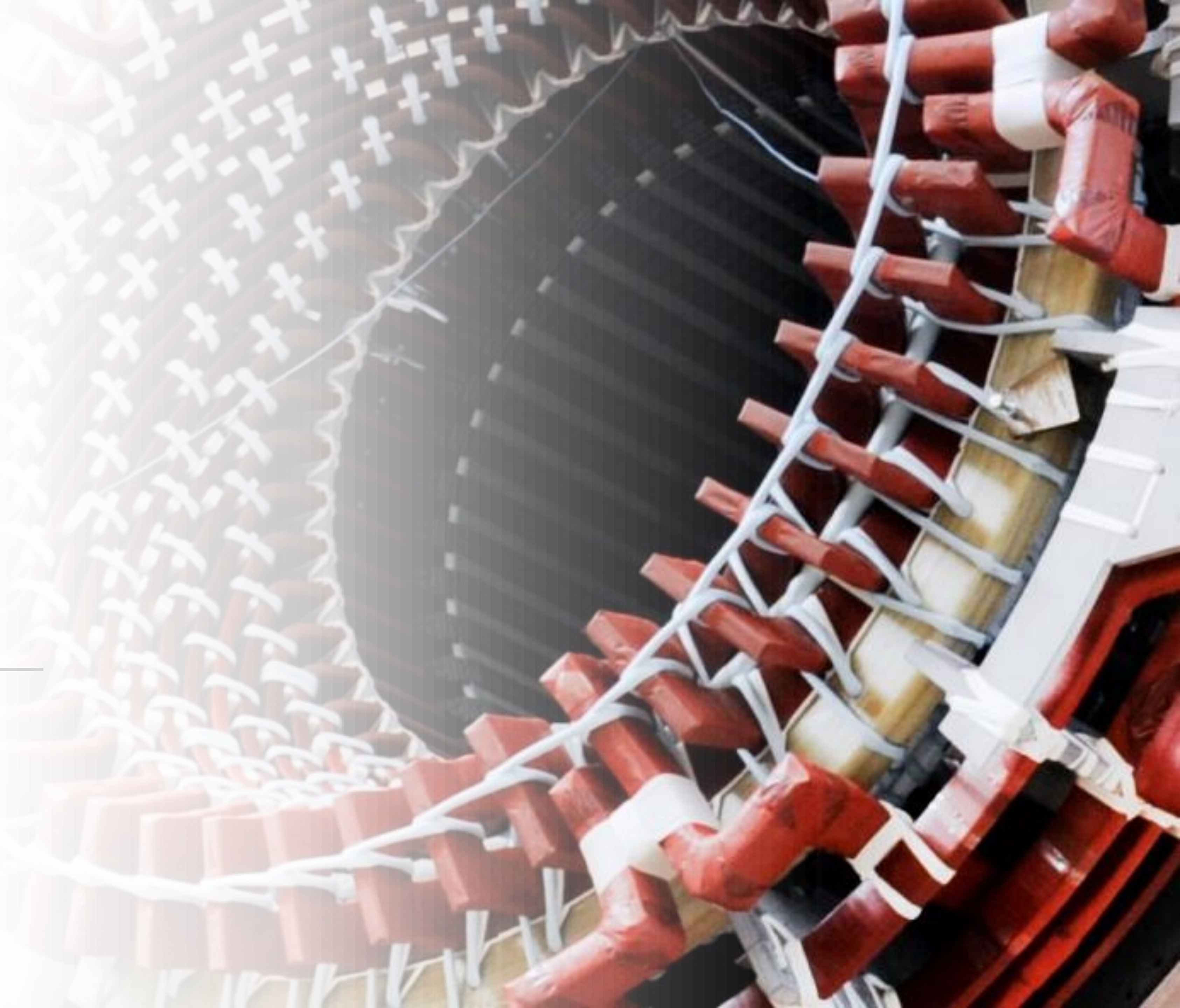
EE3124 Introduction to Electric Machines and Drives

5-Synchronous Machine

Prof. CQ Jiang



Outline

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  - Salient Poles and Non-Salient Poles
  - Field Circuit of the Rotor
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  - Power and Torque
  - Generator to Grid Synchronization

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  - Electric Power and Torque
  - The Effect of Load Changes on a Synchronous Motor
  - The Effect of Field Current Changes on a Synchronous Motor
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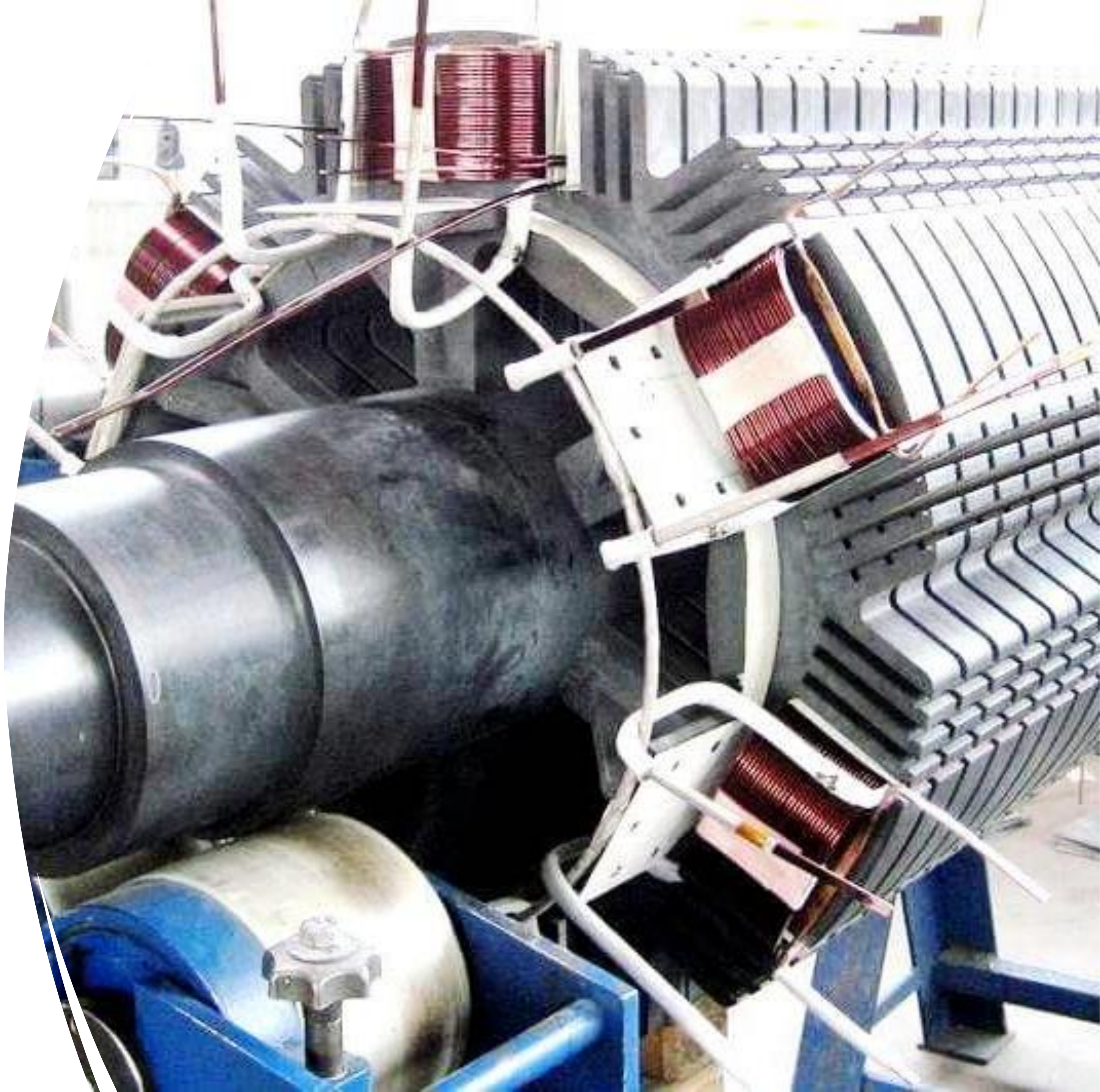
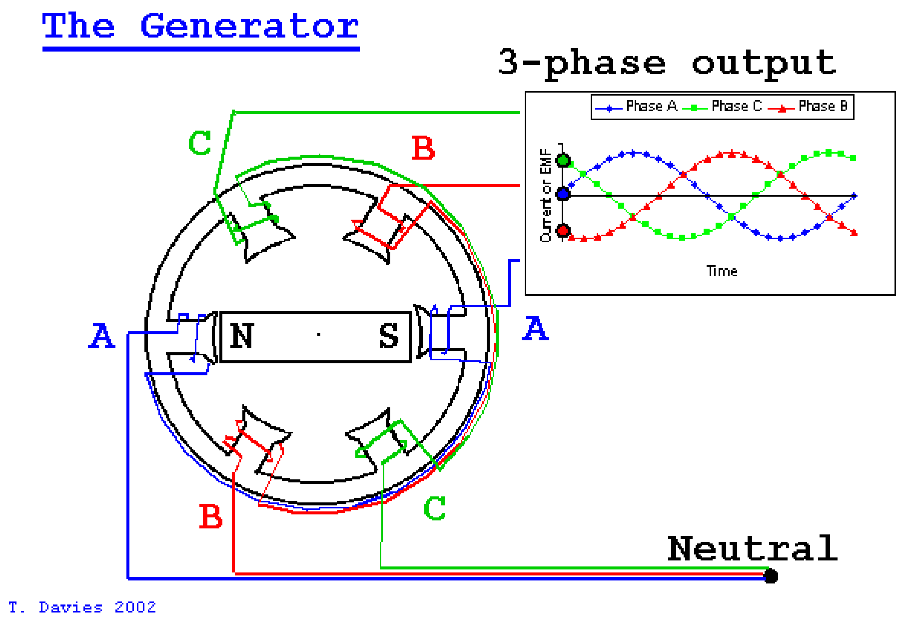
Synchronous Generators



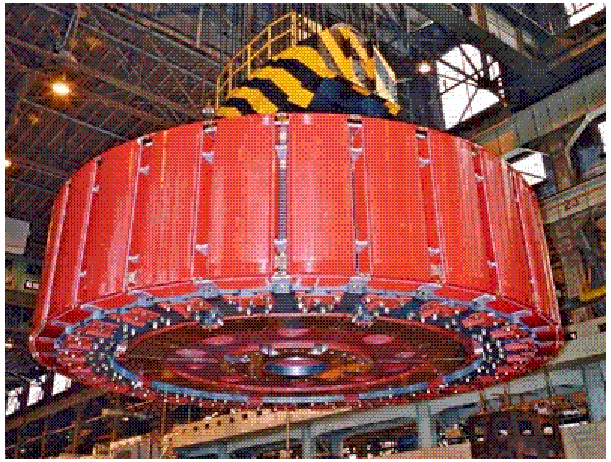
Synchronous Generators

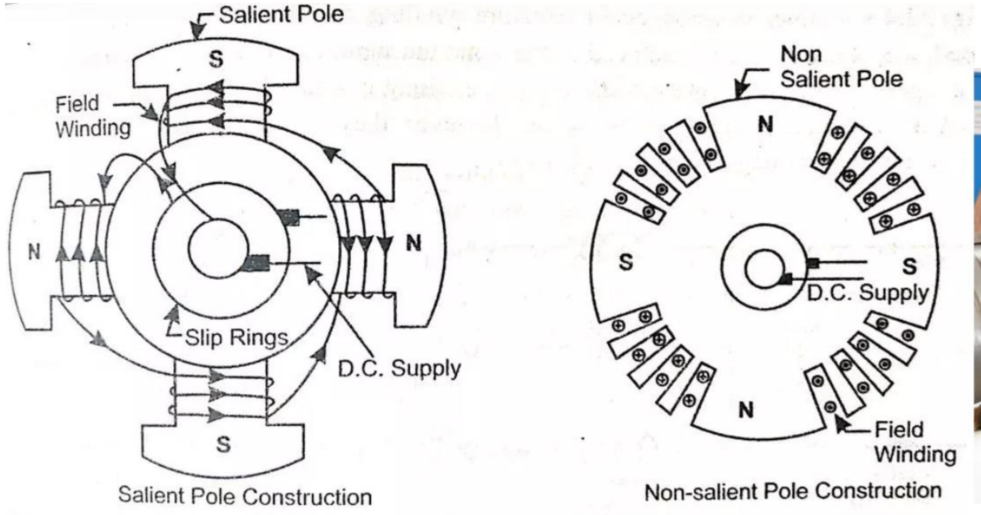
- They are machines used to convert mechanical power to AC electric power.
- A DC current is applied to the rotor winding, which produces a rotor magnetic field.
- The rotor of the generator is then turned by a prime mover, producing a rotating magnetic field within the machine.
- This rotating magnetic field induces a three-phase set of voltages within the stator windings of the generator.

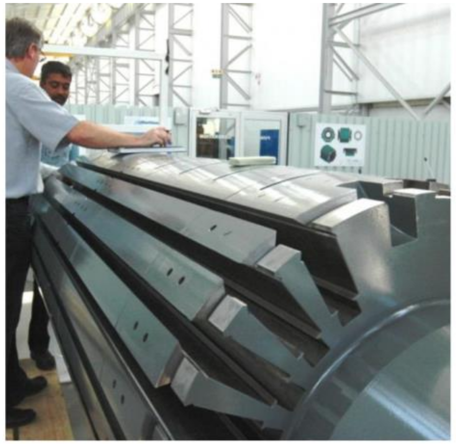


Salient Poles and Non-Salient Poles

- ❑ A salient pole is a magnetic pole that sticks out from the surface of the rotor. They are normally used for rotors with four or more poles.
- ❑ A non-salient pole is a magnetic pole constructed flush with the surface of the rotor. They are normally used for two- and four-pole rotors.

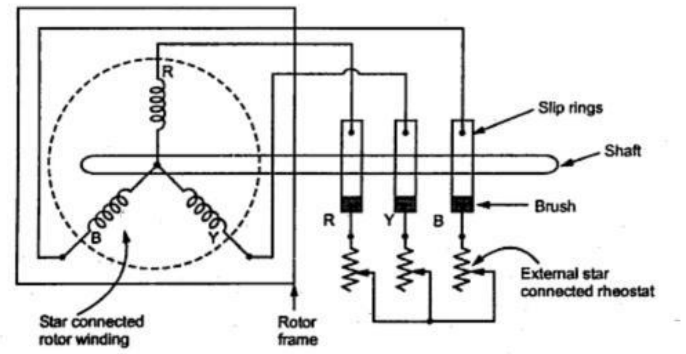


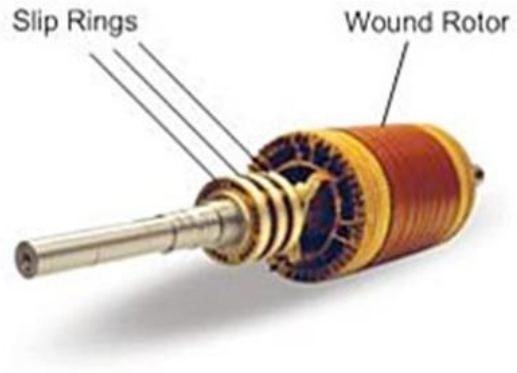




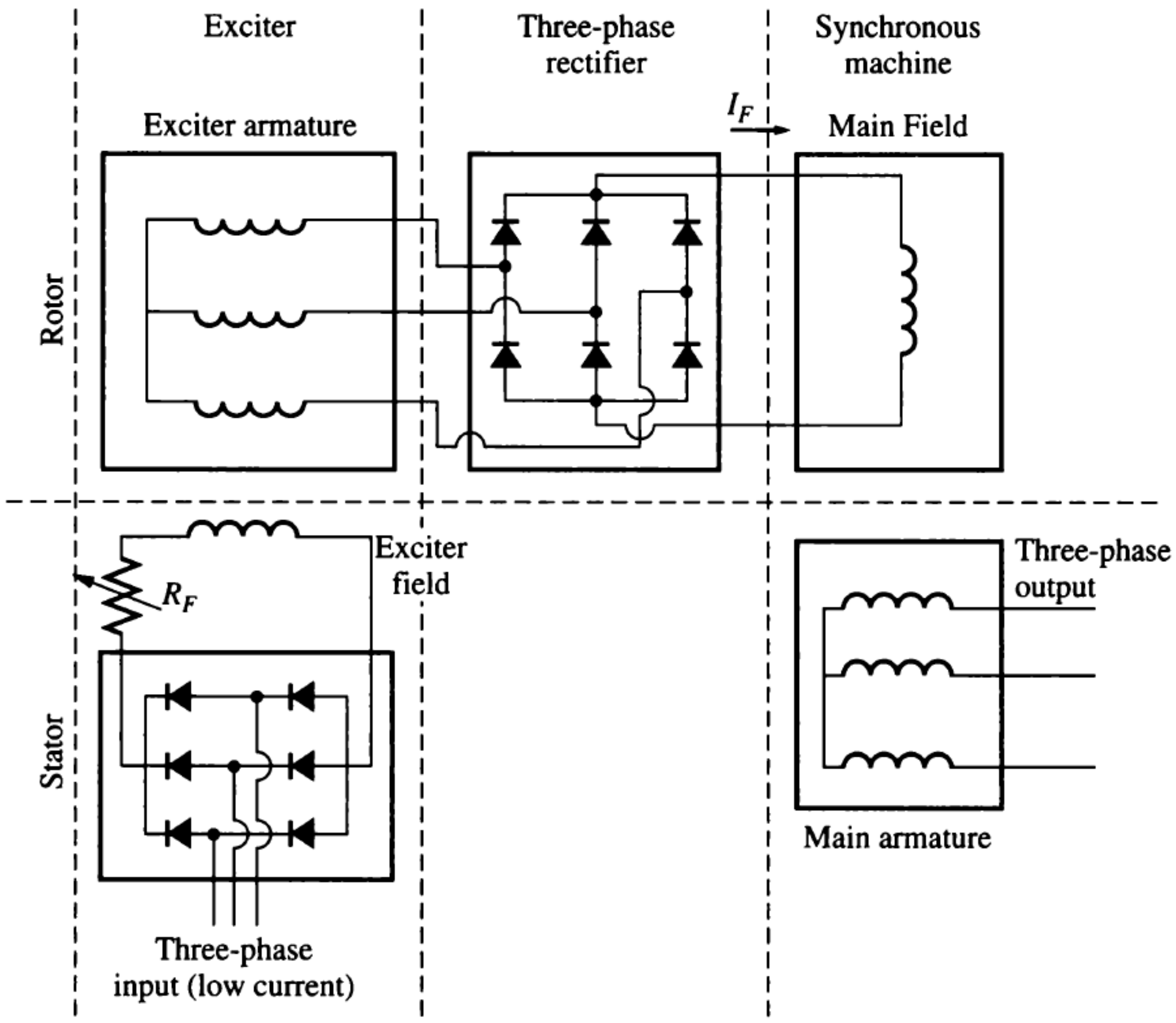
Field Circuit of the Rotor – Slip Rings

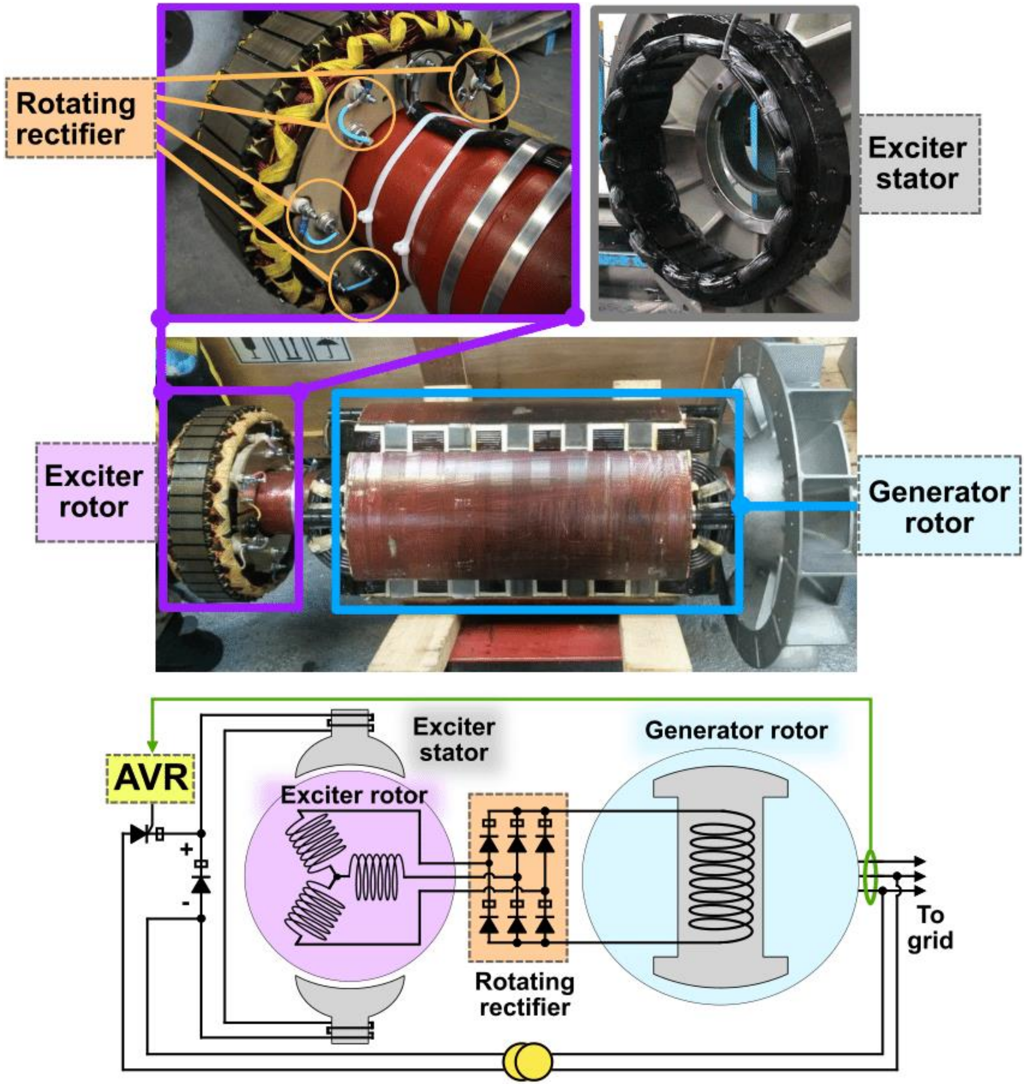
- ❑ Supply the DC power from an external DC source to the rotor by means of slip rings and brushes. Slip rings are metal rings completely encircling the shaft of a machine but insulated from it. One end of the DC rotor windings is tied to each of the two slip rings on the shaft of the synchronous machine, and a brush rides on each slip ring.
- ❑ They increase the amount of maintenance required on the machine, since the brushes must be checked for war regularly.
- ❑ Brush voltage drop can be the cause of significant power losses on machines with larger field currents.
- ❑ They are used on all smaller synchronous machines (cost-effective solution).





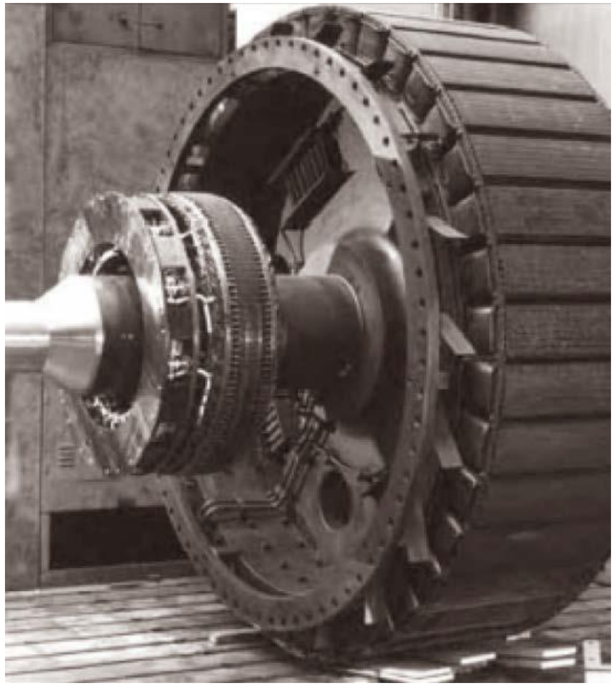
Field Circuit of the Rotor – Brushless Exciter Circuit



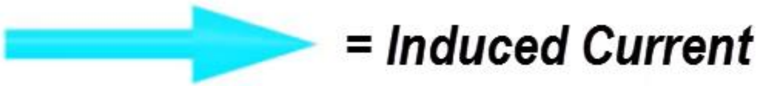


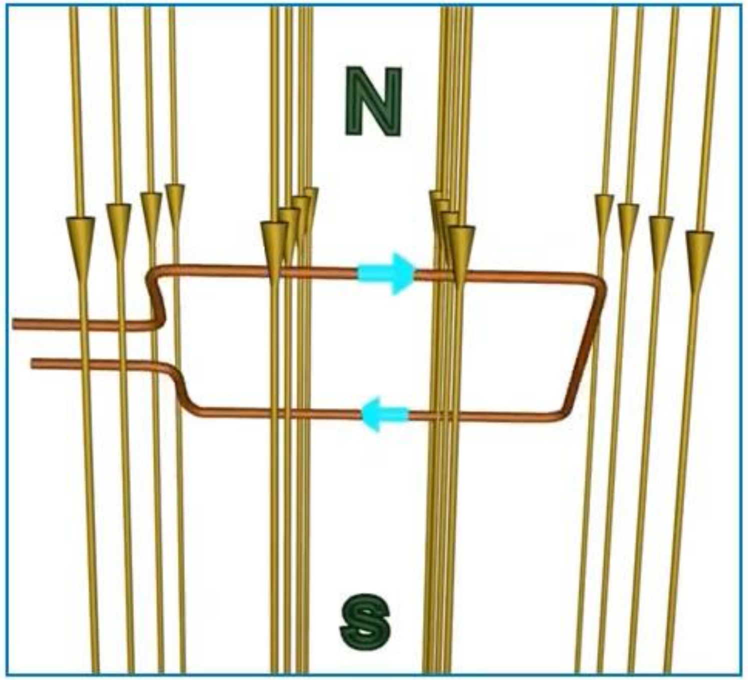
Field Circuit of the Rotor – Brushless Exciter Circuit

- On larger generators, brushless exciters are used to supply the dc field current to the machine.
- It is a small ac generator with its field circuit mounted on the stator and its armature circuit mounted on the rotor shaft.
- By controlling the small dc field current of the exciter generator, it is possible to adjust the field current on the main machine without slip rings and brushes.
- It requires much less maintenance than slip rings and brushes.
- To make it completely independent of any external power sources, a small pilot exciter (a small ac generator with permanent magnets mounted on the rotor) is often included in the system.



Synchronous Generator





ROTATING COIL

ROTATING MAGNETIC FIELD

https://www.youtube.com/watch?v=tiKH48EMgKE

The Speed of Rotation

- Since the rotor turns at the same speed as the magnetic field, this equation relates the speed of rotor rotation to the resulting electrical frequency.

$$f_e = \frac{P}{2} f_m$$

$$n_m(rpm) = \frac{2 \times f_e}{P} \times 60$$

$$\Rightarrow \quad f_e = \frac{n_m P}{120}$$

- For example, to generate 60 Hz power in a two-pole machine, the rotor must turn at 3600 r/min. To generate 50 Hz power in a four-pole machine, the rotor must turn at 1500 r/min.

The Internal Generated Voltage

- Previously, we have derived the voltage induced in each coils is expressed as

$$e_{aa'} = N_c \phi \omega_M \cos(\omega_M t)$$
$$e_{bb'} = N_c \phi \omega_M \cos(\omega_M t - 120^\circ)$$
$$e_{cc'} = N_c \phi \omega_M \cos(\omega_M t - 240^\circ)$$

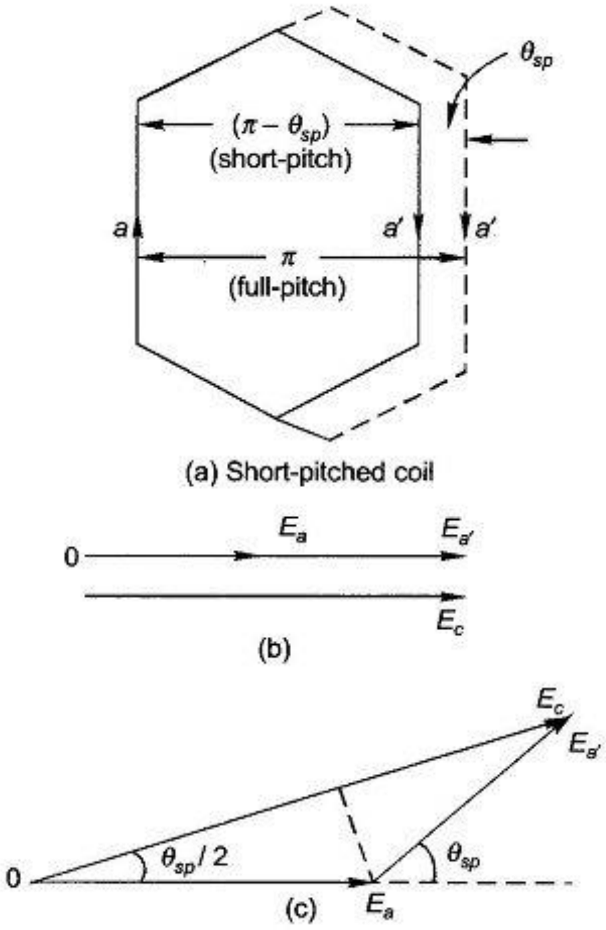
- The magnitude in rms of the voltage induced can be expressed in a simpler form

$$E_A = \frac{e_{aa'}}{\sqrt{2}} = K\phi\omega$$

- *K* is a constant representing the construction of the machine.

The Internal Generated Voltage

- K includes all the windings factors. i.e. number of turns, number of poles, pitch factor (k_p) and distribution factor (k_d).



$$K = \frac{N_c P k_p k_d}{2\sqrt{2}}$$

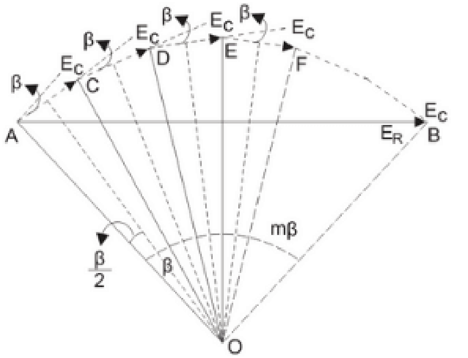
$$E_A = \frac{N_c P k_p k_d}{2\sqrt{2}} \phi\omega$$

Pitch, Winding & Distribution Factor

$$K_{dr} = \frac{\sin \frac{rm\beta}{2}}{m \sin \frac{r\beta}{2}}$$

Therefore, Winding Factor

$$K_w = K_p \times K_d = \cos\frac{\alpha}{2} \times \frac{\sin\frac{m\beta}{2}}{m \sin\frac{\beta}{2}}$$

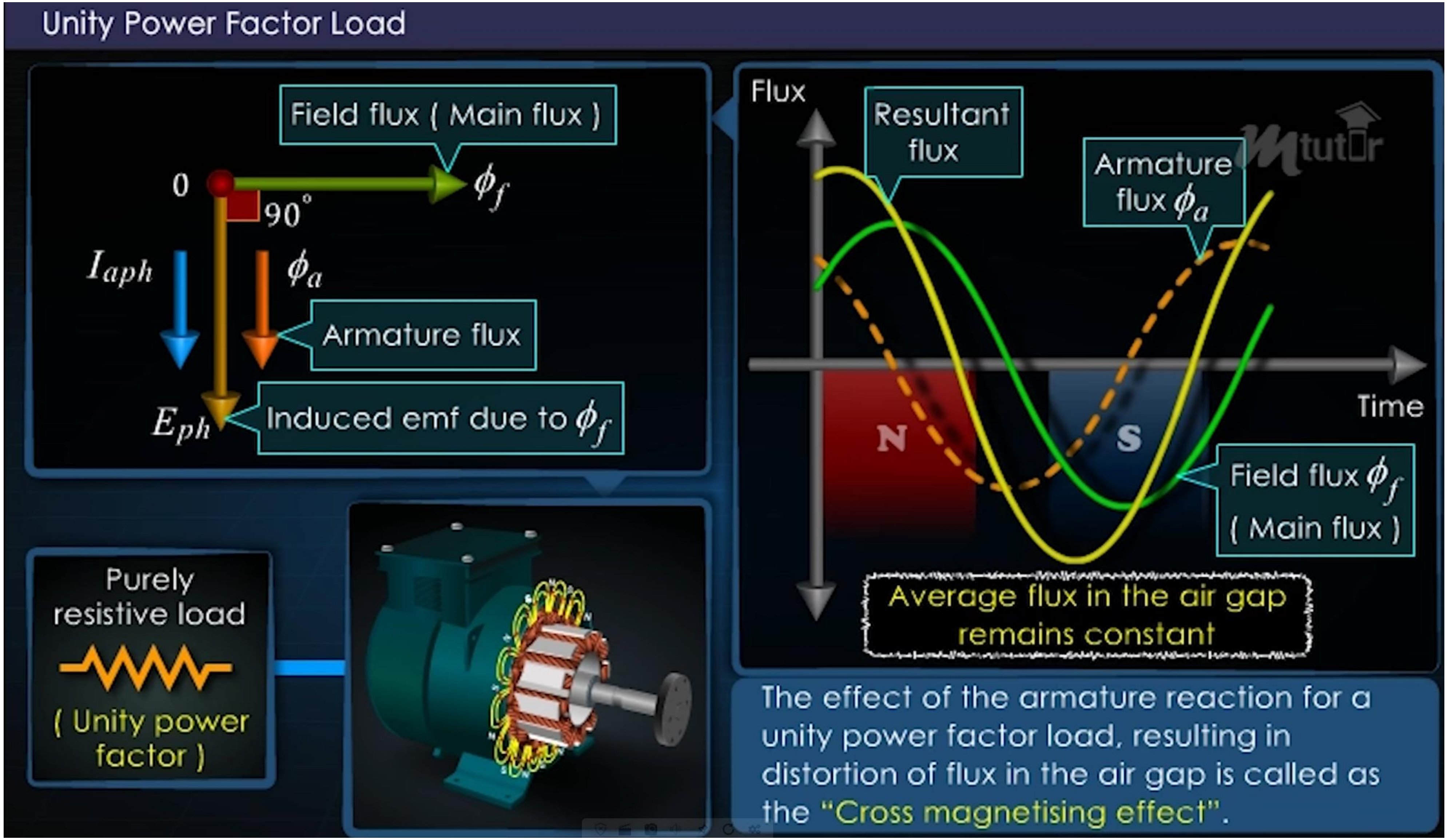


Electrical 4 U

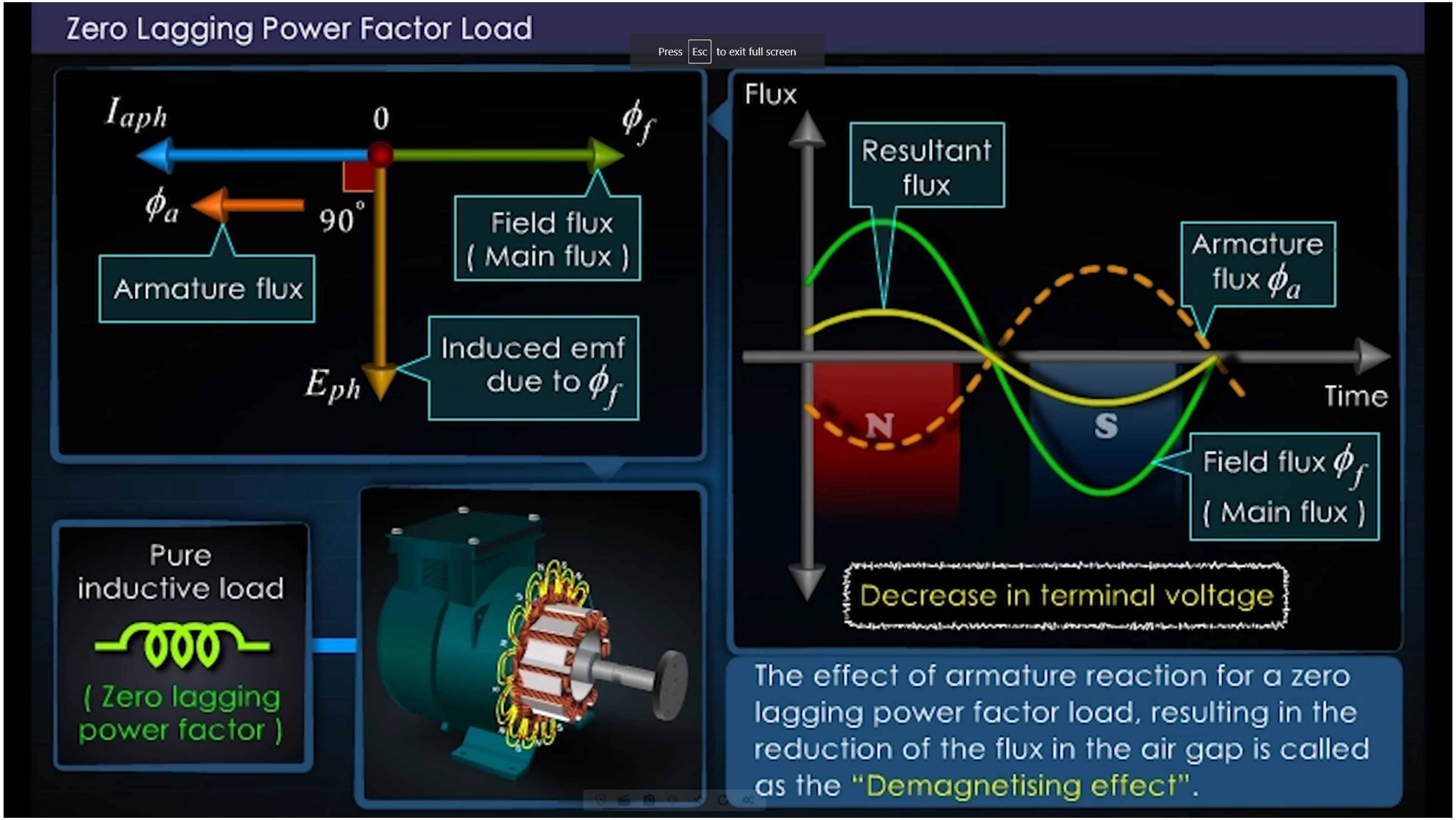
Factors Affect the Terminal Voltage

- With no load on the generator, there is no armature current flow, and E_A will be equal to the phase voltage V_{Φ}.
- E_A is the internal generated voltage produced in on phase of a synchronous generator. However, this voltage E_A is not the voltage that appears at the terminals of the generator.
- There are a number of factors that cause the difference between E_A and V_{Φ} i.e.
  - Armature reaction
  - self-inductance of the armature coils, resistance of the armature coils
  - Others, effect of salient-pole rotor shapes
- A machine model could help to describe these factors.
- Armature reaction: The distortion of the air-gap magnetic field by the current flowing in the stator.

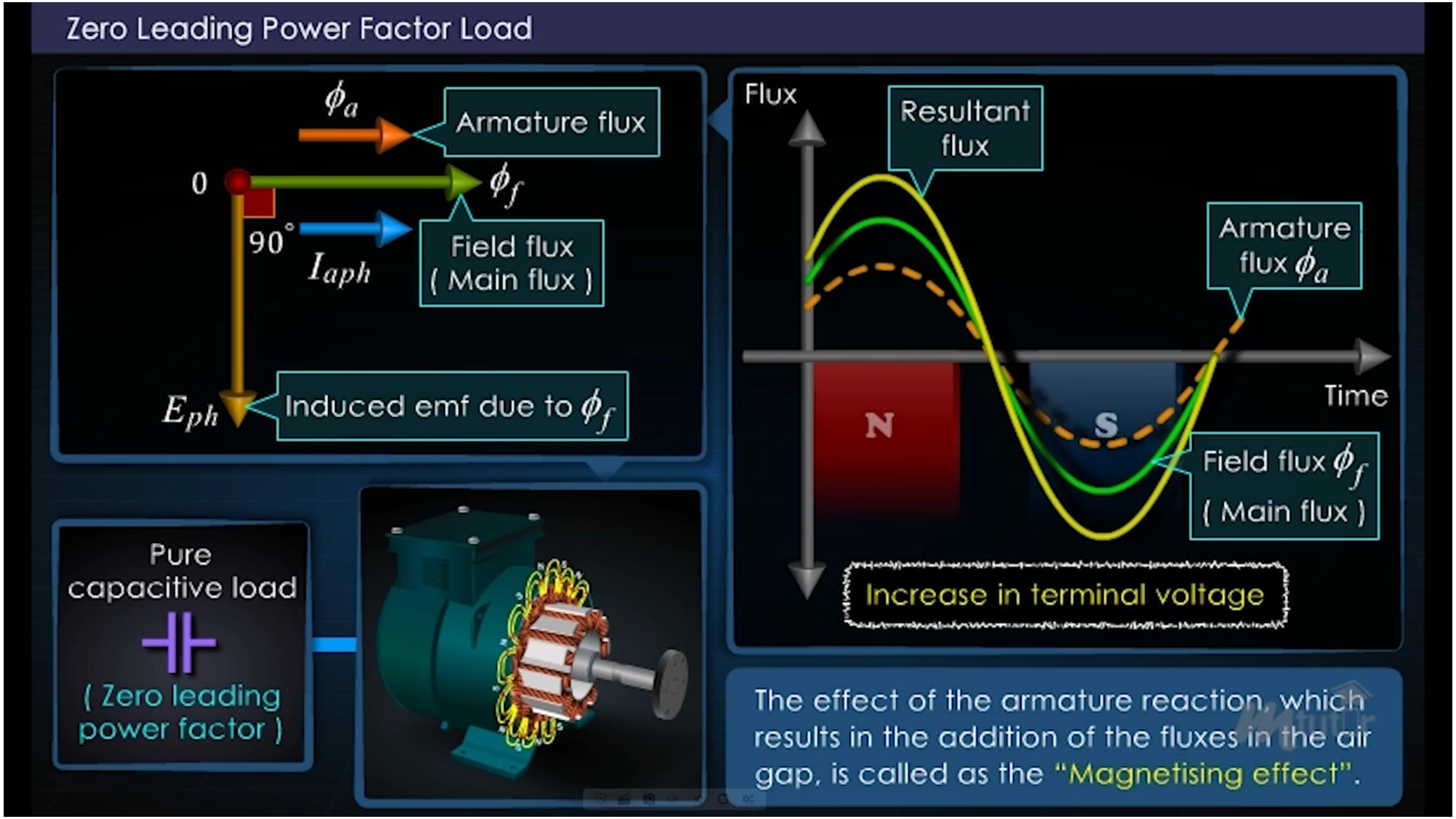
Armature reaction – Unity Power Factor Load



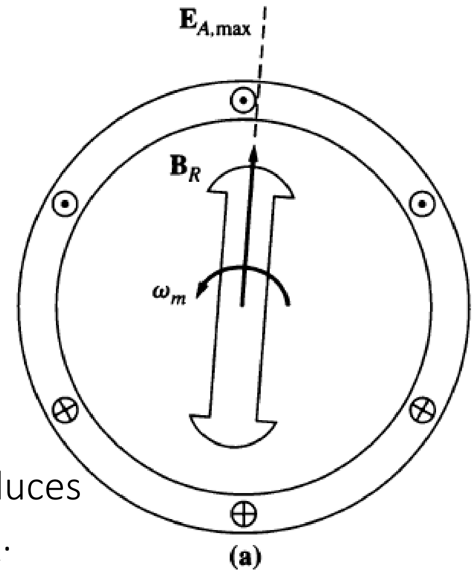
Armature reaction – Pure Inductive Load



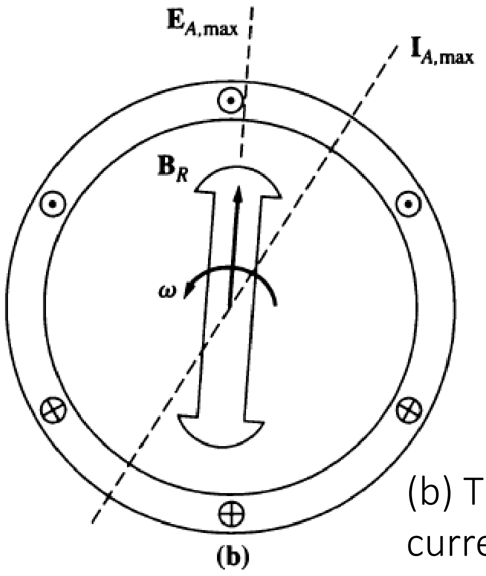
Armature reaction – Pure Capacitive Load



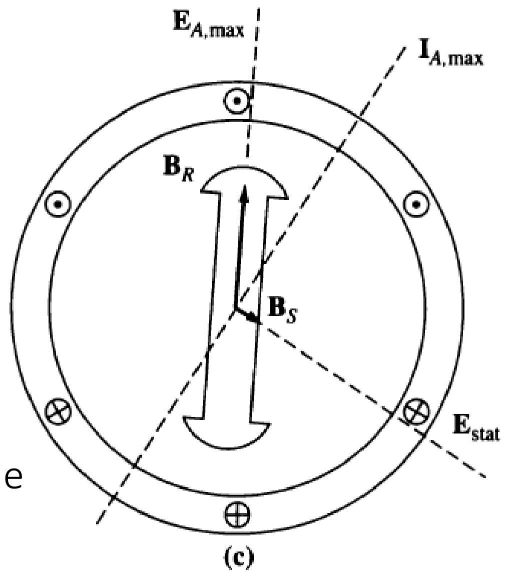
Factors Affect the Terminal Voltage



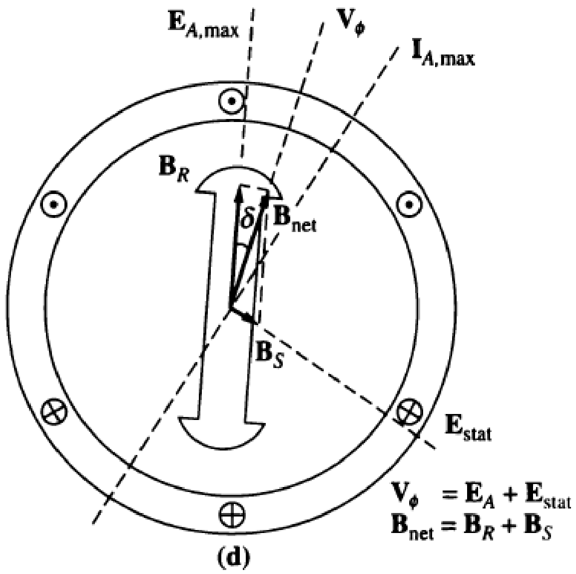
(a) A rotating magnetic field produces the internal generated voltage E_A.



(b) The resulting voltage produces a lagging current flow when connected to a lagging load.



(c) The stator current produces its own magnetic field *Bs*, which produces its own voltage E_{stat} in the stator windings of the machine.



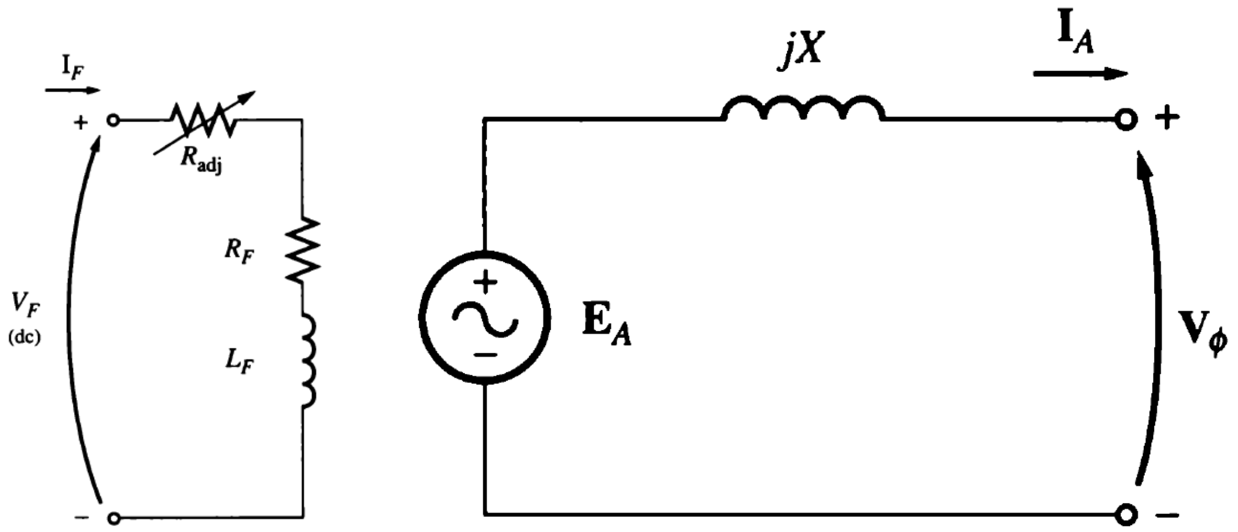
(d) The field *Bs* adds to B_R, distorting it into B_{net}. The voltage E_{stat} adds to E_A , producing V_ϕ at the output of the phase.

Self-inductance and Resistance

- Armature reaction effects and the self-inductance in the machine are both represented by reactances, called synchronous reactance of the machine.

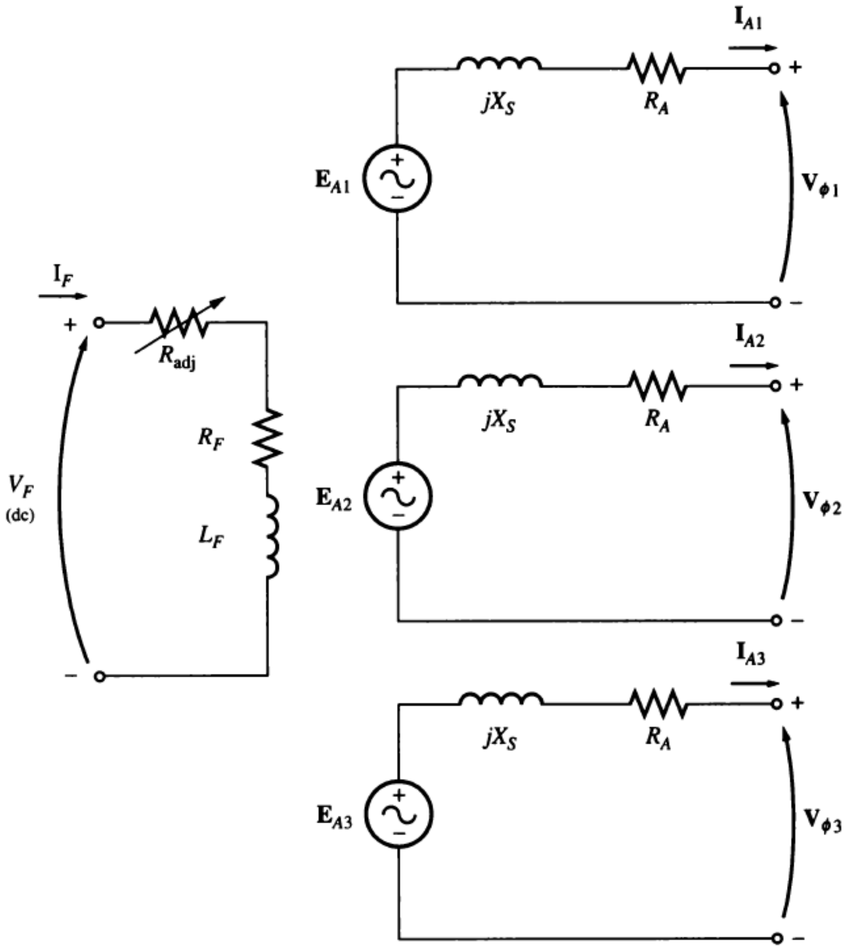
$$X_S = X + X_A$$

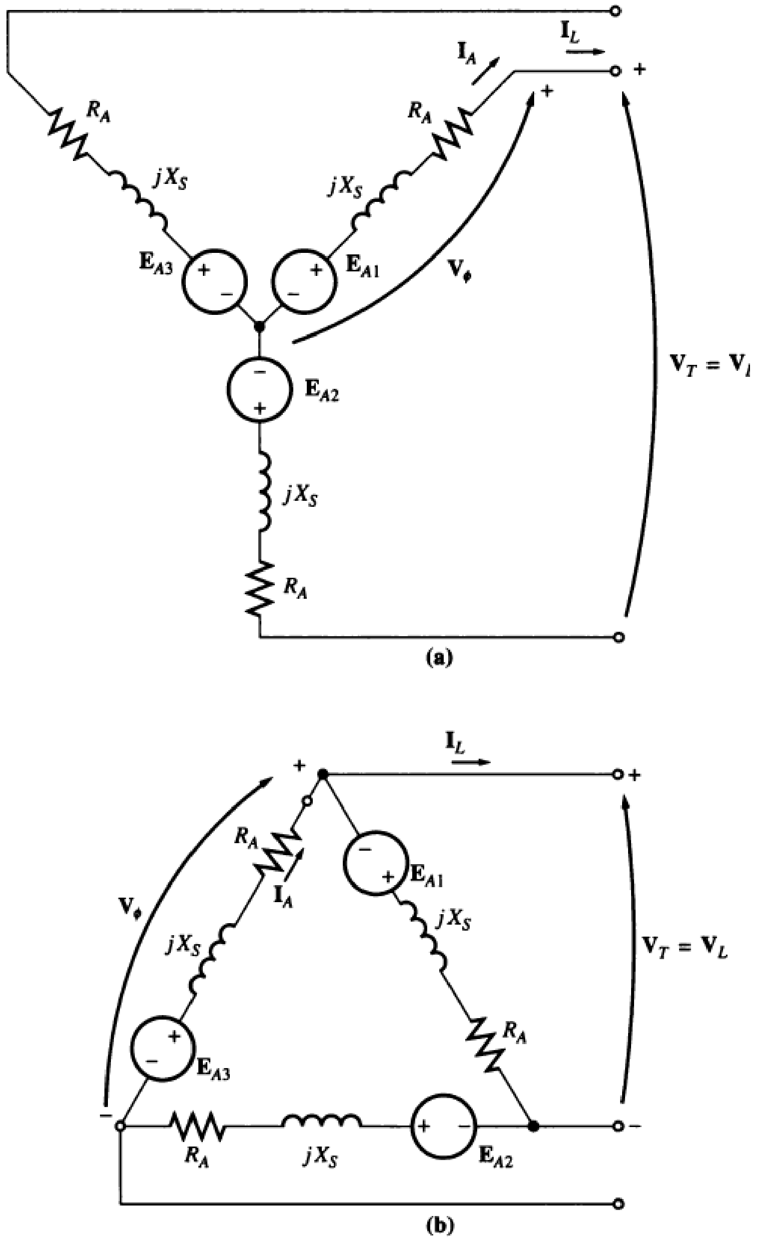
$$V_\phi = E_A - jX_S I_A - R_A I_A$$



Generator Equivalent Circuits

- The full equivalent circuit of a three-phase synchronous generator.



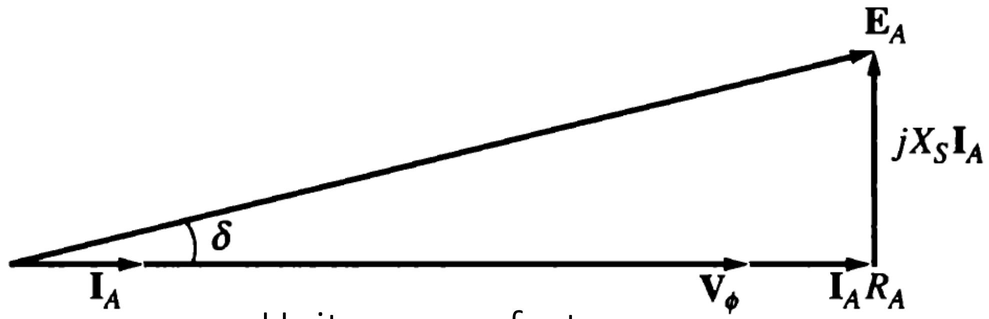


The generator equivalent circuit connected in (a) Y and (b) Δ.

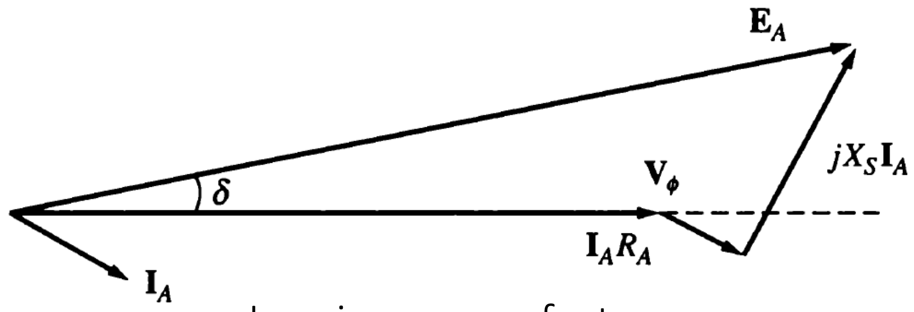
Phasor Diagram

- Terminal voltage is lower for lagging loads and higher for leading loads.
- Only a slight decrease in terminal voltage for resistive loads.
- R_A is often neglected in the real synchronous machine because the X_S is normally much larger than the R_A.

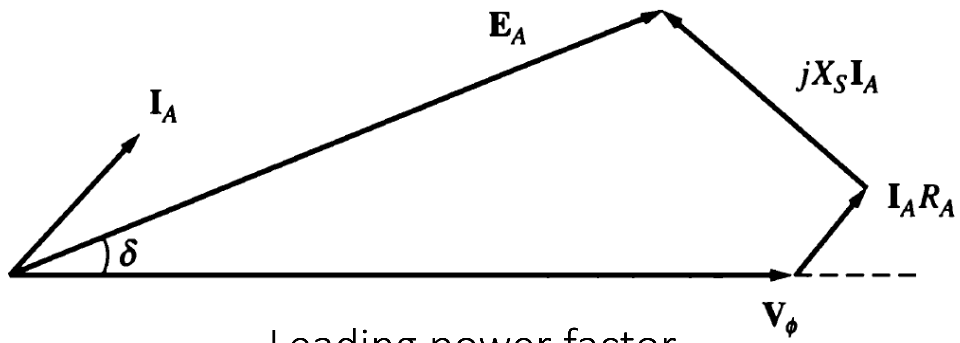
$$\mathbf{V}_\phi = \mathbf{E}_A - jX_S\mathbf{I}_A - R_A\mathbf{I}_A$$



Unity power factor

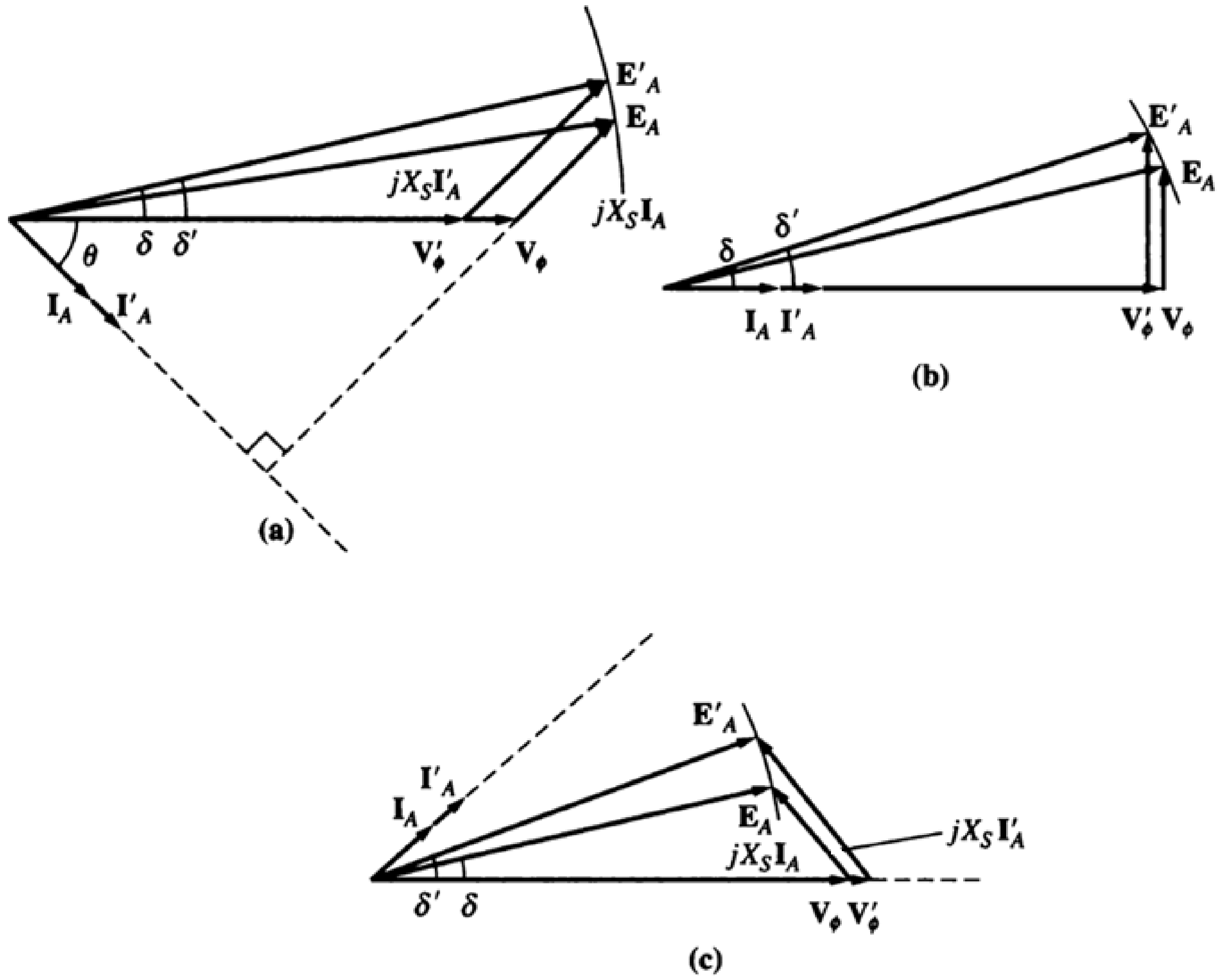


Lagging power factor



Leading power factor

Effect of Load on the Terminal Voltage



The effect of an increase in generator loads at constant power factor upon its terminal voltage, (a) Lagging power factor; (b) unity power factor; (c) leading power factor.

1. If lagging loads (+Q or inductive reactive power loads) are added to a generator, V_ϕ and the terminal voltage V_T decrease significantly.

2. If unity-power-factor loads (no reactive power) are added to a generator, there is a slight decrease in V_ϕ and the terminal voltage.

3. If leading loads (*-Q* or capacitive reactive power loads) are added to a generator, V_ϕ and the terminal voltage will rise.

$$\mathbf{V}_\phi = \mathbf{E}_A - jX_S\mathbf{I}_A$$

Power and Torque

- The real and reactive electric output power can be expressed in phase quantities as

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

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

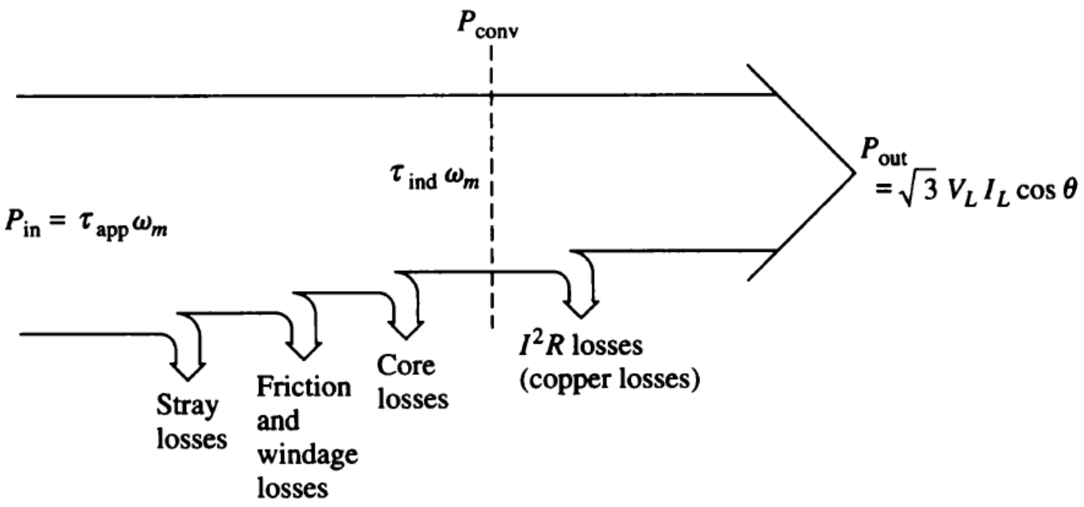
- Since

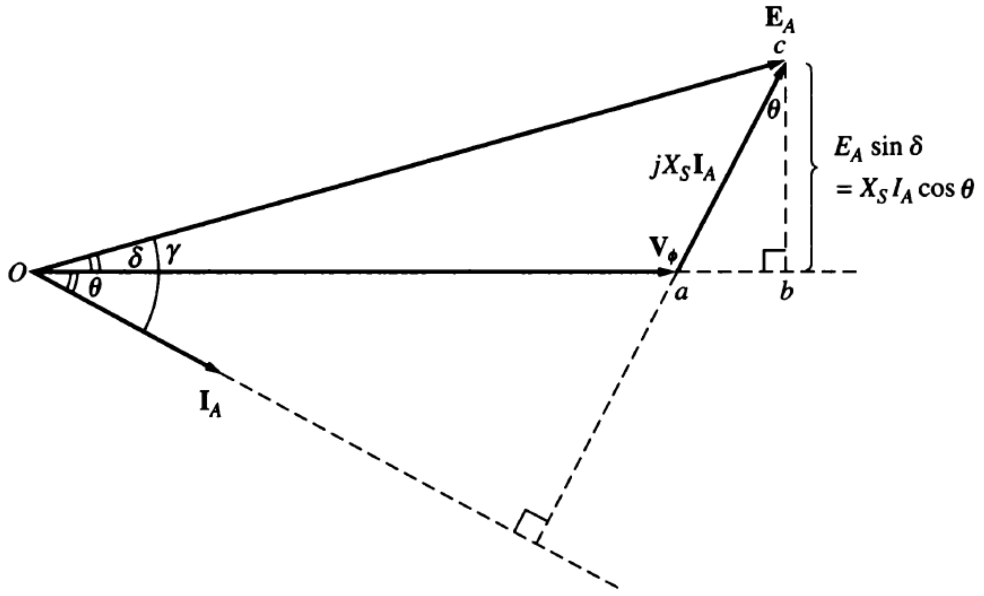
$$I_A \cos\theta = \frac{E_A \sin\delta}{X_S}$$

$$P_{out} = \tau\omega_m$$

- Therefore

$$P_{out} = \frac{3V_\phi E_A \sin\delta}{X_S} \qquad \tau = \frac{3V_\phi E_A \sin\delta}{X_S\omega_m}$$

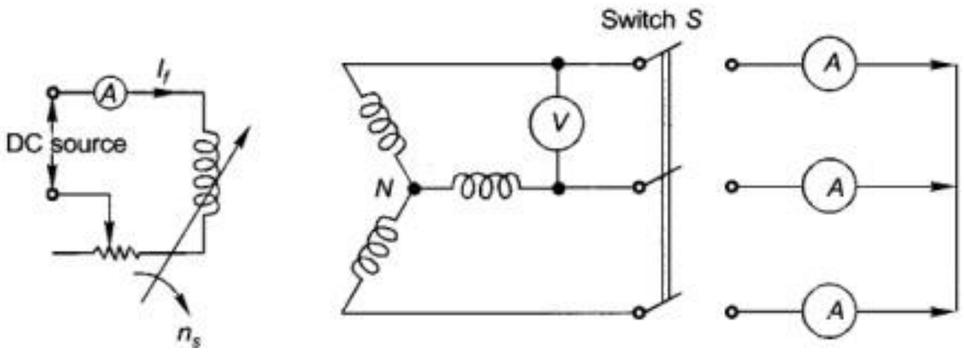




Measuring Model Parameters

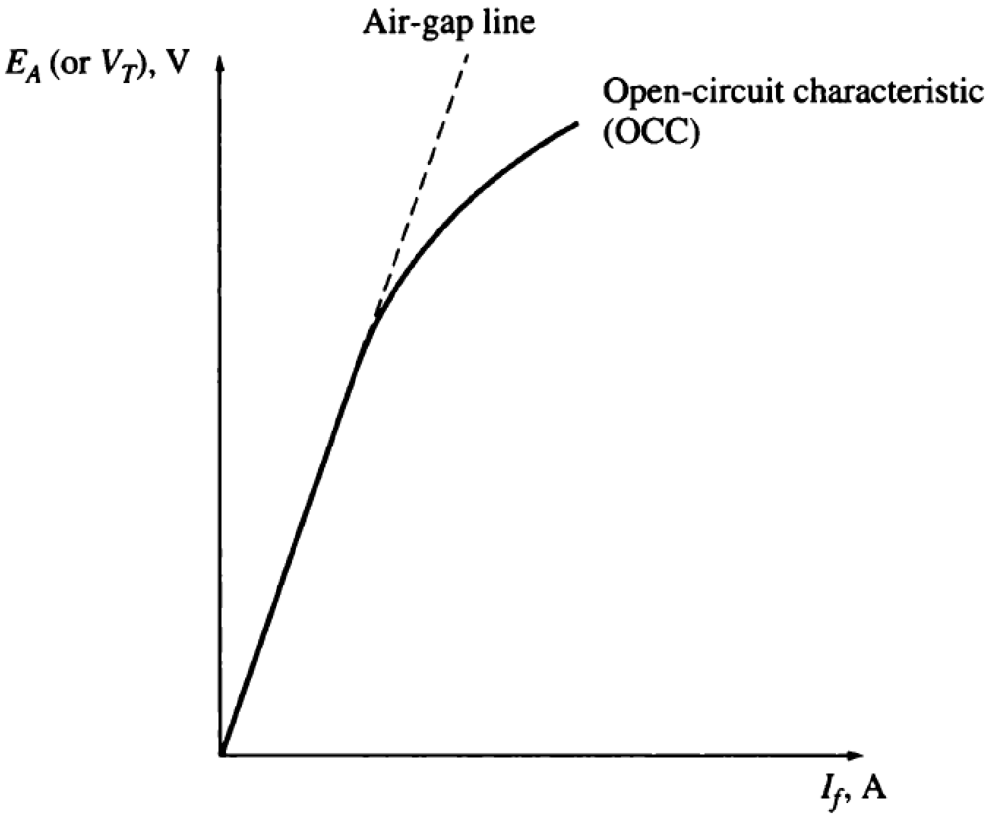
- The equivalent circuit of a synchronous generator that has been derived contains three quantities that must be determined in order to completely describe the behavior of a real synchronous generator:
  - Relationship between field current and E_A
  - Synchronous reactance
  - Armature resistance

- There are two tests:
  - Open circuit test
  - Short circuit test



Open Circuit Test

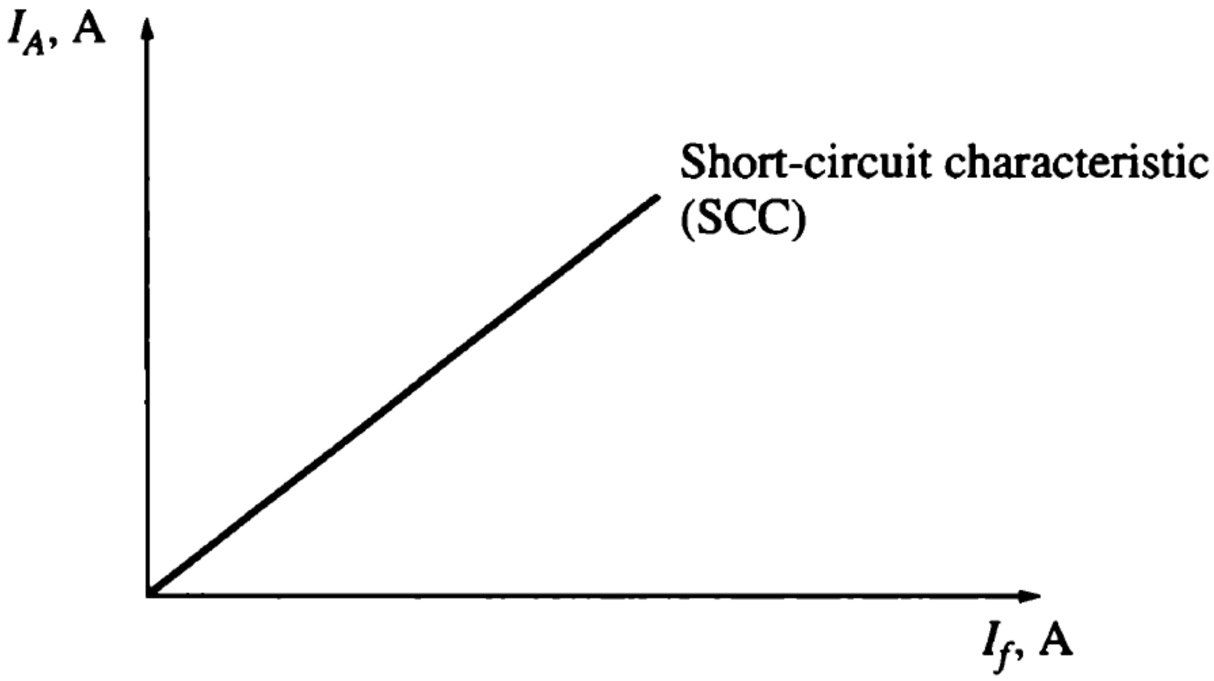
- The generator is turned at the rated speed.
- The terminals are disconnected from all loads.
- The field current is set to zero.
- Then, the field current is gradually increased in steps and the terminal voltage is measured at each step along the way.



Short Circuit Test

- Adjust the field current to zero and short circuit the terminals of the generator through a set of ammeters.
- The R_A can be approximated by applying a DC voltage to the windings and measuring the current.
- Then, the armature current I_A is measured as the field current is increased.

$$\bar{I}_A = \frac{\bar{E}_A}{R_A + jX_S} \qquad I_A = \frac{E_A}{\sqrt{R_A^2 + X_S^2}}$$



Example 1: Synchronous Generator Pole Number

- How does the number of poles of a synchronous machine affect its speed? How many poles does a synchronous machine with a rated speed of 75 RPM have? Will there be a synchronous motor with a rated speed of 1600 RPM? (All assume that under power frequency conditions (50Hz) without any converter.)

- **Solution**

(1) Under stable conditions, the rotor mechanical speed of the synchronous motor is strictly synchronized with the synchronous speed. So when the mechanical speed is constant, the power frequency is also constant. The rotor mechanical speed of a synchronous generator is proportional to the power frequency and inversely proportional to the number of poles.

$(n_r = n_s = 120f/p)$

$p = 120f/n_r = 120*50/75 = 80$ (poles)

(2) $p = 120f/n_r = 120*50/1600 = 3.75$ (poles)

Since p = 3.75, this is not an integer, so there is no such synchronous motor.

Example 2: Synchronous Generator Calculation

- A 200 kVA 480 V 50 Hz Y-connected synchronous generator with a rated field current of 5 A was tested, and the following data were taken:
    1. $V_{T,OC}$ at the rated I_F was measured to be 540 V
    2. $I_{L,SC}$ at the rated I_F was found to be 300 A
    3. When a dc voltage of 10 V was applied to two of the terminals, a current of 25 A was measured.

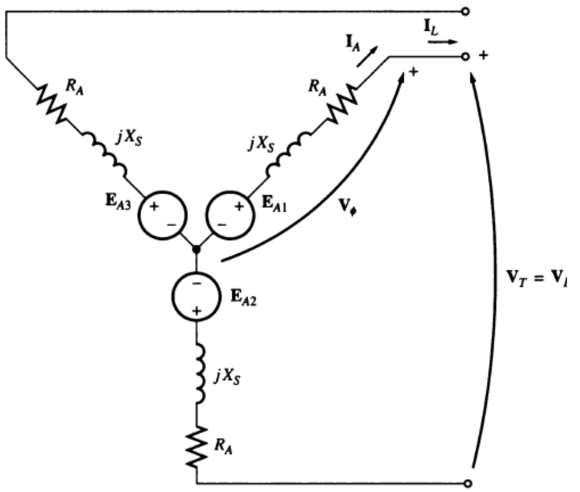
  Find the values of the armature resistance and the approximate synchronous reactance in ohms that would be used in the generator model at the rated conditions.

Example 2: Synchronous Generator Calculation

❑ Solution

The generator described above is Y-connected, so the direct current in the resistance test flows through two windings. Therefore, the resistance is given by $2R_A = \frac{V_{DC}}{I_{DC}}$

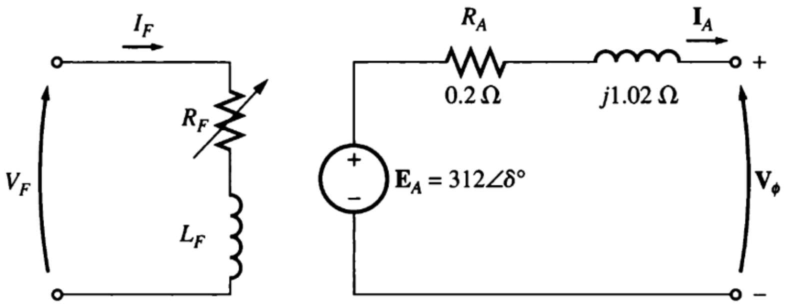
$$R_A = \frac{10}{2 \times 25} = 0.2\Omega$$



The internal generated voltage at the rated field current is equal to

$$E_A = V_{\phi,oc} = \frac{V_T}{\sqrt{3}} = \frac{540}{\sqrt{3}} = 311.8V$$

The short-circuit current IA is just equal to the line current, since the generator is Y-connected $I_{A,SC} = I_{L,SC} = 300A$



Therefore, the synchronous reactance at the rated field current can be

$$\sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A}$$

$$\sqrt{0.2^2 + X_S^2} = \frac{311.8}{300}$$

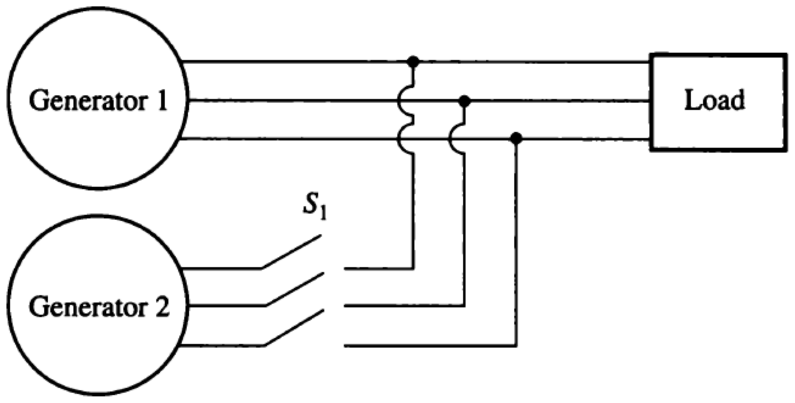
$$\Rightarrow \quad X_S^2 = 1.04$$

$$X_S = 1.02$$

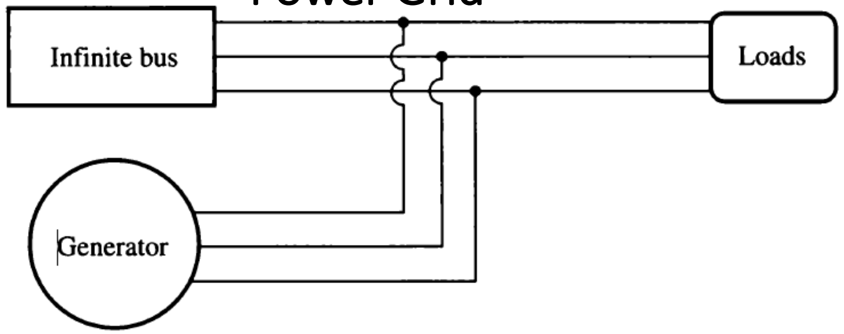
Generator to Grid Synchronization

- In today's world, an isolated synchronous generator supplying its own load independently of other generators is very rare.
- Why are synchronous generators operated in parallel? There are several major advantages to such operation:

1) Supply a bigger load than one machine by itself.
2) Having many generators increases the reliability of the power system, since the failure of any one of them does not cause a total power loss to the load.
3) Having many generators operating in parallel allows one or more of them to be removed for shutdown and preventive maintenance.
4) If only one generator is used and it is not operating at near full load, then it will be relatively inefficient. With several smaller machines in parallel, it is possible to operate only a fraction of them. The ones that do operate are operating near full load and thus more efficiently.



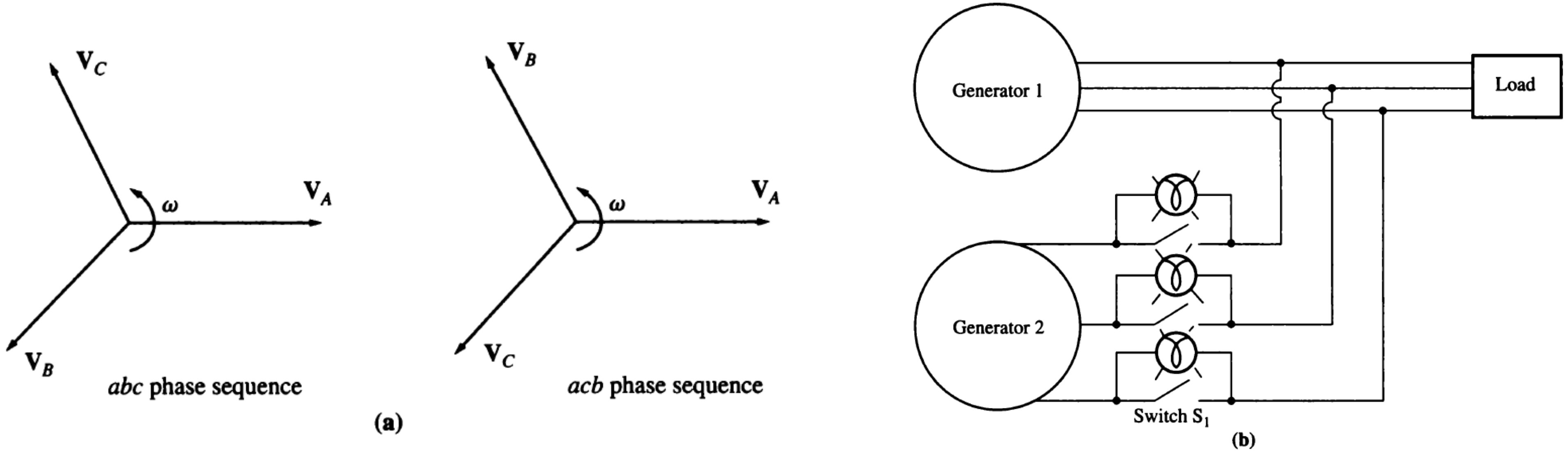
Power Grid



Generator to Grid Synchronization

The Conditions Required for Synchronization

1. The RMS line voltages of the two generators must be equal.
2. The two generators must have the same phase sequence.
3. The phase angles of the two phases must be equal.
4. The frequency of the new generator, called the oncoming generator, must be slightly higher than the frequency of the running system.

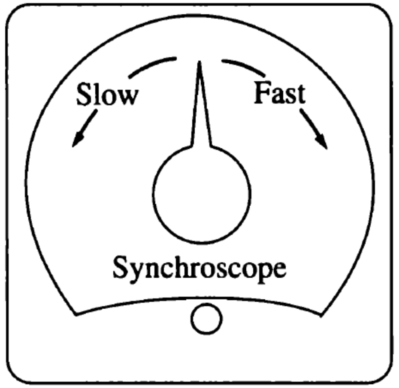


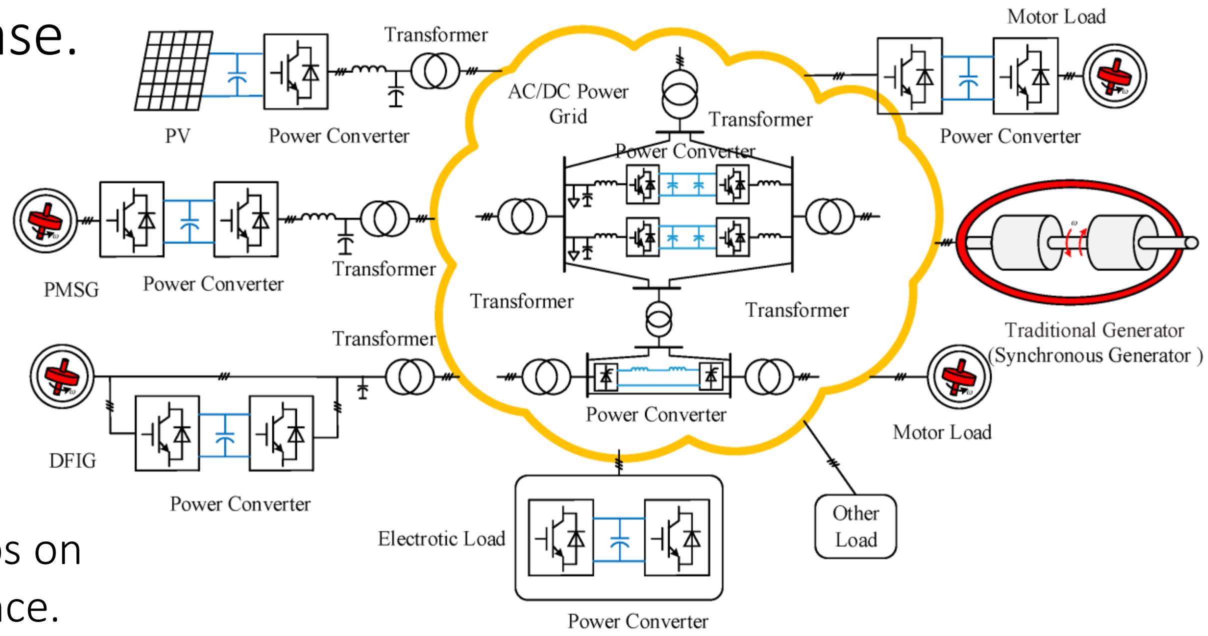
(a) The two possible phase sequences of a three-phase system. (b) The three-light-bulb method for checking phase sequence.

Generator to Grid Synchronization

❑ The General Procedure for Grid Synchronization

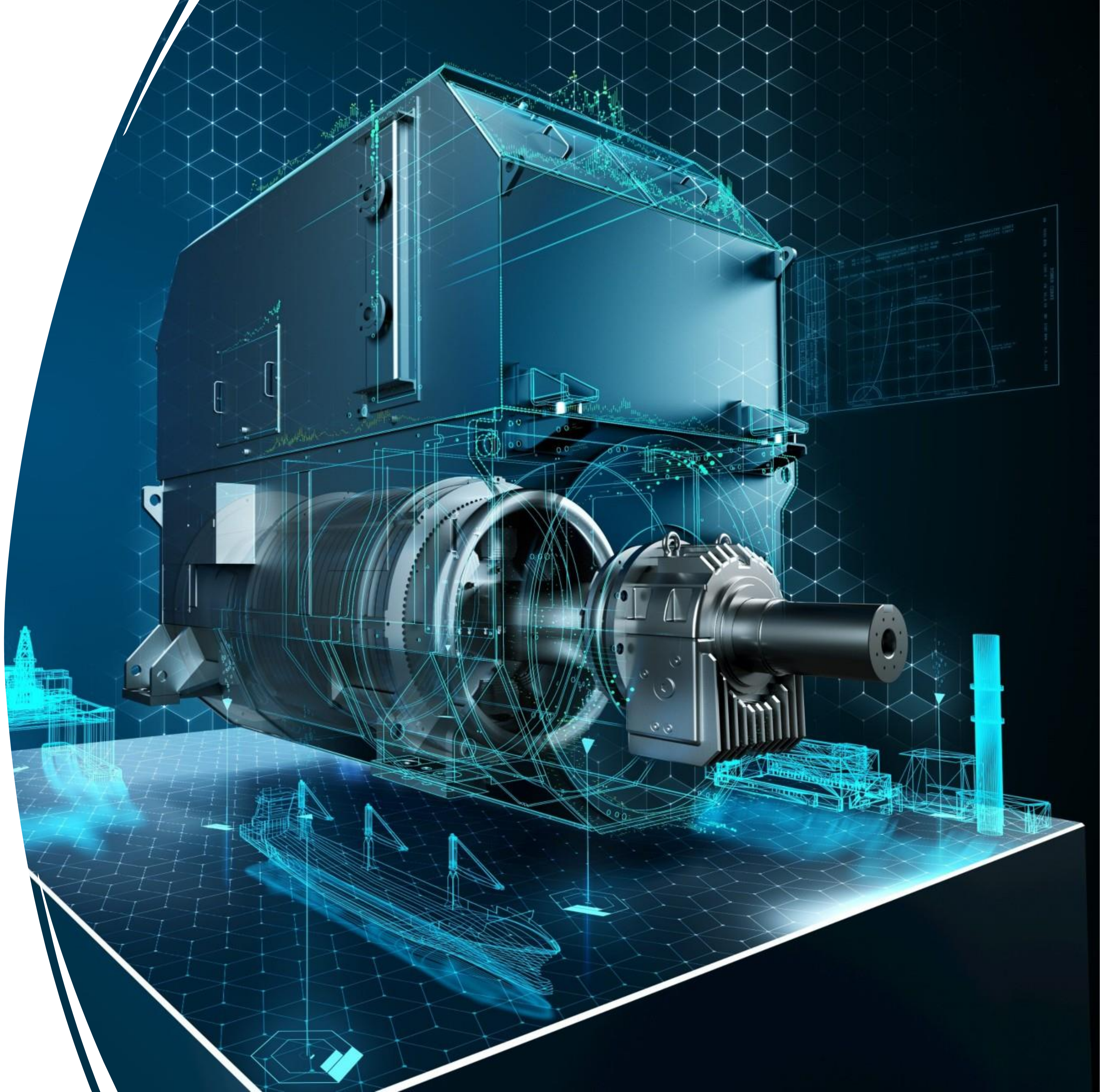
1) First, using voltmeters until its terminal voltage is equal to the out line voltage;
2) Second, the phase sequence of the oncoming generator must be compared to the phase sequence of the running system;
3) Next, the frequency of the oncoming generator is adjusted to be slightly higher than the frequency of the running system;
4) Check two systems are finally in phase.





Notice, though, that a synchroscope checks the relationships on only one phase. It gives no information about phase sequence.

Synchronous Motors



Synchronous Motors

- They are machines used to convert electric power to mechanical power.
- Since a synchronous motor is the same physical machine as a synchronous generator, all of the basic speed power and torque equations of synchronous generator apply to synchronous motors also.
- A Synchronous motor is the same in all respects as a synchronous generator, except that the direction of power flow is reversed.
- Synchronous motors supply power to loads that are basically constant-speed devices.

Synchronous Motors

- They are usually connected to power systems very much larger than the individual motors.

- The speed of rotation of the motor is locked to the applied electrical frequency, so the speed of the motor will be constant regardless of the load.

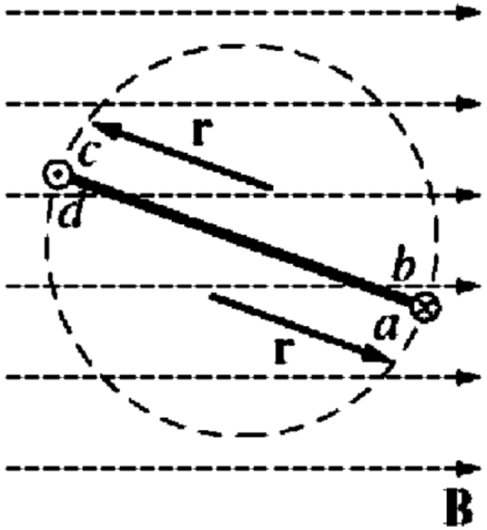
- The steady-state speed of the motor is constant from no load all the way up to the maximum torque that the motor can supply (pull-out torque).

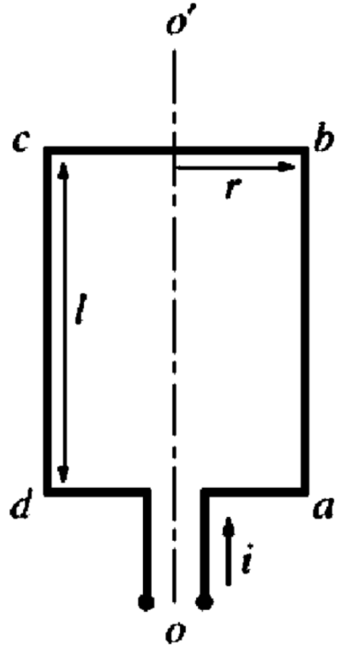
Torque Induced in a Current-carrying Loop

- Assume that the rotor loop is at some arbitrary angle δ with respect to the magnetic field, and that a current i is flowing in the loop.
- The force on each segment of the loop will be given by

$$\mathrm{F} = i(\mathrm{l} \times \mathrm{B})$$

- Where
  - i = magnitude of current in the segment
  - l = length of the segment, with direction of l defined to be in the direction of current flow
  - B = magnetic flux density vector



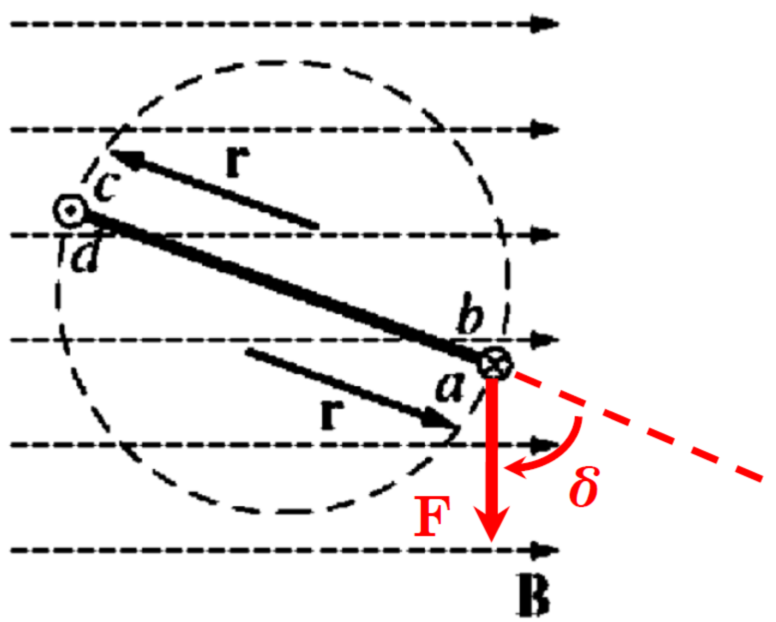


Torque Induced in a Current-carrying Loop

- Then, the torque on that segment will then be given by

$$\begin{aligned}\tau &= (\text{force applied})(\text{perpendicular distance}) \\ &= (F)(r\sin\delta) \\ &= rF\sin\delta\end{aligned}$$

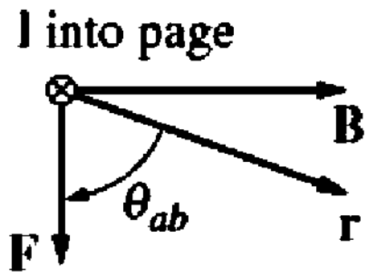
- Where δ is the angle between the vector r and the vector F.

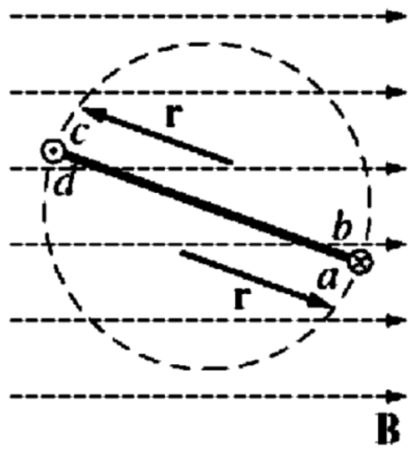


Torque Induced in a Current-carrying Loop

- Segment ab

$$\mathrm{F} = i(\mathrm{l} \times \mathrm{B})$$
$$= ilB \quad \text{down}$$



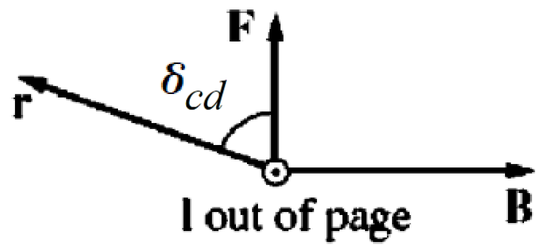


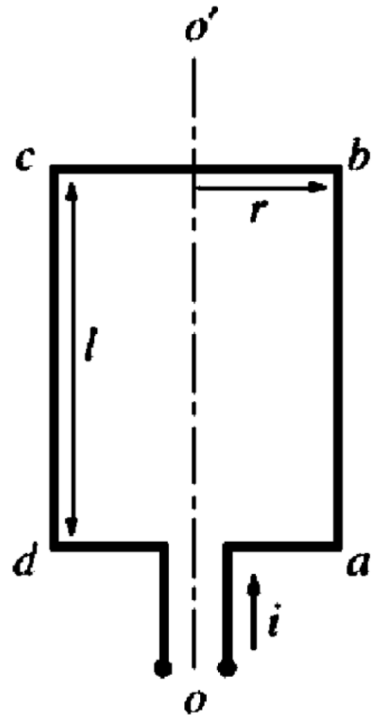
- The resulting torque is

$$\tau_{ab} = (\mathrm{F})(r \sin \delta)$$
$$= rilB \sin \delta_{ab}$$

- Segment cd

$$\mathrm{F} = i(\mathrm{l} \times \mathrm{B})$$
$$= ilB \quad \text{up}$$





- The resulting torque is

$$\tau_{cd} = (\mathrm{F})(r \sin \delta)$$
$$= rilB \sin \delta_{cd}$$

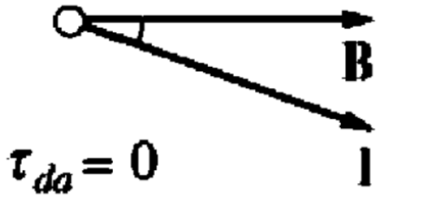
Torque Induced in a Current-carrying Loop

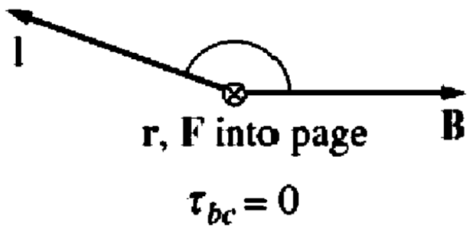
- Segments bc and da,
- the resulting torque is

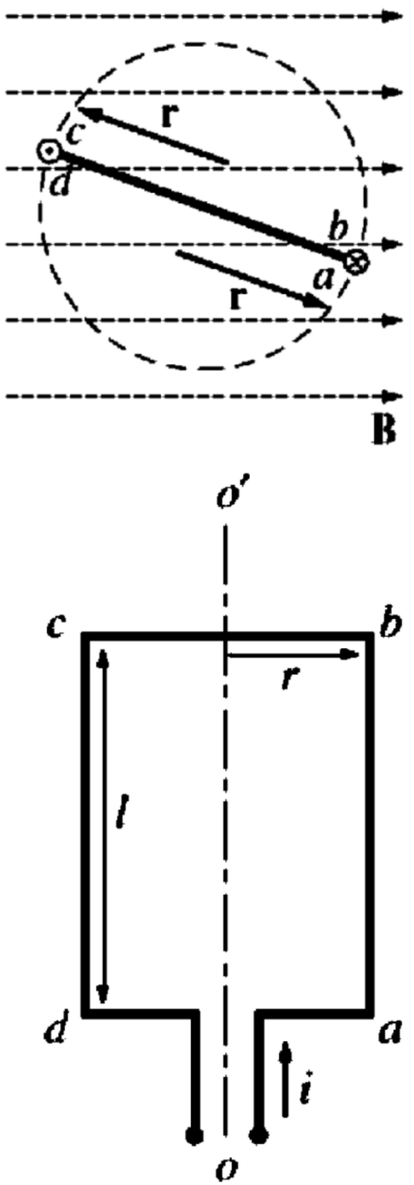
$$\tau_{bc} = (F)(r \sin \delta_{bc}) = 0$$

$$\tau_{da} = (F)(r \sin \delta_{da}) = 0$$

- Vector *r* and *l* are parallel





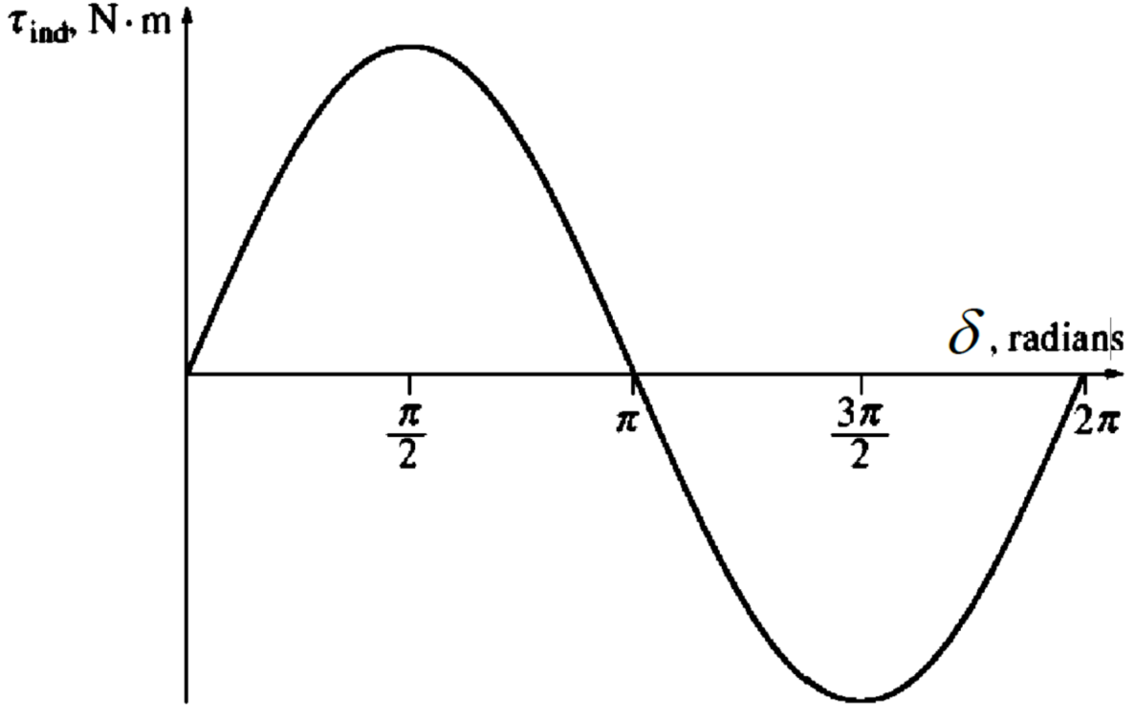


Torque Induced in a Current-carrying Loop

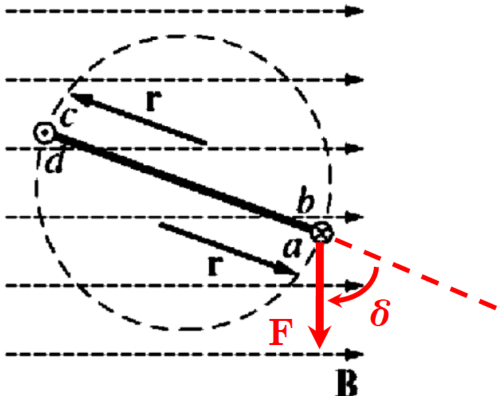
- The total induced torque

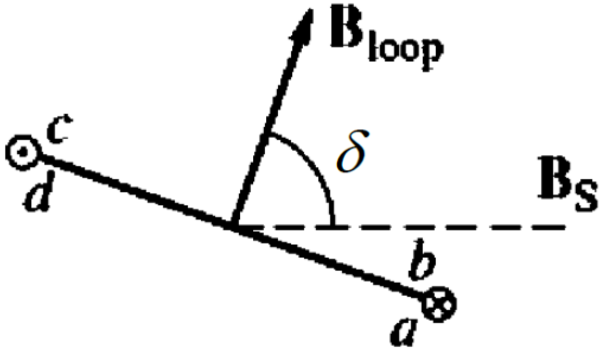
$$\begin{aligned}\tau_{\text{ind}} &= \tau_{ab} + \tau_{bc} + \tau_{cd} + \tau_{da} \\ &= rilB\sin\delta_{ab} + rilB\sin\delta_{cd} \\ &= 2rilB\sin\delta\end{aligned}$$

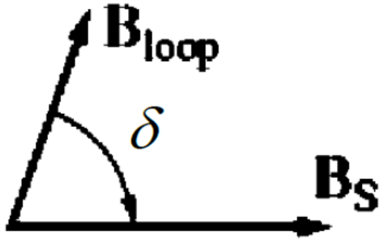
- Because δ_{ab}=δ_{cd}



Torque Induced in a Current-carrying Loop







$$B_{\text{loop}} = \frac{\mu i}{G}$$

$$\tau_{\text{ind}} = 2rilB \sin \delta$$

$$\tau_{\text{ind}} = \frac{AG}{\mu} B_{\text{loop}} B_S \sin \delta$$

$$= kB_{\text{loop}} B_S \sin \delta$$

- ❑ There is an alternative way to express the torque equation

$$\tau_{\text{ind}} = kB_{loop} B \sin \delta$$

Where A is just equal to $2rl$
G is a factor that depends on the geometry of the loop

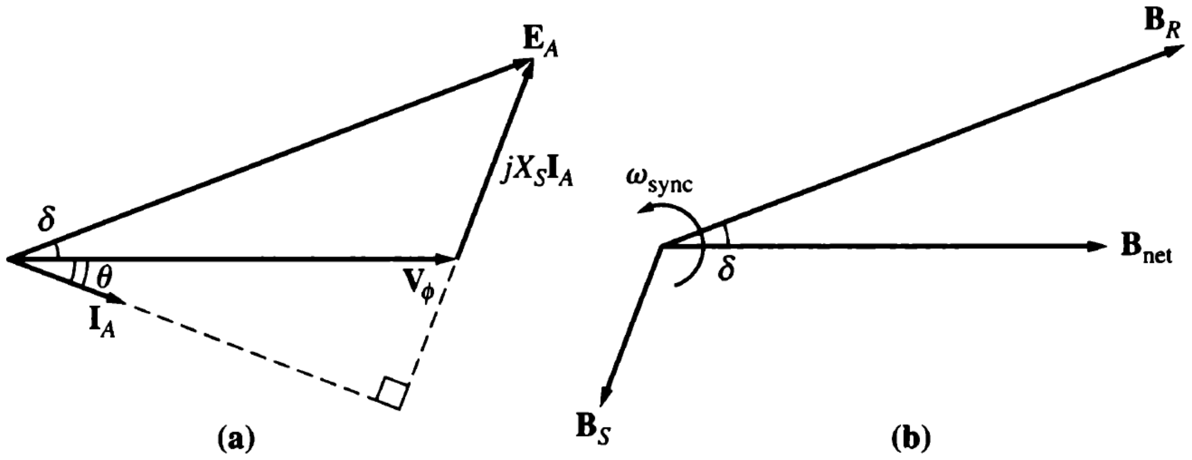
- ❑ where k is a factor depending on the construction of the machine. It can be further expressed as

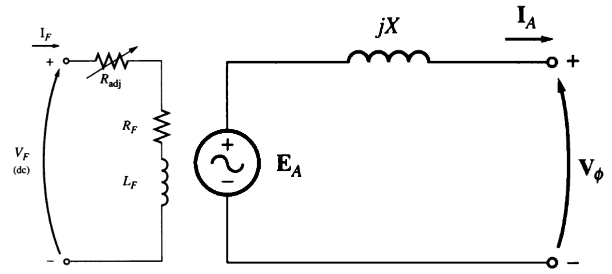
$$k = \frac{A_R G}{\mu}$$

How a Generator Becomes a Motor?

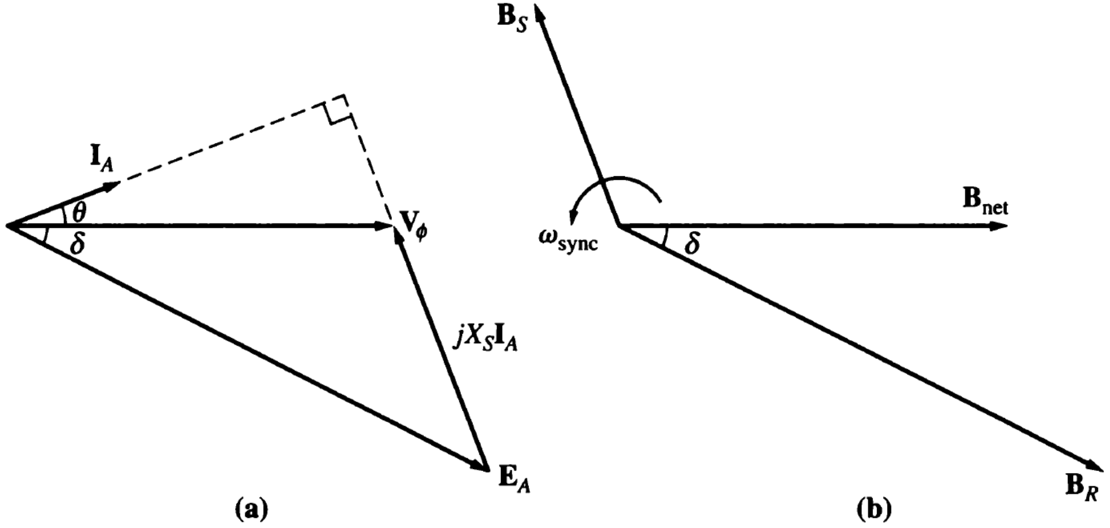
- Assume that a synchronous generator has a prime mover turning its shaft, causing it to rotate.
- Suppose the prime mover suddenly loses power and starts to drag on the machine's shaft.
- The rotor slows down and falls behind the net magnetic field B_{net} in the machine.
- The rotor magnetic field B_R falls behind the B_{net}.
- The increasing torque angle results in a larger and larger torque in the direction of rotation, until motor's induced torque equals the load torque on its shaft.
- Machine will be operating at steady state and synchronous speed again, but now as a motor.

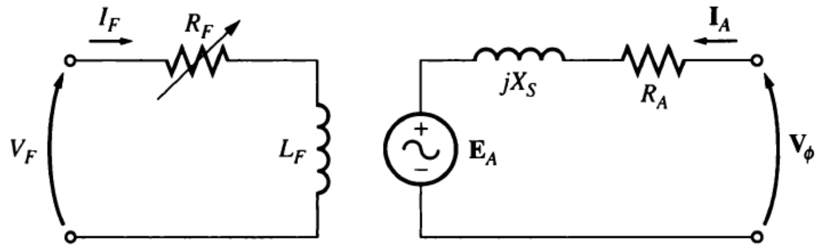
How a Generator Becomes a Motor?





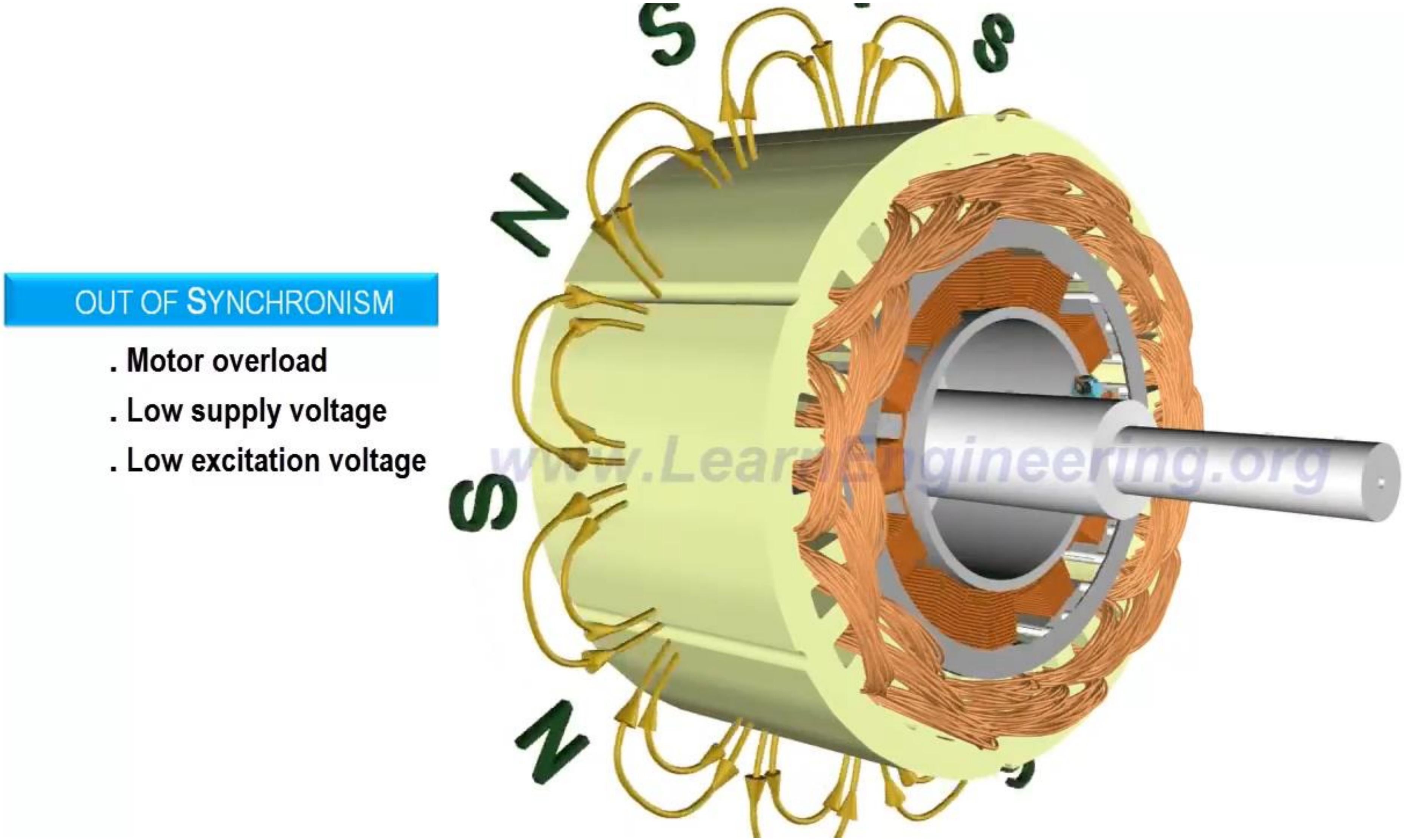
(a) Phasor diagram of a synchronous generator operating at a lagging power factor.
(b) The corresponding magnetic field diagram.





(a) Phasor diagram of a synchronous motor. (b) The corresponding magnetic field diagram.

Synchronous Motors



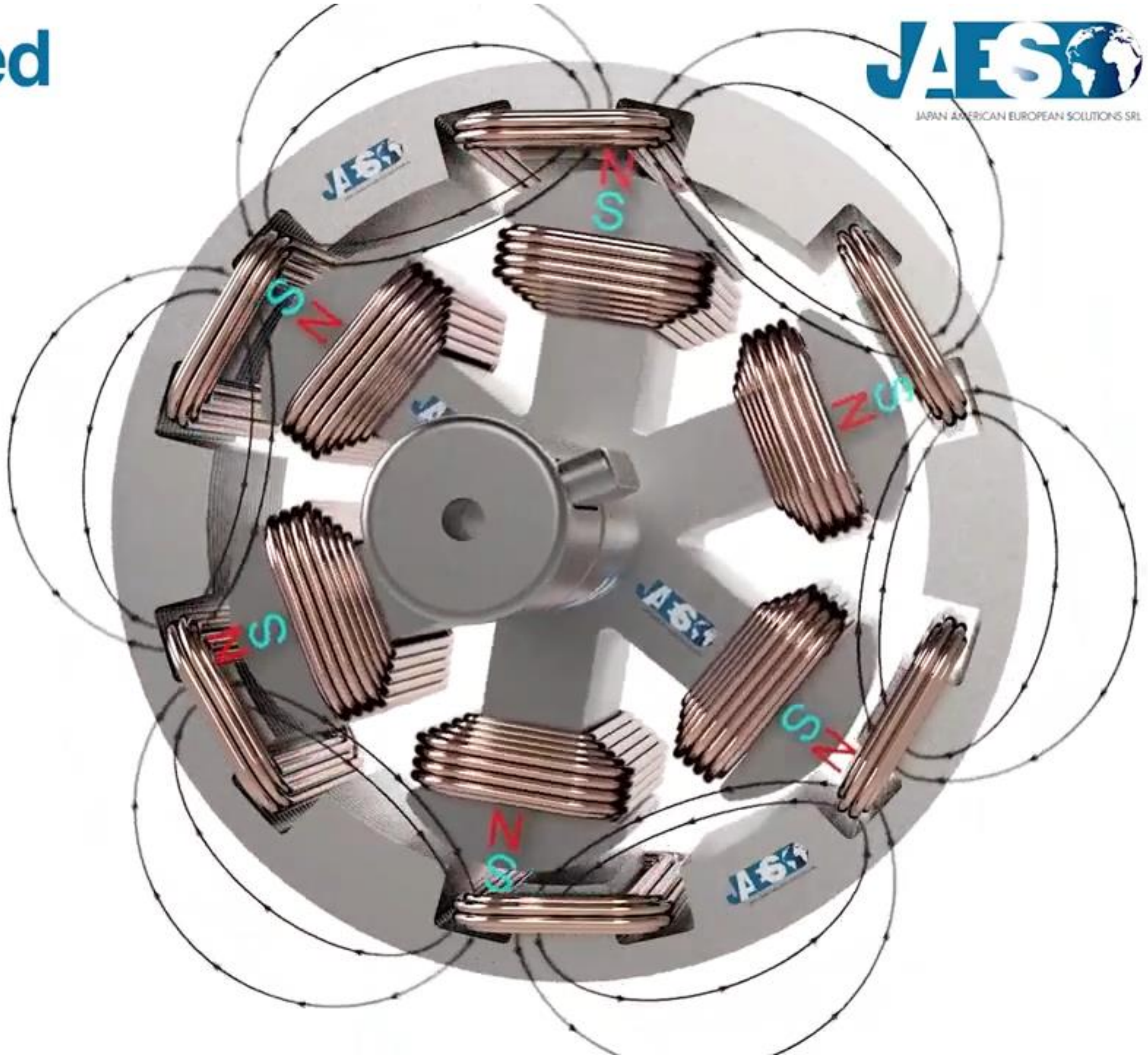
https://www.youtube.com/watch?v=Vk2jDXxZIhs

Synchronous Motors

synchronous speed

$$N_{s\,(RPM)} = 60\,\frac{f_{(Hz)}}{P}$$

$$\omega_{s\,(rad/s)} = 2\pi\,\frac{f_{(Hz)}}{P}$$

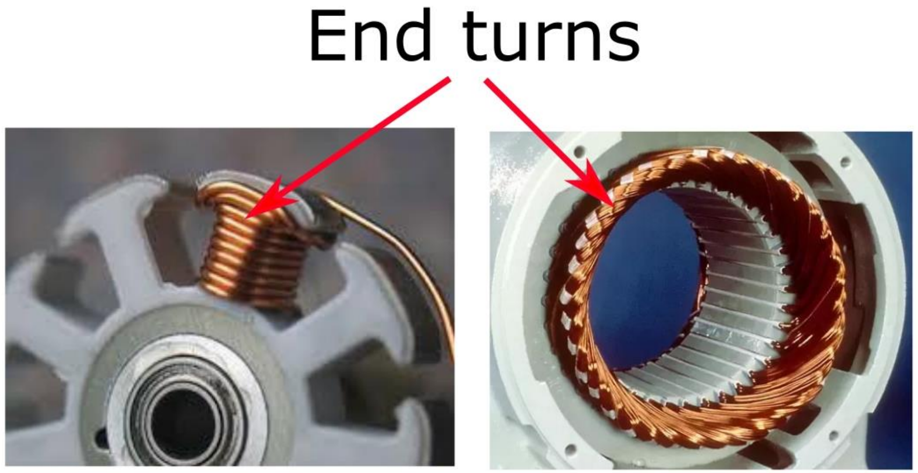


https://www.youtube.com/watch?v=Vk2jDXxZIhs

Motor windings in Synchronous Motors

Key Differences

Feature	Concentrated Winding	Distributed Winding
Structure	Wound around a single tooth	Spread over multiple slots
Back-EMF	Trapezoidal	Sinusoidal
Torque Ripple	Higher	Lower
End Windings	Short	Long
Manufacturing	Simple	Complex



Concentrated winding

Distributed winding

- **Advantages:** Shorter end-windings (lower copper usage), higher efficiency in specific designs, and easier to manufacture.
- **Applications:** Suitable for motors with shorter axial length and large diameter, such as servo motors.
- **Disadvantages:** Higher harmonic content, higher torque ripple, and, in some cases, lower efficiency.

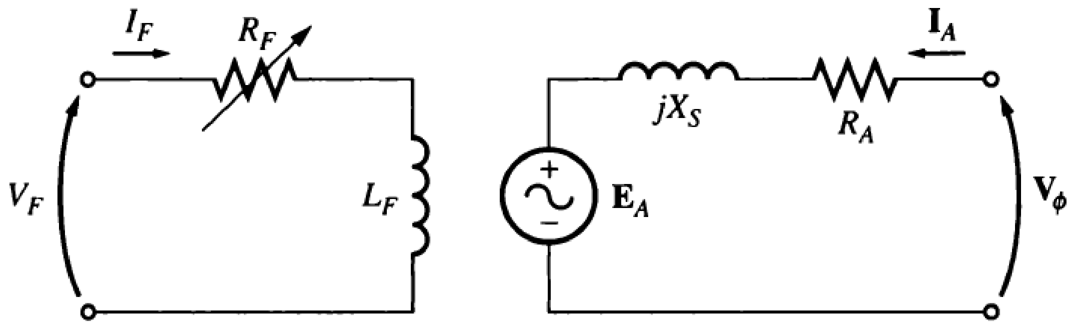
- **Advantages:** Produces a near-sinusoidal back-EMF, lower harmonic content, reduced torque ripple, and better thermal management.
- **Applications:** Ideal for high-speed, high-efficiency, and low-vibration applications.
- **Disadvantages:** Longer end-windings (larger copper usage) and more complex manufacturing

Equivalent Circuit of Synchronous Motor

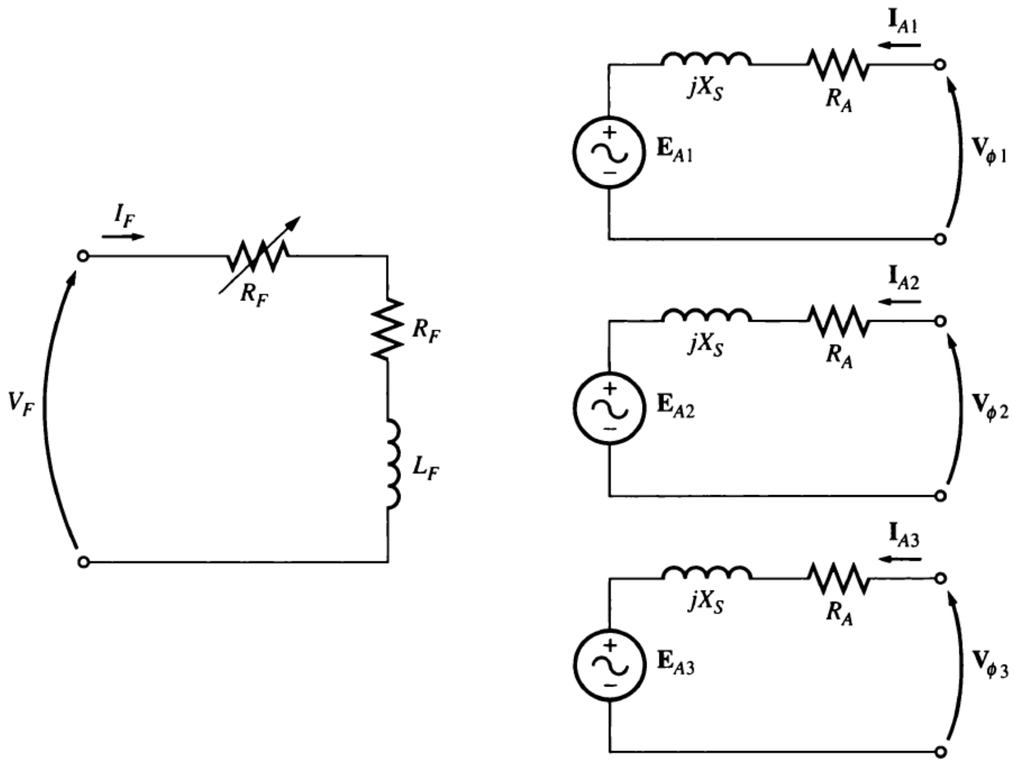
- The equivalent circuit of a synchronous motor is exactly the same as the equivalent circuit of a synchronous generator, except that the reference direction of I_A is reversed
- Kirchhoff's voltage law equation

$$\mathbf{V}_\phi = \mathbf{E}_A + jX_S\mathbf{I}_A + R_A\mathbf{I}_A$$

$$\mathbf{E}_A = \mathbf{V}_\phi - jX_S\mathbf{I}_A - R_A\mathbf{I}_A$$



The per-phase equivalent circuit.



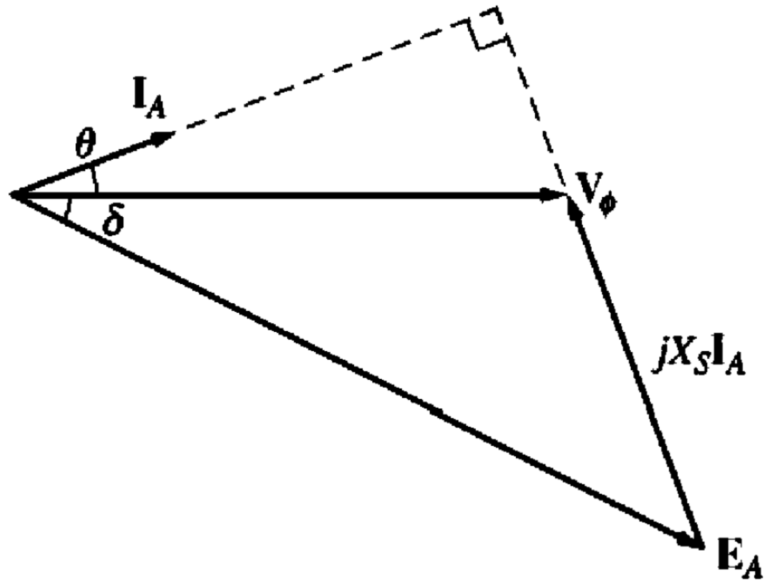
The full equivalent circuit of a three-phase synchronous motor.

Electric Power and Torque

- The real and reactive electric input power can be expressed in phase quantities as

$$P_{in} = 3V_\phi I_A \cos\theta$$

$$Q_{in} = 3V_\phi I_A \sin\theta$$



- Since

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

- Therefore

$$P_{in} = \frac{3V_\phi E_A \sin\delta}{X_S}$$

$$P_{in} = \tau\omega_m$$

$$\tau = \frac{3V_\phi E_A \sin\delta}{X_S \omega_m}$$

Electric Power and Torque

- The maximum of pullout torque of the motor is given by

$$\tau_{\max} = \frac{3V_{\phi}E_{A}}{X_{S}\omega_{m}}$$

- When the torque on the shaft of a synchronous motor exceeds the pullout torque, the rotor can no longer remain locked to the stator and net magnetic fields. The rotor starts to slip behind them.
- As the rotor slows down, the stator magnetic field "laps" it repeatedly, and the direction of the induced torque in the rotor reverses with each pass. The resulting huge torque surges, first one way and then the other way, cause the whole motor to vibrate severely.

The Effect of Load Changes on a Synchronous Motor

- If a load is attached to the shaft of a synchronous motor, the motor will develop enough torque to keep the motor and its load turning at a synchronous speed.

- If the load on the shaft of the motor is increased, the rotor will initially slow down.

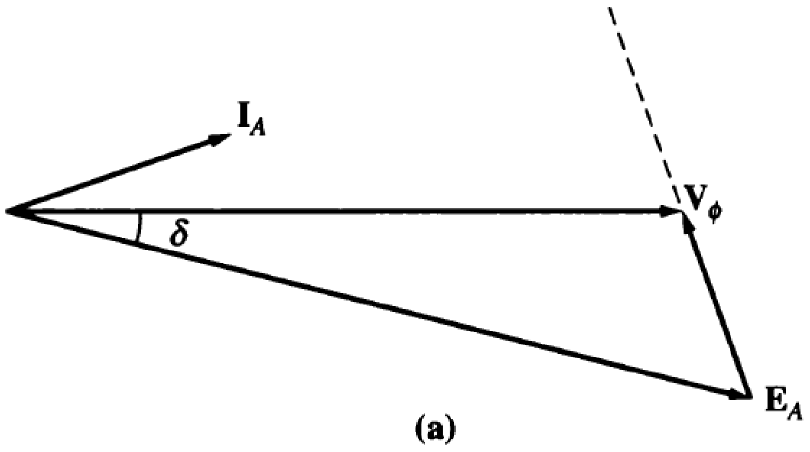
- The torque angle δ becomes larger, and the induced torque increases.

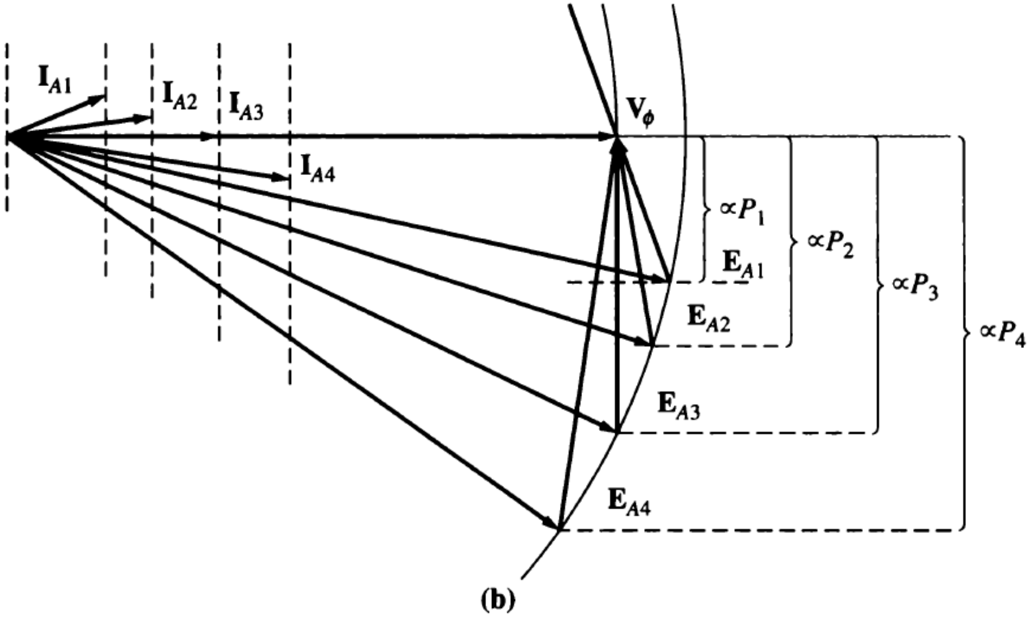
- The increase in induced torque eventually speeds the rotor back up, and the motor again turns at synchronous speed but with a larger torque angle δ.

The Effect of Load Changes on a Synchronous Motor

Note:

- E_A is equal to $K\phi\omega$ and so depends on only the field current.
- E_A sinδ proportional to power. I_A also increases.
- $|E_A|$ must be constant as the load changes.





(a) Phasor diagram of a motor operating at a leading power factor.
(b) The effect of an increase in load on the operation of a synchronous motor.

Example 3: Synchronous Motor Load Changed

- A 208 V, 45 kVA, Δ-connected, 60 Hz synchronous machine has a synchronous reactance of 2.5 Ω and a negligible armature resistance. Its friction and winding losses are 1.5 kW, and its core losses are 1.0 kW. Initially, the shaft is supplying a 15 hp load and the motor's power factor is 0.8 leading.

a) Sketch the phasor diagram of this motor, and find the values of I_A, I_{Line} and E_A.

b) Assume that the shaft load is now increased to 30 hp. Sketch the behavior of the phasor diagram in response to this change.

c) Find I_A, I_{Line} and E_A after the load change. What is the new motor power factor?

Example 3: Synchronous Motor Load Calculation

❑ Solution

(a) Initially, the motor's output power is 15 hp. This corresponds to an output of

$$P_{out} = (15)(0.746) = 11.19\ \text{kW}$$

Therefore, the electric power supplied to the machine is

$$P_{in} = P_{out} + P_{loss,mech} + P_{loss,core} = 11.19 + 1.5 + 1 = 13.69\ \text{kW}$$

Since the motor's power factor is 0.80 leading, the resulting line current flow is

$$I_{Line} = \frac{P_{in}}{\sqrt{3}V_T \cos\theta} = \frac{13.69}{\sqrt{3} \times 208 \times 0.8} = 47.5\ \text{A}$$

and the armature current is $I_L/\sqrt{3}$, with 0.8 leading power factor, which gives the result

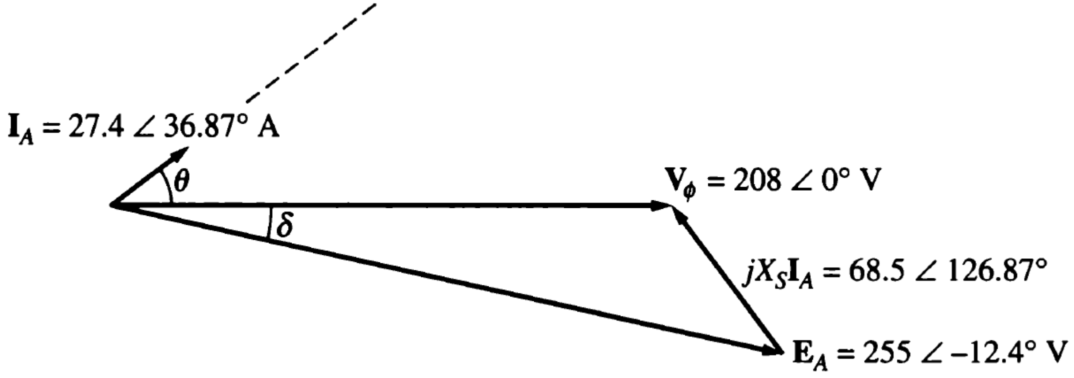
$$I_{Line}/\sqrt{3} = 47.5/\sqrt{3} = 27.4\angle 36.87^\circ\ \text{A}$$

To find E_A, apply Kirchhoff's voltage law

$$E_A = V_\phi - jX_S I_A = 208 \text{ -}j(2.5)(27.4\angle 36.87^\circ)$$

$$= 208 - 68.5\angle 126.87^\circ = 208 - (-41.1 + j54.8)$$

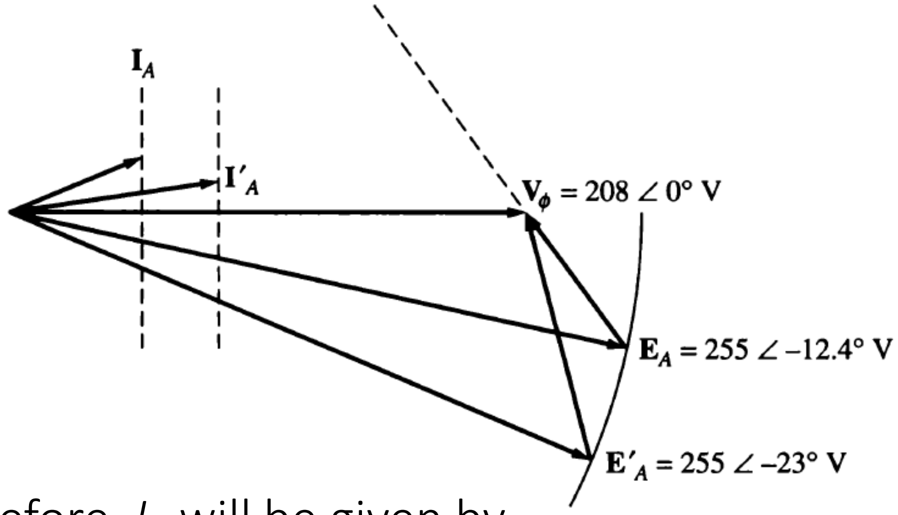
$$= 249.1 - j54.8 = 255.06\angle -12.41\ \text{V}$$



Example 3: Synchronous Motor Load Calculation

❑ Solution

(b) As the power on the shaft is increased to 30 hp, the shaft slows momentarily, and the internal generated voltage E_A swings out to a larger angle δ while maintaining a constant magnitude.



(c) After the load changes, the electric input power of the machine becomes

$$P_{in} = P_{out} + P_{loss,mech} + P_{loss,core} = 22.38 + 1.5 + 1 = 24.88\,\text{kW}$$

From the equation for power in terms of torque angle, it is possible to find the magnitude of the angle δ (remember that the magnitude of E_A is constant):

$$P_{in} = \frac{3V_\phi E_A \sin\delta}{X_S}$$

$$\delta = \sin^{-1}\frac{P_{in}X_S}{3V_\phi E_A} = \sin^{-1}\frac{24880 \times 2.5}{3 \times 208 \times 255} = 23°$$

The internal generated voltage thus becomes E_A

$$E_A = 255.06\angle -23°\,\text{V}$$

Therefore, I_A will be given by

$$I_A = \frac{V_T - E_A}{jX_S}$$

$$= \frac{208\angle 0 - 255\angle -23}{j2.5} = \frac{103.1\angle 105°}{j2.5} = 41.2\angle 15°\,\text{A}$$

New line current will become

$$I_{Line} = \sqrt{3}I_A = 71.4\,\text{A}$$

Finally, PF. is

$$\text{P.F.} = \cos(\quad 15°) = 0.966\ \text{leading}$$

The Effect of Field Current Changes on a Synchronous Motor

- The power supplied by the motor changes only when the shaft load torque changes.

- A change in I_F does not affect the shaft speed n_m and since the load attached to the shaft is unchanged, the real (active) power supplied is unchanged.

- An increase in field current increases the magnitude of E_A but does not affect the real (active) power supplied by the motor.

- The distances proportional to power on the phasor diagram ($E_A \sin \delta$) must therefore be constant.

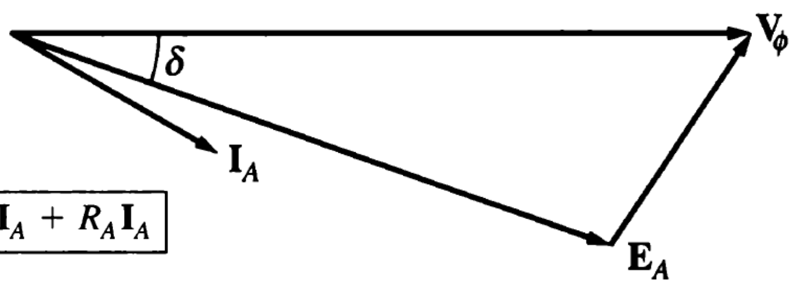
The Effect of Field Current Changes on a Synchronous Motor

Note:

- ❑ The I_A first decreases and then increases again, R_A ignored .
- ❑ At low E_A, I_A is lagging, the motor is an inductive load.
- ❑ As I_F is increased, the I_A eventually lines up with V_Φ, the motor looks purely resistive.
- ❑ At high E_A, I_A is leading, the motor is a capacitive load.

$$P_{in} = \frac{3V_\phi E_A \sin\delta}{X_S}$$

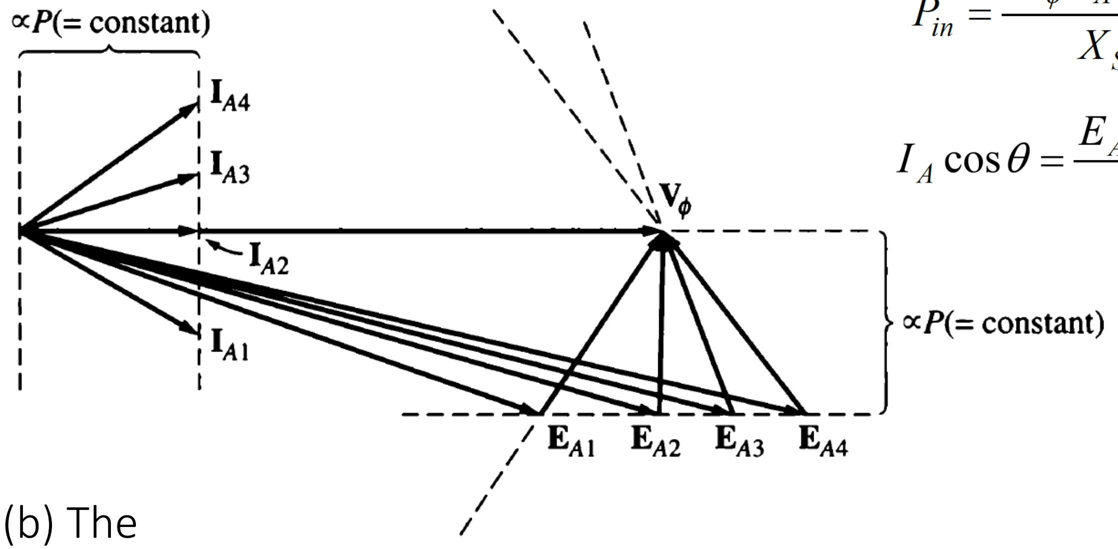
$$I_A \cos\theta = \frac{E_A \sin\delta}{X_S}$$



$$\mathbf{V}_\phi = \mathbf{E}_A + jX_S\mathbf{I}_A + R_A\mathbf{I}_A$$

$$\mathbf{E}_A = \mathbf{V}_\phi - jX_S\mathbf{I}_A - R_A\mathbf{I}_A$$

(a)

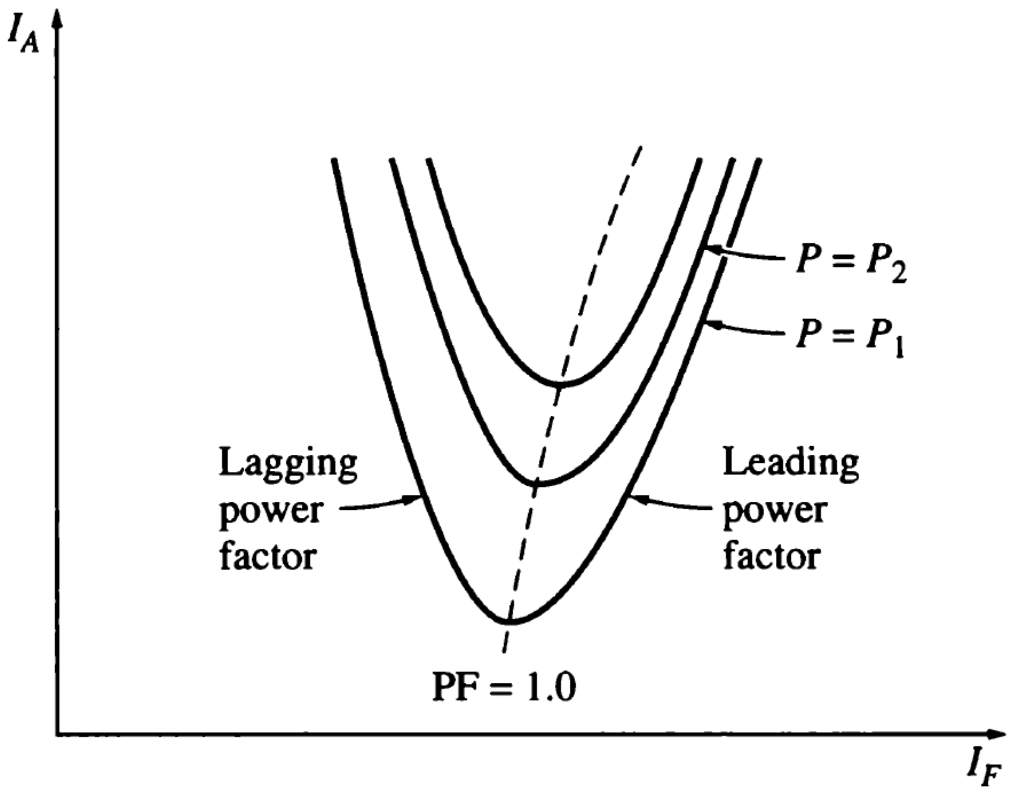


(b)

(a) A synchronous motor operating at a lagging power factor. (b) The effect of an increase in field current on the operation of this motor.

The Effect of Field Current Changes on a Synchronous Motor

- This plot is called synchronous motor V curve.
- Different V curves correspond to different real (active) power levels.
- Each curve, the minimum I_A occurs at PF=1. only real power is being supplied to the motor.
- When I_F is less than the value giving minimum I_A, the motor is underexcited and it consumes Q from the power system.
- When I_F is greater than the value giving minimum I_A, the motor is overexcited and it supplies Q to the power system.



Example 4: Synchronous Motor Field Current Changed

- A 208 V, 45 kVA, Δ-connected, 60 Hz synchronous machine has a synchronous reactance of 2.5 Ω and a negligible armature resistance. Its friction and winding losses are 1.5 kW, and its core losses are 1.0 kW. Initially, the shaft is supplying a 15 hp load and the motor's power factor is 0.85 lagging. The field current I_F at these conditions is 4 A.

  a) Sketch the phasor diagram of this motor, and find the values of I_A and E_A.

  b) If the motor's flux in increased by 25 percent, sketch the new phasor diagram of the motor. What are E_A, I_A and the PF of the motor?

Example 4: Synchronous Motor Field Current Changed

❑ Solution

(a) Initially, the motor's output power is 15 hp. This corresponds to an output of

$$P_{out} = (15)(0.746) = 11.19\ \text{kW}$$

Therefore, the electric power supplied to the machine is

$$P_{in} = P_{out} + P_{loss,mech} + P_{loss,core} = 11.19 + 1.5 + 1 = 13.69\ \text{kW}$$

Since the motor's power factor is 0.85 lagging, the resulting armature (phase) current flow is

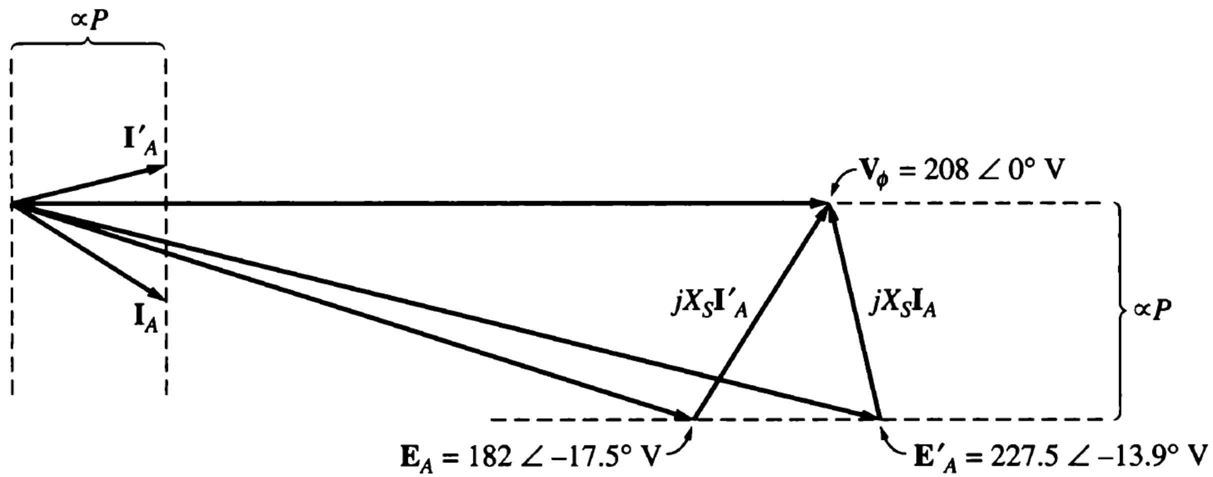
$$I_A = \frac{P_{in}}{3V_\phi \cos\theta} = \frac{13.69}{3 \times 208 \times 0.85} = 25.8\ \text{A}$$

The angle θ is $\cos^{-1} 0.85 = 31.8°$, so the phase current I_A is equal to $\mathbf{I_A} = 25.8 \angle -31.8°\ \text{A}$

To find E_A, apply Kirchhoff's voltage law

$$E_A = V_\phi - jX_S I_A = 208 - j(2.5)25.8 \angle -31.8°\ \text{A}$$

$$= 182 \angle -17.5°\ \text{V}$$



Example 4: Synchronous Motor Field Current Changed

❑ Solution

(b) If flux ϕ is increased by 25%, $E_A = K\phi\omega$ will increase by 25%

$$E_A = 1.25(182) = 227.5\ \text{V}$$

However, the power supplied to the load must remain constant. Since the distance EA sinδ is proportional to the power, that distance on the phasor diagram must be constant from the original flux level to the new flux level. Therefore

$$E_{A,1} \sin \delta_1 = E_{A,2} \sin \delta_2$$

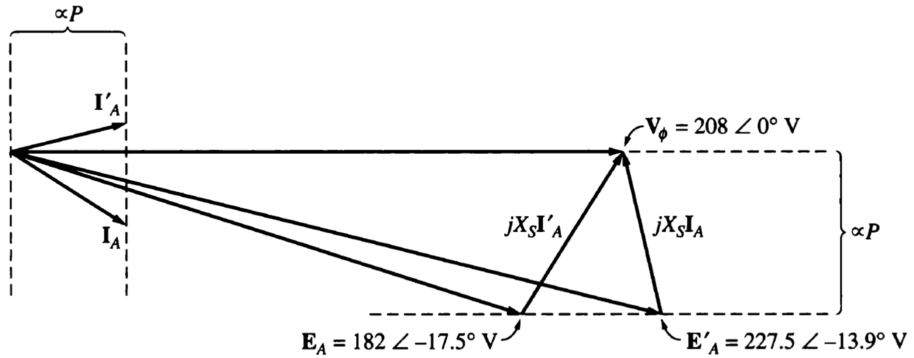
$$\delta_2 = \sin^{-1} \frac{E_{A,1} \sin \delta_1}{E_{A,2}} = \sin^{-1} \frac{182 \sin(-17.5°)}{227.5} = -13.9°$$

The armature current can now be found from Kirchhoff's voltage law:

$$I_{A,2} = \frac{V_\phi - E_{A,2}}{jX_S} = \frac{208 - 227.5\angle -13.69}{j2.5} = 22.5\angle 13.2° \text{A}$$

Finally, the motor's power factor is now

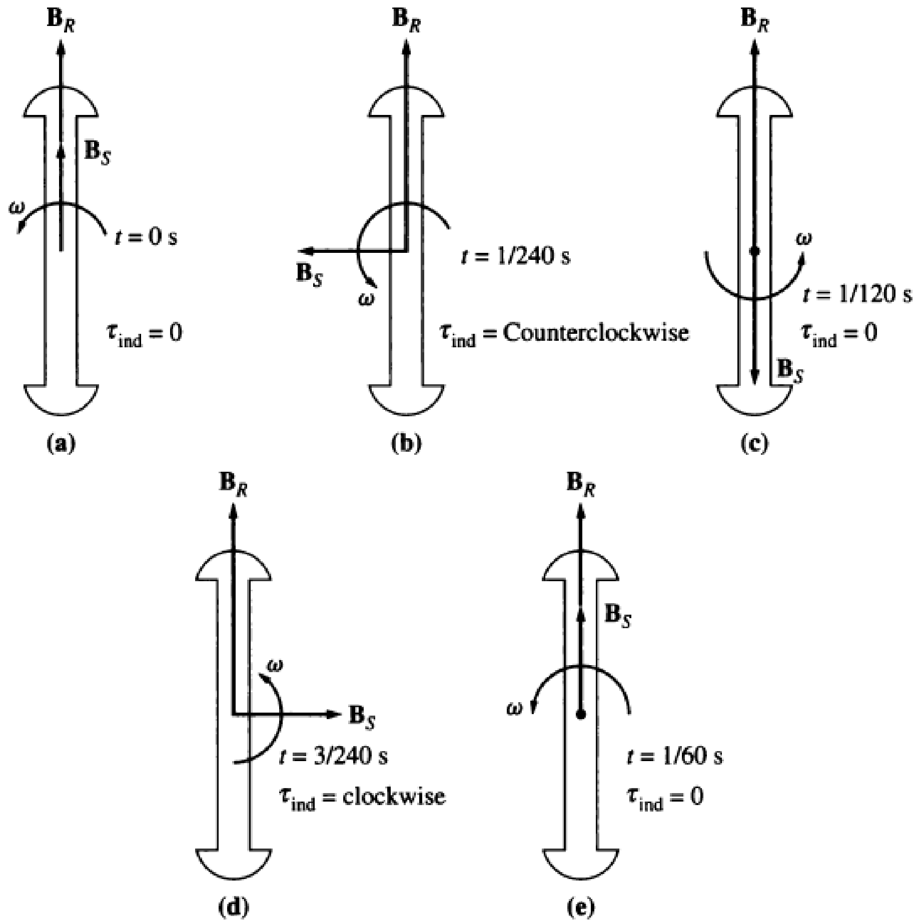
$$\text{PF} = \cos(13.2) = 0.974 \quad \text{(leading)}$$



Starting Synchronous Motors

- Previously, the motor was always assumed to be initially turning at synchronous speed. What has not yet been considered is the question: How did the motor get to synchronous speed in the first place?

$$\tau_{\text{ind}} = kB_{loop}B\sin\delta$$



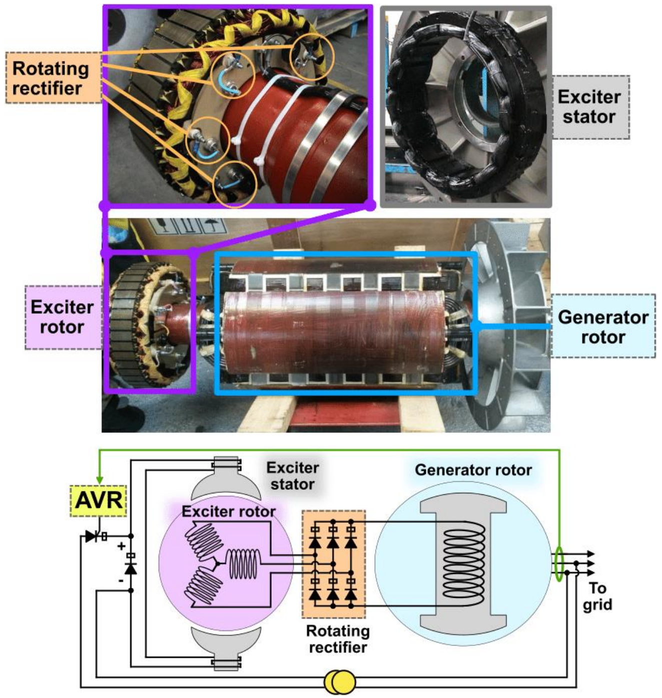
Starting problems in a synchronous motor—the torque alternates rapidly in magnitude and direction, so that the net starting torque is zero.

Synchronous Motor Starting by Reducing Electrical Frequency

- Reduce the speed of the stator magnetic field to a low enough value that the rotor can accelerate and lock in with it during one half-cycle of the magnetic field's rotation. This can be done by reducing the frequency of the applied electric power.
- This approach to starting synchronous motors makes a lot of sense.
- Solid-state motor controllers can be used to convert a constant input frequency to any desired output frequency. With the development of modem solid-state variable-frequency drive packages, it is perfectly possible to continuously control the electrical frequency applied to the motor all the way from a fraction of a hertz up to and above full rated frequency.
- With the help of advance motor controller, the starting of a synchronous motor is very easy—simply adjust the frequency to a very low value for starting, and then raise it up to the desired operating frequency for normal running.

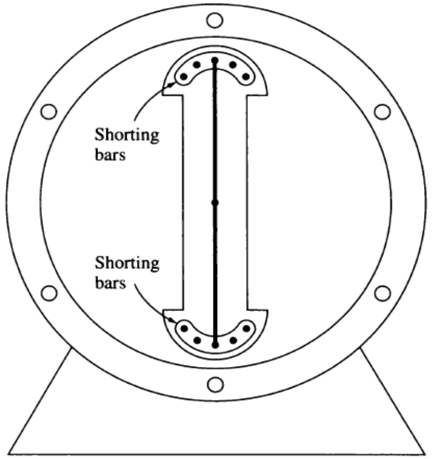
Synchronous Motor Starting with an External Prime Mover

- Use an external prime mover to accelerate the synchronous motor up to synchronous speed, go through the paralleling procedure, and bring the machine on the line as a generator. Then, turning off or disconnecting the prime mover will make the synchronous machine a motor.
- Since most large synchronous motors have brushless excitation systems mounted on their shafts, it is often possible to use these exciters as starting motors.
- For many medium-size to large synchronous motors, an external starting motor or starting by using the exciter may be the only possible solution, because the power systems they are tied to may not be able to handle the starting currents needed to use the amortisseur winding approach described next.



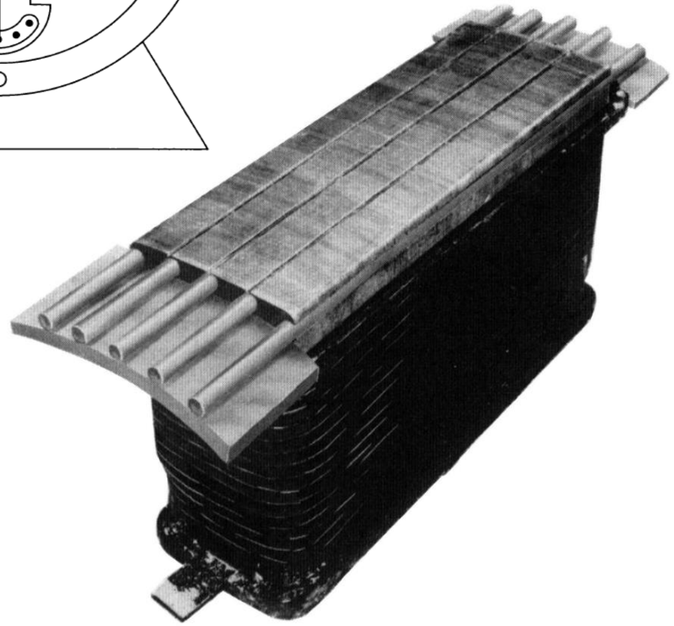
Synchronous Motor Starting by Using Amortisseur Windings

- Reduce the speed of the stator magnetic field to a low enough value that the rotor can accelerate and lock in with it during one half-cycle of the magnetic field's rotation. This can be done by reducing the frequency of the applied electric power.



- A popular way to start a synchronous motor is to employ amortisseur or damper windings. Amortisseur windings are special bars laid into notches carved in the face of a synchronous motor's rotor and then shorted out on each end by a large shorting ring.

- Although the motor's rotor will speed up, it can never quite reach synchronous speed. But getting close to synchronous speed will pull into step with the stator magnetic fields



Other Issues and Summary

- ❑ A synchronous motor can be operated without a load, simply for power factor correction (in the past).
- ❑ Synchronous machine can supply/consume real power or reactive power to/from a power system. All four combinations of real and reactive power flows are possible.
  - Generator mode: E_A lies ahead of V_ϕ.
  - Motor mode: E_A lies behind of V_ϕ.
  - Inductive mode (Lagging PF): $E_A \cos\delta < V_\phi$.
  - Capacitive mode (Leading PF): $E_A \cos\delta > V_\phi$.
- ❑ Synchronous motor cannot start direct-online.
- ❑ Use an external prime mover to accelerate the synchronous motor up to synchronous speed (generator mode). Then turning off the prime mover (motor mode).