EEE 322

Electromechanical Energy Conversion – II

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CHAPTER 3

SYNCHRONOUS MOTORS

Synchronous Motors

- **Synchronous motors** are synchronous machines used to convert AC electric power into mechanical power.
- **Synchronous motors** are required for **constant speed** applications.
- They are used

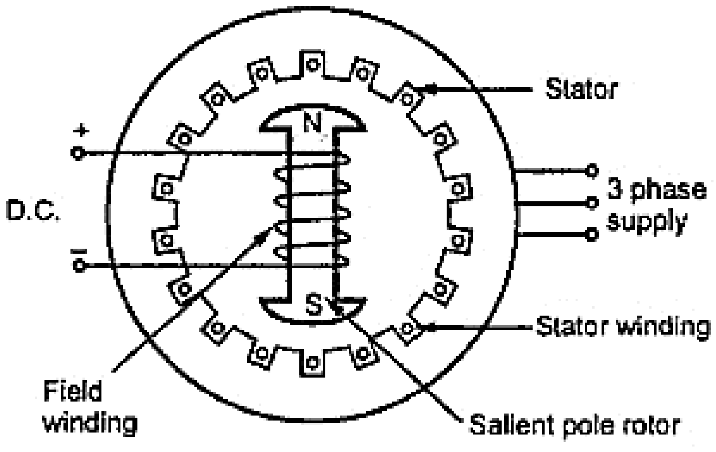
In conveyor belt applications

In ball mill in a mine ore process

In paper mills

Synchronous Motors

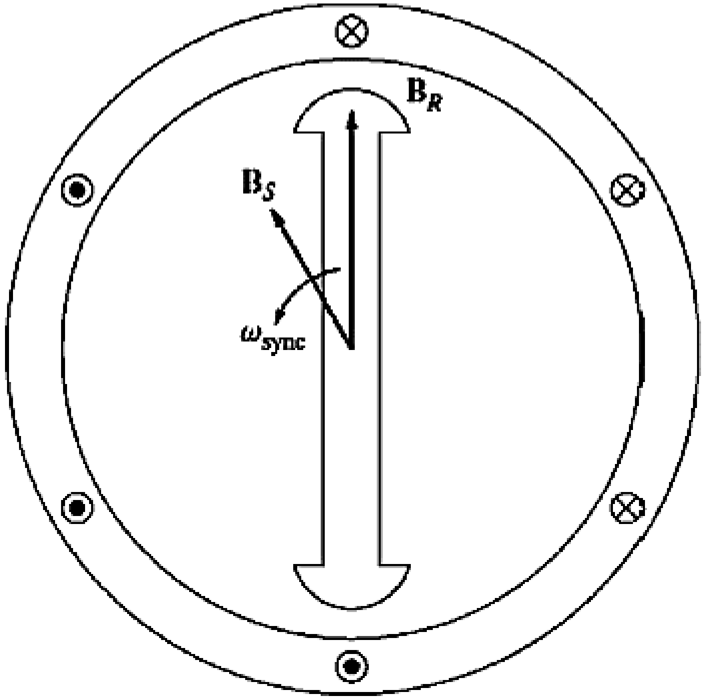
- Physically, **synchronous motors** **are exactly the same** as **synchronous generators.**



Schematic representation of three phase two-pole synchronous motor

Operation principle of synchronous motors

- The field current ***IF*** of the motor produces a steady-state magnetic field ***BR***.
- A three-phase set of voltages is applied to the stator, which produces a three-phase current flow in the windings.
- A three-phase set of currents in an armature winding produces a uniform rotating magnetic field ***Bs***.
- Therefore, there are **two magnetic fields** present in the machine.
- The rotor field will tend to line up with the stator field, just as two bar magnets will tend to line up if placed near each other.
- Since the stator magnetic field is rotating, the rotor magnetic field (and the rotor itself) will constantly try to catch up.
- The rotor "**chases**" the rotating stator magnetic field around in a circle, never quite catching up with it.



A two-pole synchronous motor

Per-phase equivalent circuit of sync. motor

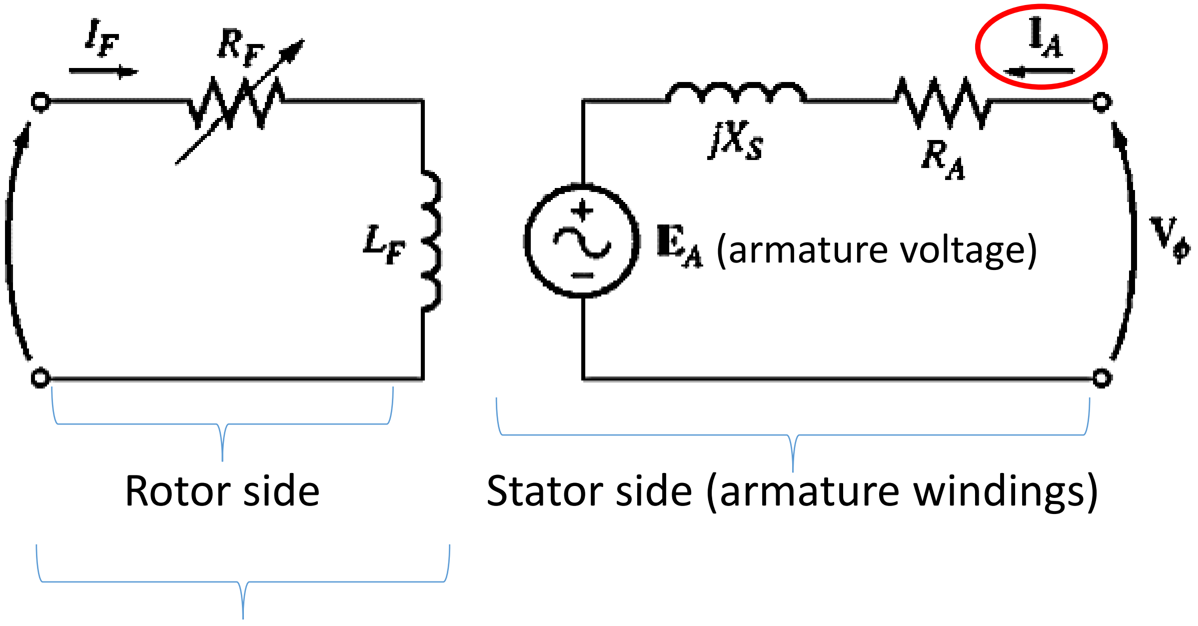
- A **synchronous motor** is the **same** in all respects as a **synchronous generator**, **except** that the **direction of power flow is reversed**.

- Since the **direction of power flow is reversed**, the **direction of current flow in the stator of the motor** is also **reversed**.

- Therefore, **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 armature current**.

- The stator of the synchronous motor can be either **wye** or **delta** connected.

Per-phase equivalent circuit of sync. motor



Field current (DC)

Armature current (AC)

DC voltage source for field circuit

(armature voltage)

Phase voltage (AC)

Rotor side

Stator side (armature windings)

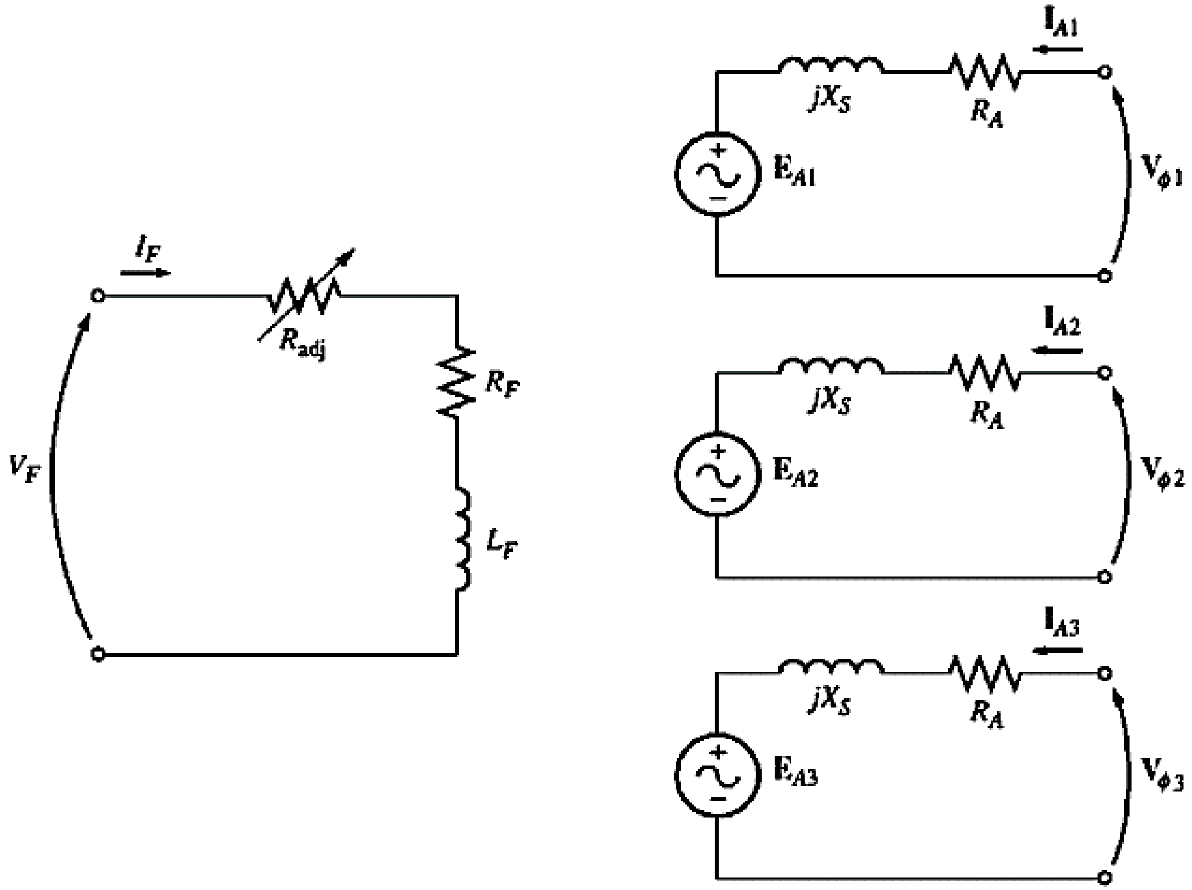
Field circuit

NOTE: By changing ***R***

$R_F \downarrow$ $I_F \uparrow$ $|E_A| \uparrow$

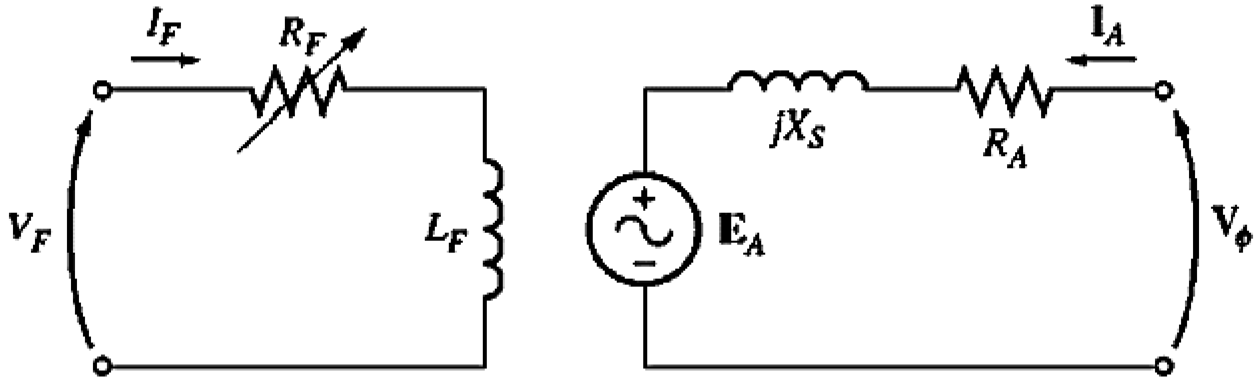
$R_F \uparrow$ $I_F \downarrow$ $|E_A| \downarrow$

Per-phase equivalent circuit of sync. motor



The full equivalent circuit of a three-phase synchronous motor

Per-phase equivalent circuit of sync. motor



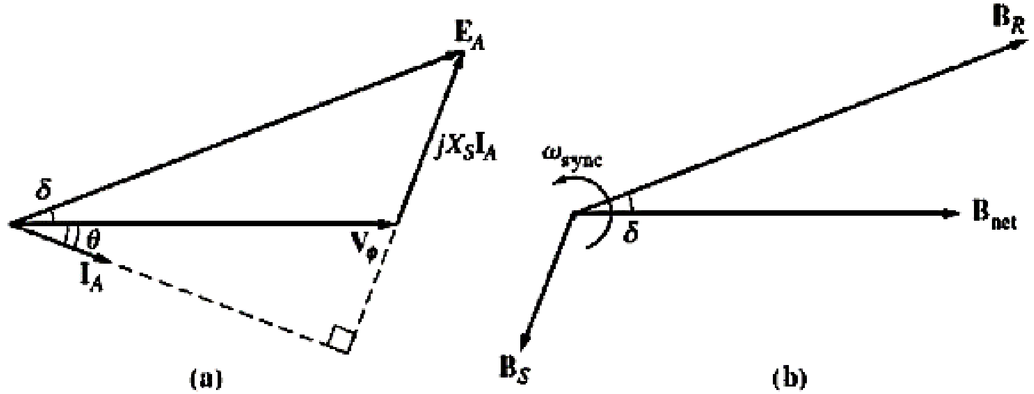
$$P_{in} = 3.V_{\emptyset}.I_A.cos\theta$$

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

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

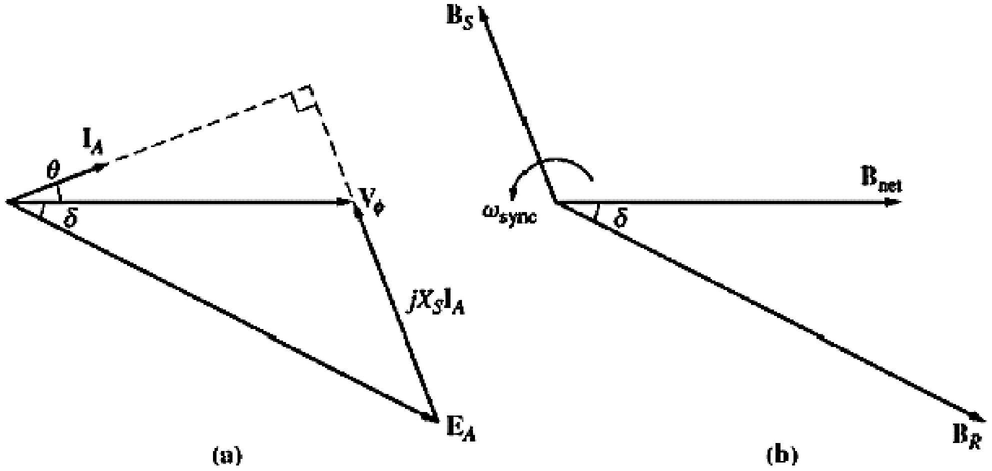
Voltage equations of the per-phase equivalent circuit of synchronous motor

Comparison of phasor diagrams of synch. gen. and motor



*Phasor diagram of a **synchronous generator** operating at a **lagging power factor** and the corresponding magnetic field diagram.*

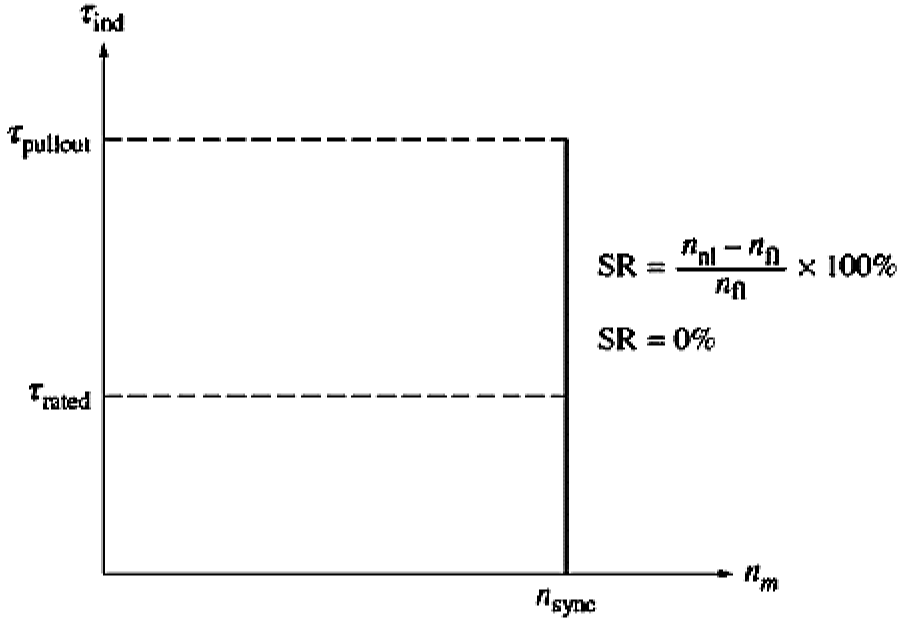
Transition from generator to motors occurs when **the prime mover torque is removed**



*Phasor diagram of a **synchronous motor** operating at a **leading power factor** and the corresponding magnetic field diagram.*

Synchronous motor torque-speed characteristics

- **Synchronous motors** supply power to electrical loads that are basically **constant-speed devices**.
- **Synchronous motors** are usually connected to **infinite buses**. This means that the **terminal voltage** and **system frequency** will be **constant** regardless of the amount of power drawn by the motor.
- 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 amount of the load.
- Since the **speed of the motor is constant**, its **speed regulation is zero**.



The torque-speed characteristic of a synchronous motor

Torque equations of synchronous motor

- **Induced torque** of the synchronous motor (*ignoring armature resistance*):

$$\tau_{ind} = \frac{3V_{\emptyset}E_A sin\delta}{w_m X_s}$$

- **Maximum (*pull-out*)** induced torque occurs when $\delta = 90°$

$$\tau_{ind(max)} = \frac{3V_{\emptyset}E_A}{w_m X_s}$$

- Normally, **full-load torque** of the synchronous motor is **much less** than maximum induced torque.

$$\tau_{(full-load)} \ll \tau_{ind(max)}$$

- In fact, the **pullout torque** may typically be **3 times** the **full-load torque** of the motor.

$$\tau_{ind(max)} \approx 3\ x\ \tau_{(full-load)}$$

“Loss of synchronism” of synchronous motor

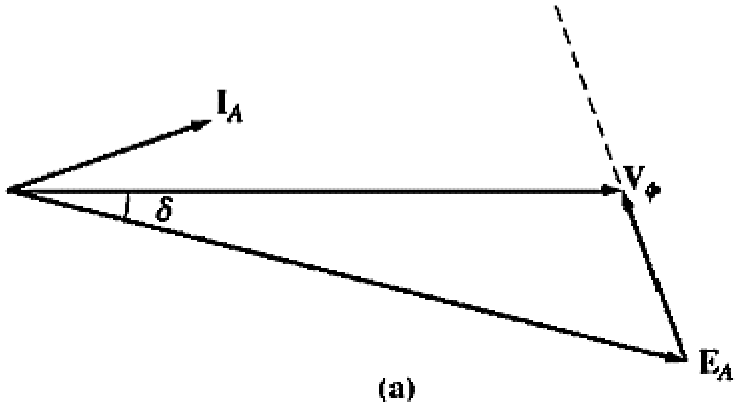
- When the **torque on the shaft of a synchronous motor** (*load torque*) exceeds the **pullout torque**, the rotor can no longer remain locked to the stator.
- Instead, the rotor starts to **slip behind** rotating stator magnetic field (Bnet).
- As the **rotor slows down**, the stator magnetic field "**laps**" it repeatedly, and cause the whole motor to **vibrate** severely.
- **The “loss of synchronization”** after the pullout torque is exceeded is known as “***slipping poles***”.
- Since maximum induced torque is proportional to E_A, the larger E_A (hence the larger **field current, *IF***) gives a stability advantage to the synchronous motor.
- Therefore it is usually better to operate the synchronous motor with a **large field current, *IF***.

$$\uparrow \tau_{ind(max)} = \frac{3V_{\emptyset}E_A}{w_m X_s} \uparrow$$

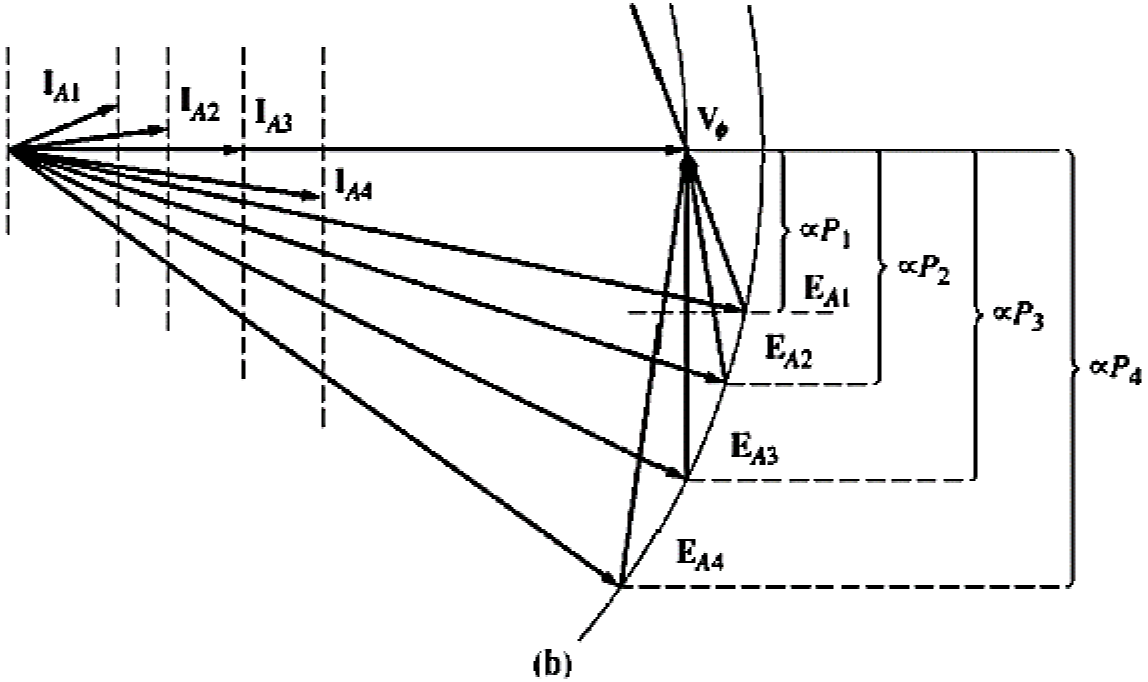
Effect of load changes on a synchronous motor

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

- What happens when the **load is changed** on a synchronous motor? (***Field current is kept constant***)



*Phasor diagram of a sync. motor operating at a **leading power factor***



*The effect of an **increase in load** on the operation of a synchronous motor*

Effect of load changes on a synchronous motor: An example

Example: A **208-V**, **45-kVA**, **0.8-PF-leading**, **delta-connected**, **60-Hz synchronous motor** has a synchronous reactance of **2.5 ohm**, and a **negligible armature resistance**. Its friction and windage 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 lA, IL, and EA.

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

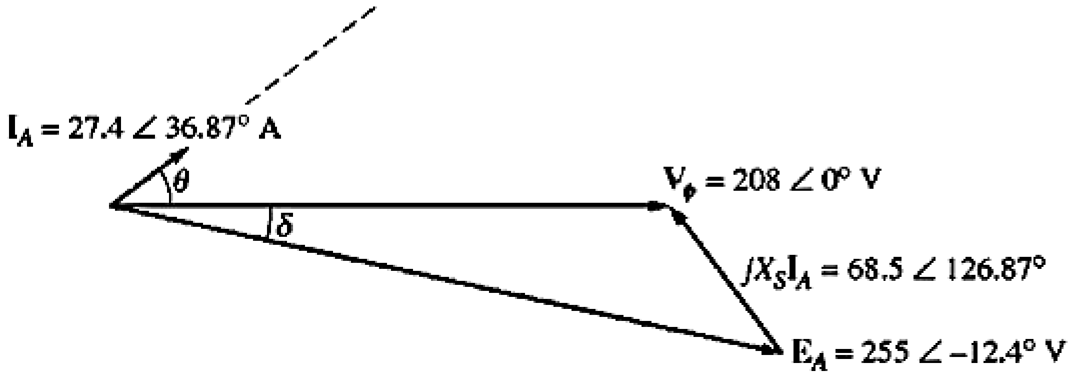
(c) Find lA, IL, and EA after the load change. What is the new power factor of the motor?

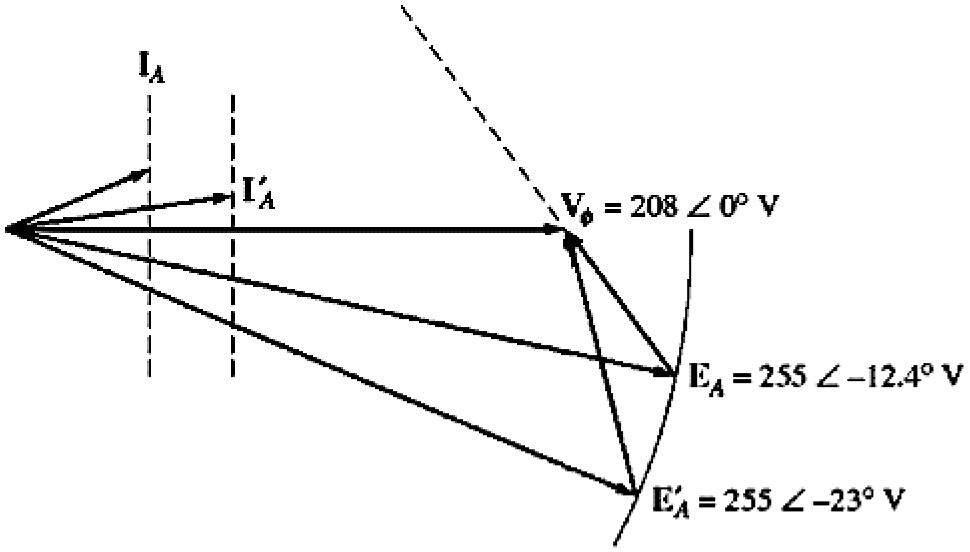
$$P_{in} = 3V_{\emptyset}\frac{E_A sin\delta}{X_S}$$

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

Effect of load changes on a synchronous motor: An example

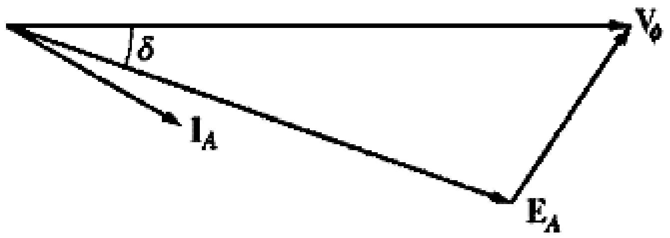
Solution: Resultant phasor diagrams of the synchronous motor under increasing load



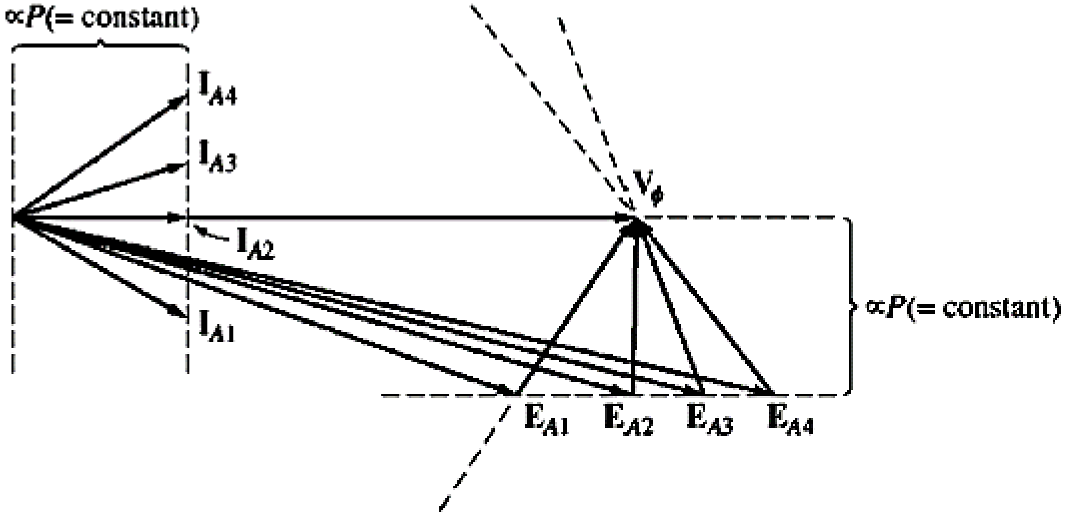


Effect of field current changes on sync. motor

- What happens when the field current of the synchronous motor changes ? (***load is constant***)



A synchronous motor operating at a ***lagging power factor***

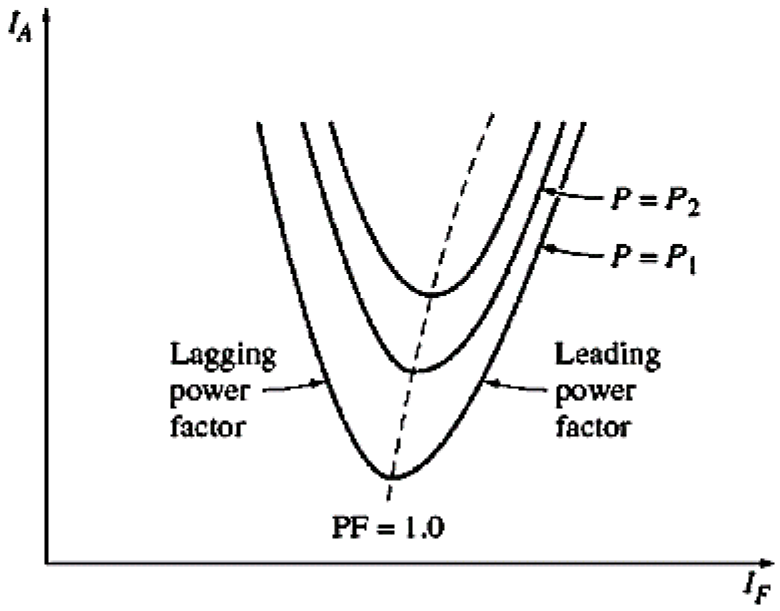


The effect of an ***increase in field current*** *on the operation of this motor.*

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

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

Synchronous motor V curves

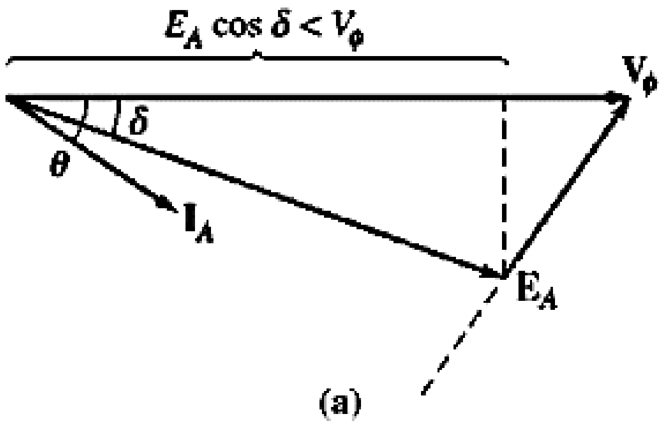


Synchronous motor V curves.

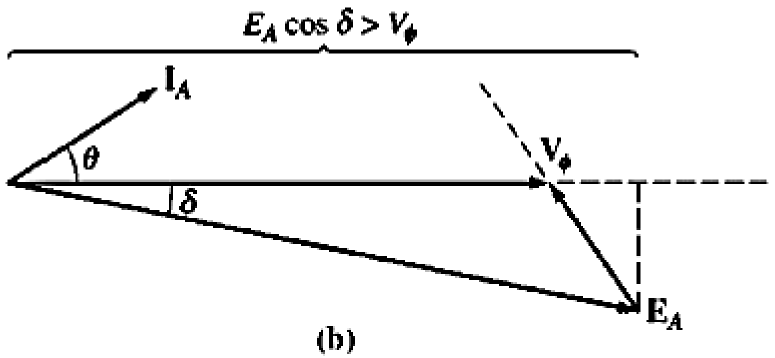
$P_2 > P_1$

While the load is kept constant, **controlling the field current** of a synchronous motor will **change the reactive power supplied or consumed by the motor to or from the power system**.

Underexcited vs overexcited cases

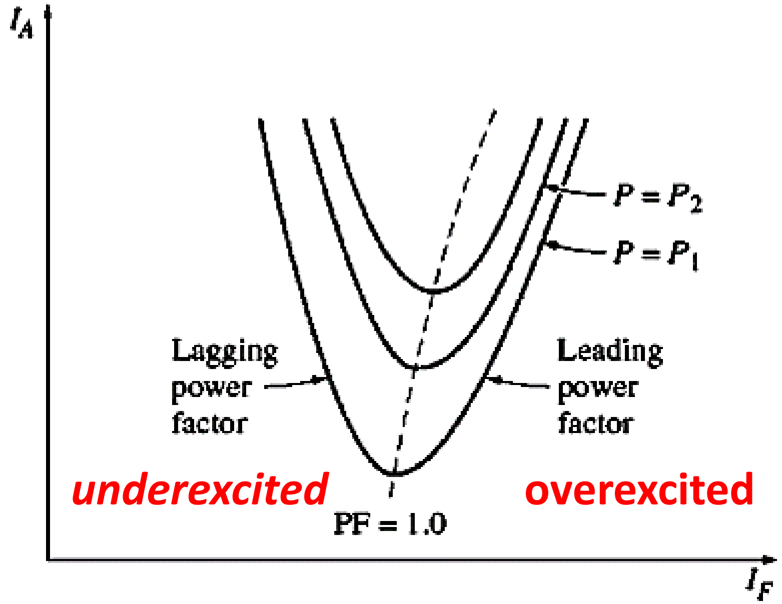


The phasor diagram of an ***underexcited*** *synchronous motor.*



The phasor diagram of an **overexcited** synchronous motor.

Underexcited vs overexcited cases



Synchronous motor V curves.

Effect of field current change on a synchronous motor: An example

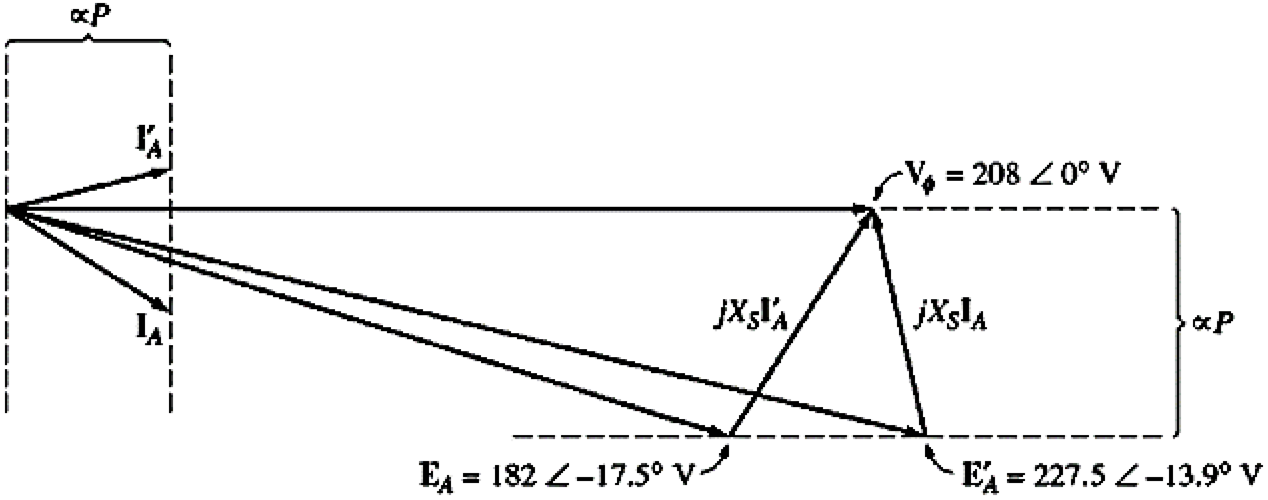
Example: The **208-V**, **45-kVA**, **0.8 PF-leading**, **delta-connected**, **60-Hz** synchronous motor of the previous example is supplying a **15-hp load** with an initial power factor of **0.85 PF lagging**. The **field current** at these conditions is **4.0 A**.

(a) Sketch the initial phasor diagram of this motor, and find the values of ***IA*** and ***EA***.

(b) If the **motor's flux is increased by 25 percent**, sketch the new phasor diagram of the motor. What are ***EA, IA***, and **the power factor of the motor** now?

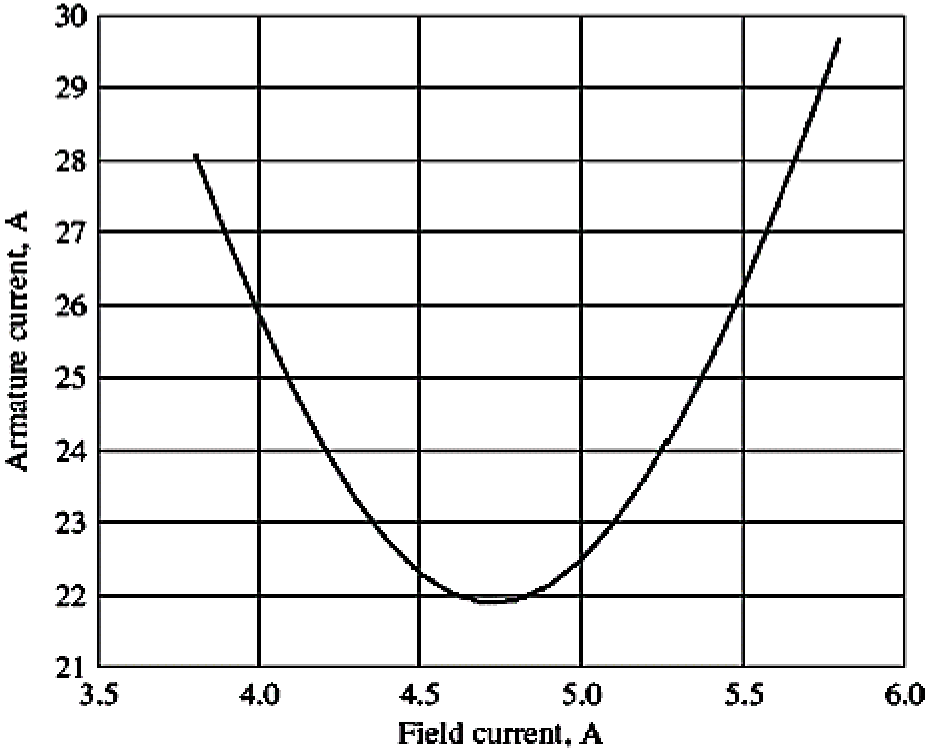
Effect of field current change on a synchronous motor: An example

Solution:



The phasor diagram of the motor in Example

Effect of field current change on a synchronous motor: An example

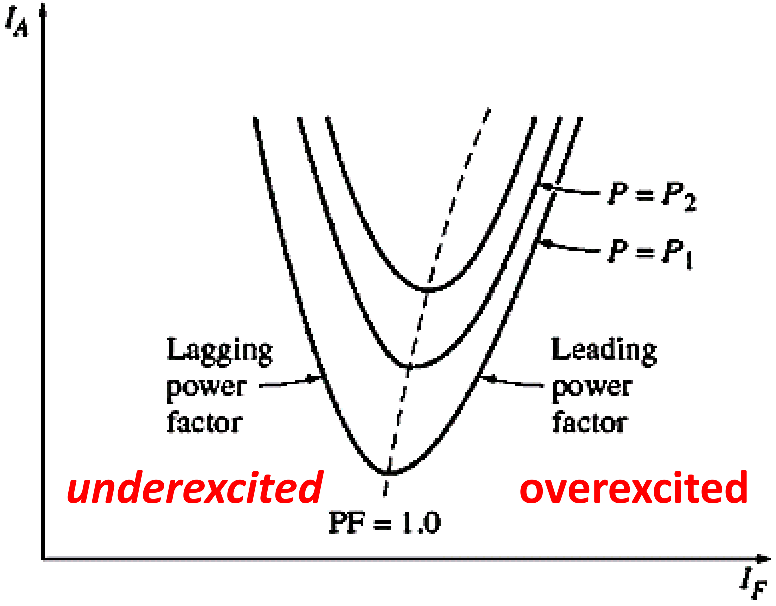


V curve of the synchronous motor in the example

Synchronous motor and power factor correction

- We have seen so far that the **power factor of the synchronous motor** can be controlled by **changing the field current** (*See the figure*).

- So if a **synchronous motor** is operated with an electrical load (or a group of loads), it can be used for **reactive power compensation (*power factor correction*) while it is rotating**.



Synchronous motor V curves.

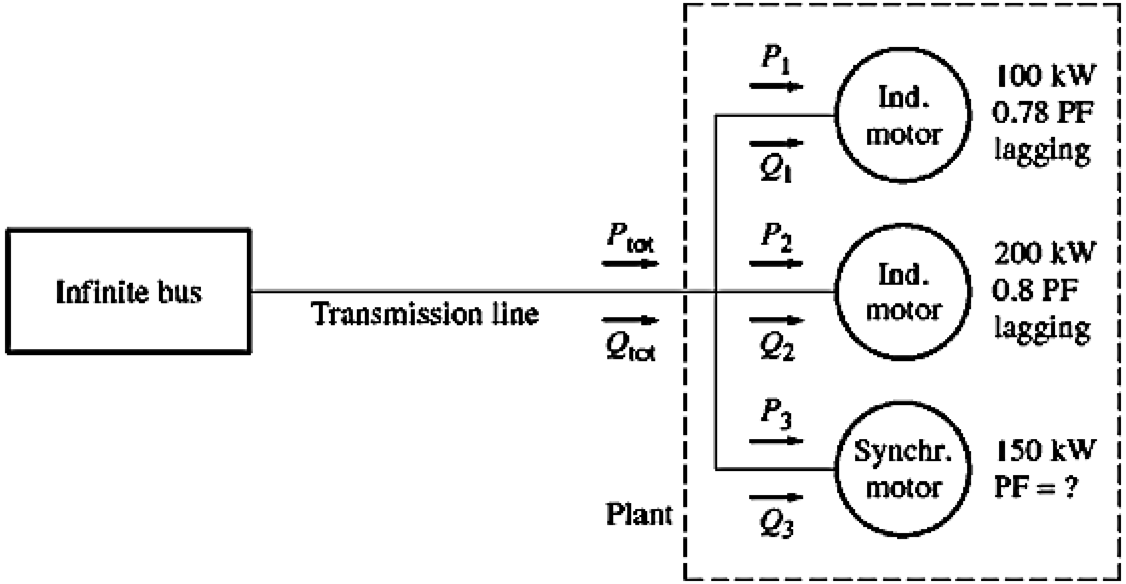
Synchronous motor and power factor correction: An example

The infinite bus in the figure operates at **480 V**. Load 1 is an induction motor consuming **100 kW** at **0.78 PF lagging**, and load 2 is an induction motor consuming **200 kW** at **0.8 PF lagging**. Load 3 is a **synchronous motor** whose real power consumption is **150 kW**.

(a) If the synchronous motor is adjusted to operate **at 0.85 PF lagging**, what is the transmission line current in this system?

(b) If the synchronous motor is adjusted to operate at **0.85 PF leading**, what is the transmission line current in this system?

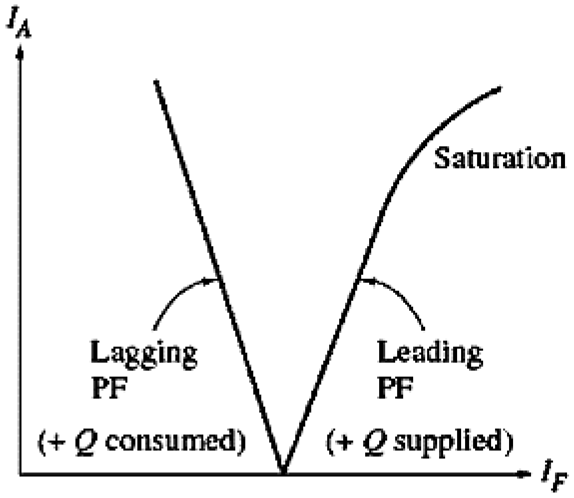
(c) How do the transmission losses compare in the two cases?



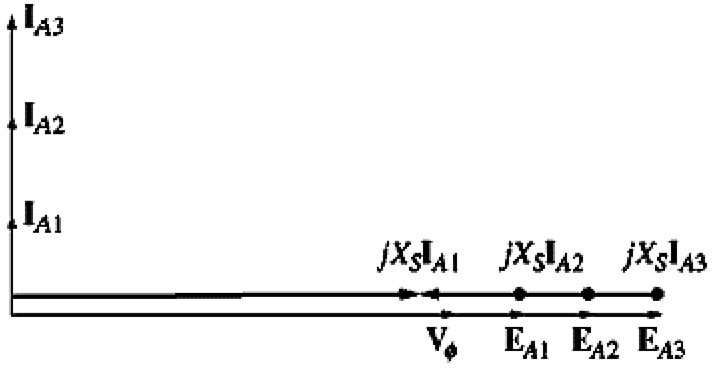
A simple power system consisting of an infinite bus supplying an industrial plant through a transmission line.

Synchronous condenser

- **Synchronous condenser** (or *synchronous capacitor*) is a synchronous motor **without a mechanical load attached to its shaft**.
- **Synchronous condenser** is used for **reactive power compensation** (***power factor correction***).
- If its **field current is increased,** the power factor of the machine changes from **lagging-to-unity-to-leading power factor**



The V curve of a synchronous condenser



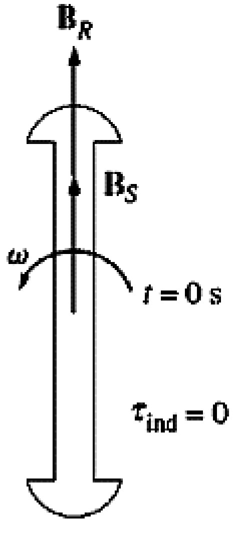
The phasor diagram of a synchronous condenser

Synchronous condenser

A synchronous condenser installation at Templestowe substation, Melbourne, Victoria, Australia. Built in 1966, the unit is hydrogen cooled and capable of providing ±125 MVAR of three-phase reactive power.

Starting synchronous motors

- Assume that the synchronous motor is **stationary** (*not rotating)* at **t=0$^-$**
- Now at **t=0$^+$** ;
  - we apply **60-Hz three-phase voltages** to the stator windings so that B_S **(*stator magnetic field*)** is produced.
  - We apply **DC current** to the rotor windings so that B_R (***rotor magnetic field***) is produced.
- Induced torque (τ_{ind}) in the motor is **zero**, because of the following equation:

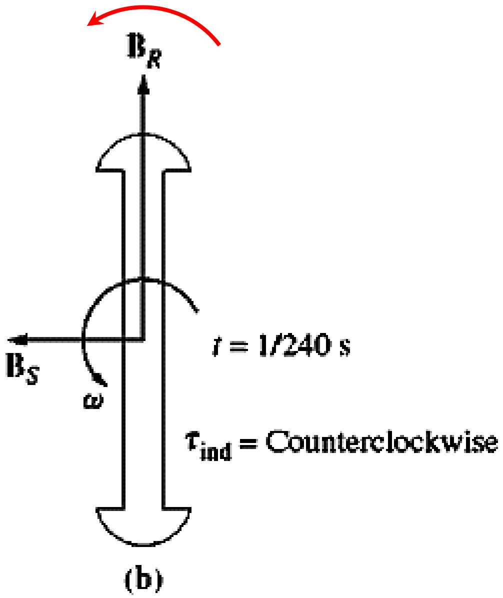


(a)

$$\tau_{ind} = k\underbrace{B_R \, x \, B_S}_{B_R \text{ and } B_S \text{ are parallel}} = 0$$

Starting synchronous motors

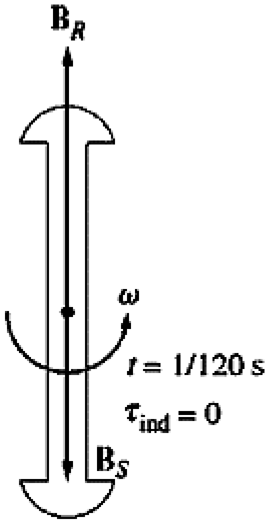
- At **t = 1/(4*60) seconds** (*quarter of one period*), the orientation of both magnetic fields are shown in the figure.
- **Rotating stator magnetic field** (B_S) comes to the position as shown in the figure.
- Now, there is an induced torque in the motor, because of the following equation.
- This torque is in the **counterclockwise direction** as shown in the figure.
- Because of this induced torque, the **rotor** and **rotor magnetic field** (B_R) **barely moved to the left.**
- Because, stator magnetic field is **rotating much faster than rotor**, so the **duration of this torque is very little**.



$$\tau_{ind} = kB_R \, x \, B_S$$

Starting synchronous motors

- At **t = 1/(2*60) seconds** (*half of one period*), the orientation of both magnetic fields are shown in the figure.
- We assume that the **rotor position <u>approximately did not change.</u>**
- However, **rotating stator magnetic field** (B_S) comes to the position as shown in the figure.
- Again induced torque in the motor is **zero** because of the following equation.

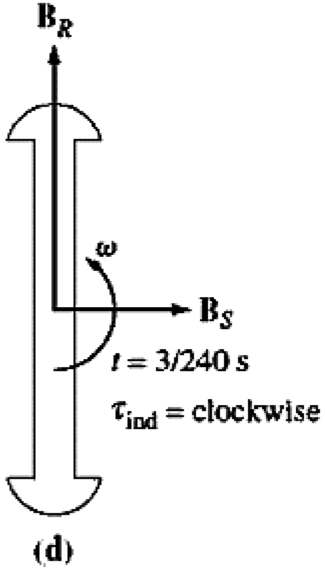


(c)

$$\tau_{ind} = k\underbrace{B_R \, x \, B_S}_{B_R \text{ and } B_S \text{ are reverse-parallel}} = 0$$

Starting synchronous motors

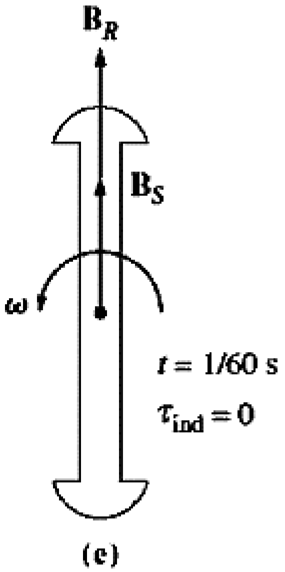
- At **t = 3/(4*60) seconds** (*3. quarter of one period*), the orientation of both magnetic fields are shown in the figure.
- We assume that the **rotor position is <u>still same</u>**
- However, **rotating stator magnetic field** (B_S) comes to the position as shown in the figure.
- Now, there is an induced torque in the motor, given by the following equation.
- This torque is in the **clockwise direction** as shown in the figure.



$$\tau_{ind} = kB_R \, x \, B_S$$

Starting synchronous motors

- At **t = 4/(4*60) seconds** (*4. quarter of one period*), the orientation of both magnetic fields are shown in the figure.
- We assume that the **rotor position is <u>still same</u>**
- However, **rotating stator magnetic field** (B_S) comes to the position as shown in the figure.
- Again induced torque in the motor is **zero** because of the following equation.



$$\tau_{ind} = k\underbrace{B_R \; x \; B_S}_{B_R \text{ and } B_S \text{ are parallel}} = 0$$

Starting synchronous motors

- In summary;
- In one period of stator voltage, the **net induced torque** in the machine is **zero**.

$$\tau_{ind(net)} = 0 + \underset{\substack{\downarrow \\ \text{Counterclockwise} \\ \text{direction}}}{\tau_{ind}} + 0 + \underset{\substack{\downarrow \\ \text{Clockwise} \\ \text{direction}}}{\tau_{ind}} = 0$$

- The synchronous motor **vibrates heavily** in each electrical period and **overheats**.
- The synchronous motor can be **easily damaged because of overheating**.
- So a synchronous motor **cannot be started directly** like DC motors and induction motors.
- There are **different methods** to **start up a synchronous motor**.

Starting synchronous motors

- There are **three basic approaches** to **safely start a synchronous motor**:

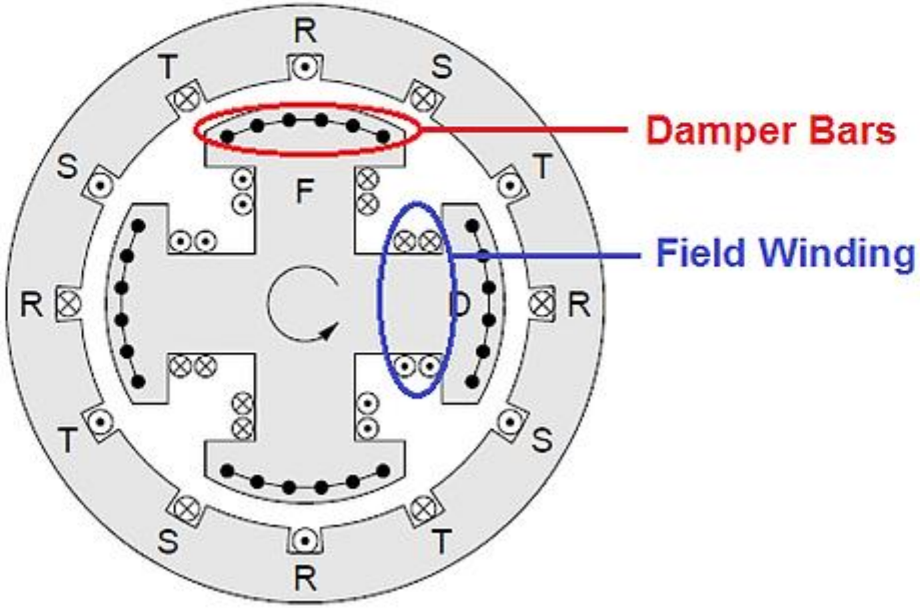
1) ***Reduce the speed of the stator magnetic field*** to a low enough value that the rotor can accelerate and lock in with it during stator magnetic field's rotation. This can be done by **reducing the frequency** of the **applied three-phase stator voltage**. We can use a **three-phase inverter** to **reduce this frequency**.

2) ***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**.

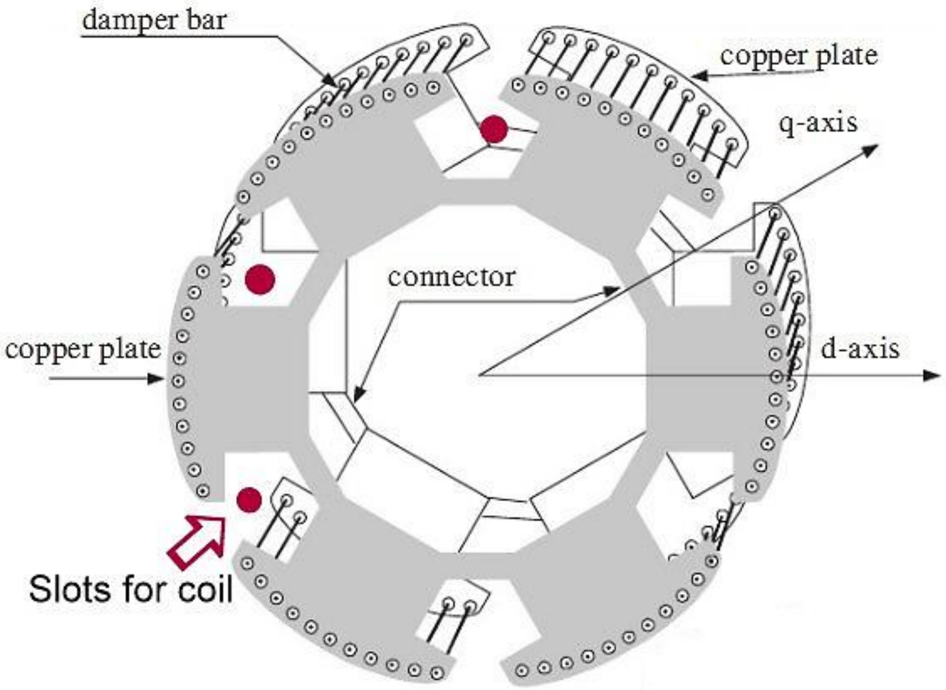
3) **Use damper windings (amortisseur windings)** on the rotor of the machine. (*the most popular method*)

Damper windings

- **Damping** (*amortisseur*) windings (*bar*) 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 **shorting ring**.



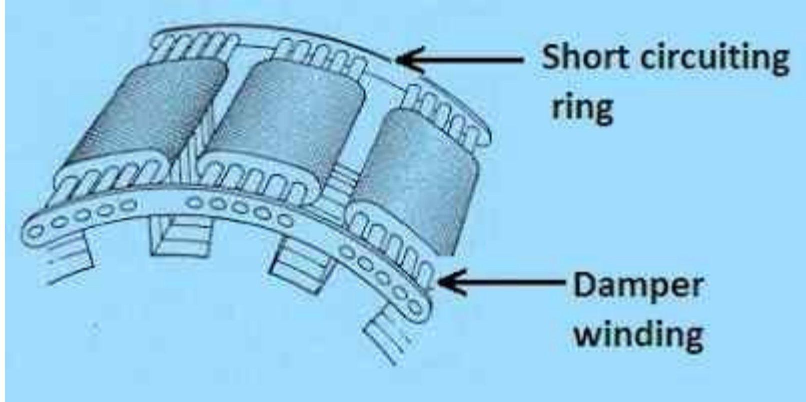
2 dimensional view

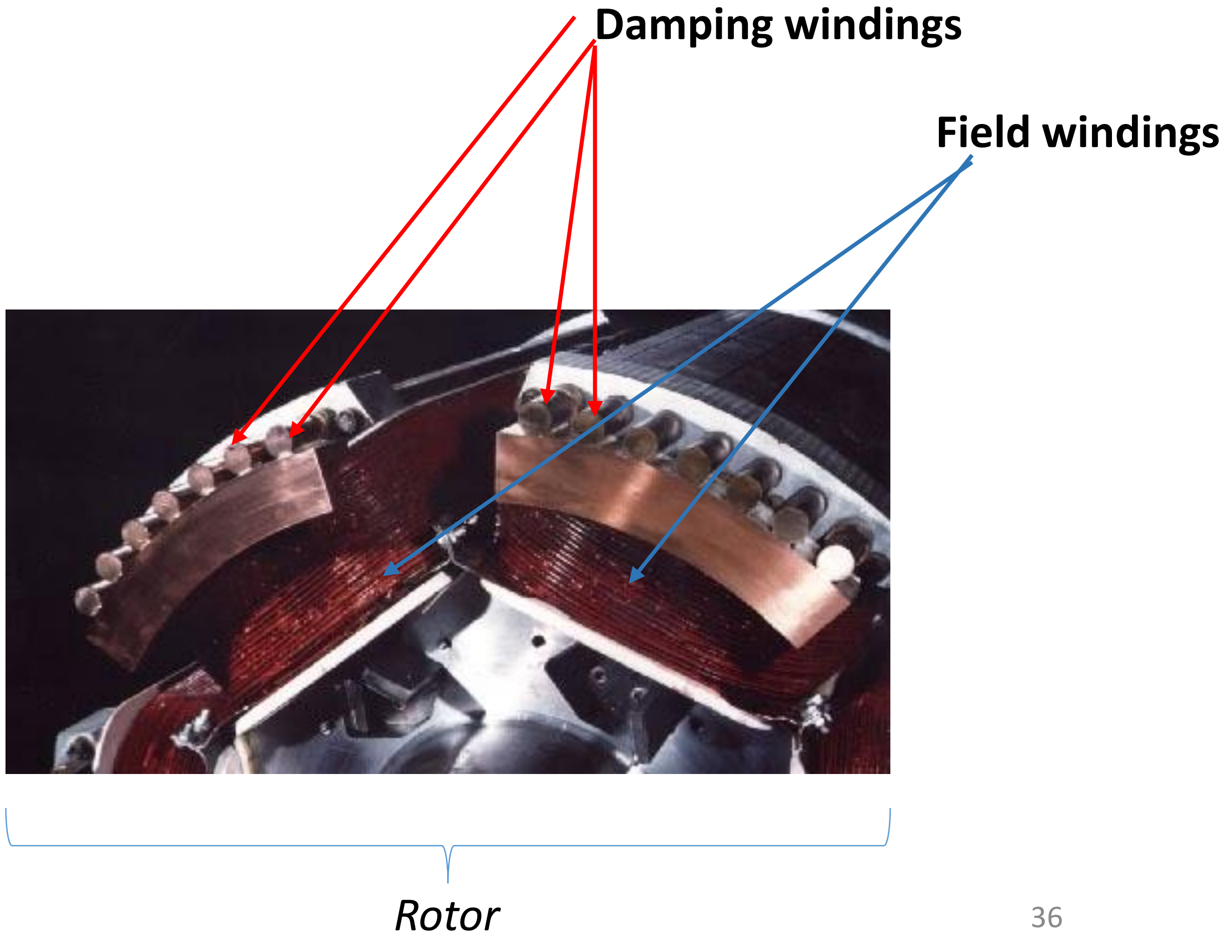


3 dimensional view

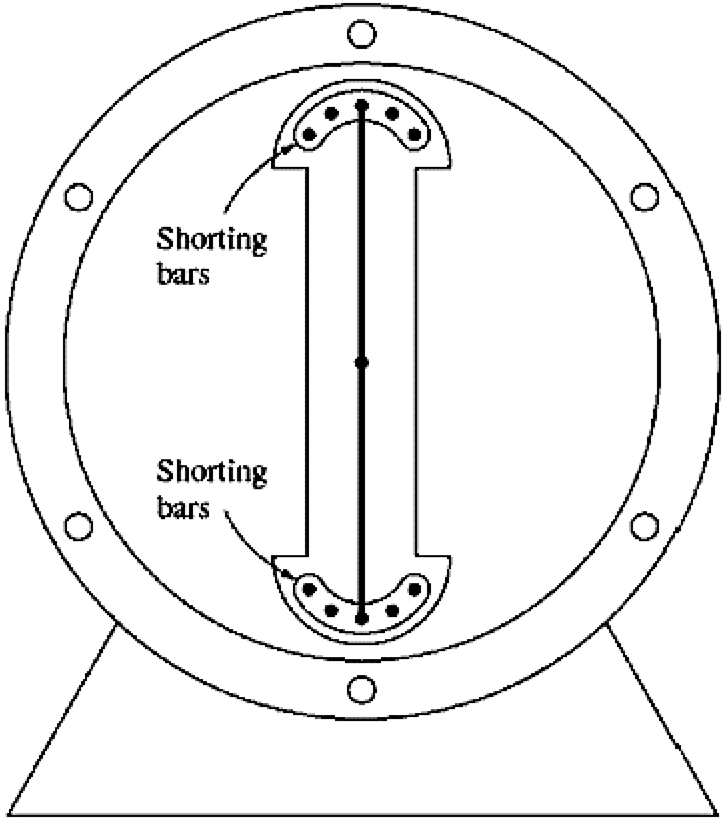
Damper windings

- **Damping windings** are **short-circuited** using **short circuiting ring** as shown in the figure.





How do damper windings operate ?



A simplified diagram of a salient two-pole machine showing damper windings

How do damper windings operate ?

- Assume that initially, the ***rotor field winding is disconnected*** ($B_R = 0$) and a **three-phase set of voltages is applied to the stator** at **t=0⁺**.
- At **t=0⁺**, B_S orientation is shown in the figure.
- As the **rotating stator magnetic field** B_S sweeps along in a counterclockwise direction, it induces a voltage in the bars, given by the following equation:

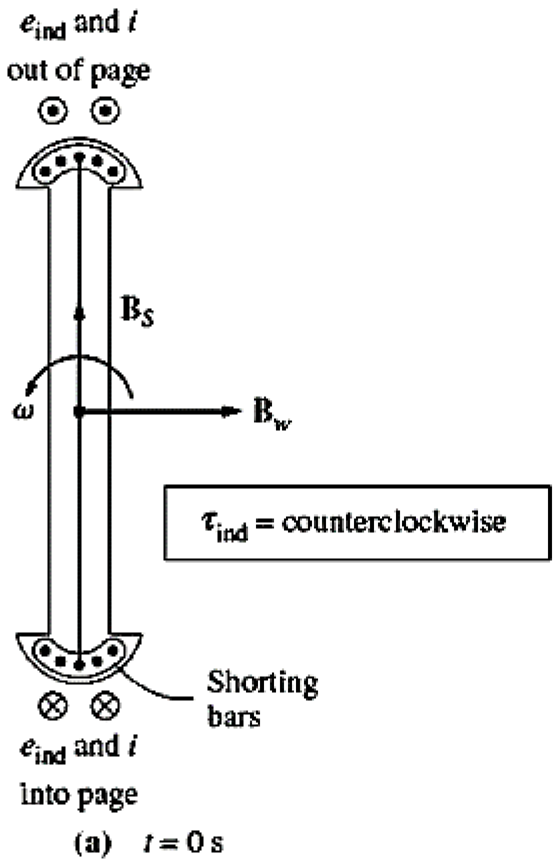
$$e_{ind} = (v\ x\ B).l$$

where v = velocity of the bar *relative to the magnetic field*

B = magnetic flux density vector

l = length of conductor in the magnetic field

- The **bars** at the **top of the rotor** are moving to the **right** *relative to the magnetic field,* so the resulting direction of the **induced voltage** is **out of the page**.
- Similarly, the **induced voltage** is **into the page** in the **bottom bars** .

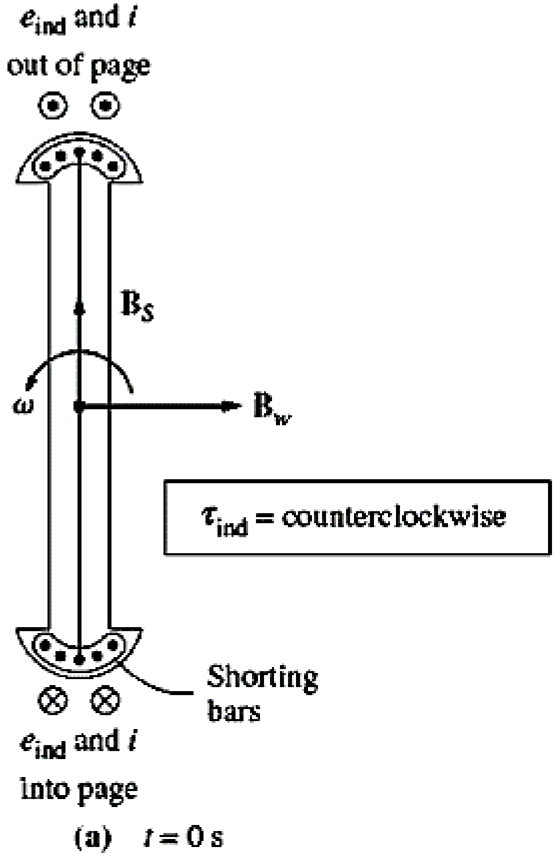


How do damper windings operate ?

- These voltages produce a **current flow** from the top bars to the bottom bars.
- This current produces **damper winding magnetic field**, B_w **pointing to the right** as shown in the figure.
- Now, there are **two magnetic fields** in the synchronous motor (B_w, B_S) and they produce a **torque**, given by the following equation:

$$\tau_{ind} = kB_w \, x \, B_S$$

- This **induced torque** is in the direction of **counterclockwise** as shown in the figure.



How do damper windings operate ?

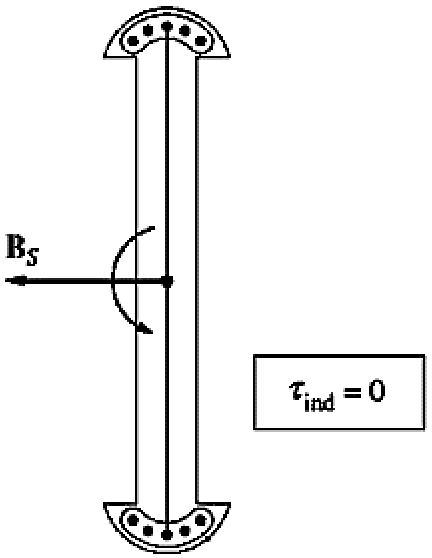
- At **t = 1/(4x60) seconds**, the stator magnetic field B_S has rotated **90°** while the rotor has **barely moved** (*it simply cannot speed up in so short a time*).

- At this point, the voltage induced in the damper windings is **zero**, because **v is parallel to B**.

$$e_{ind} = \underbrace{(v\ x\ B)}_{\mathbf{0}}.\, l = 0$$

- With **no induced voltage**, **there is no current** in the windings, and hence B_w and τ_{ind} are both **zero**.

$$\tau_{ind} = k\underset{\substack{\downarrow \\ \mathbf{0}}}{B_w}\ x\ B_S = 0$$



(b) $t = 1/240$ s

How do damper windings operate ?

- At **t = 1/(2x60) seconds**, the **stator magnetic field** B_S has rotated **90°** while the rotor **still has not moved yet**. (*it simply cannot speed up in so short a time*).

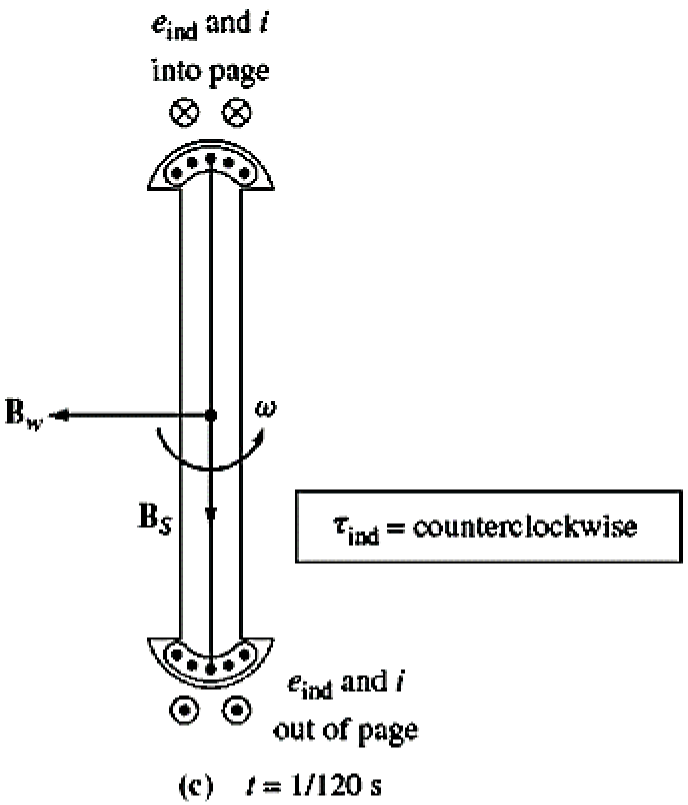
- The **induced voltage** in the damper windings is **out of the page** in the **bottom bars** and **into the page** in the **top bars**.

$$e_{ind} = (v \; x \; B).l$$

- The resulting current flow is **out of the page** in the **bottom bars** and **into the page** in the **top bars**, causing a **magnetic field** B_W , **pointing to the left** as shown in the figure.

- The resulting **induced torque** is given by the following equation and it is in the direction of **counterclockwise:**

$$\tau_{ind} = kB_W \; x \; B_S$$



How do damper windings operate ?

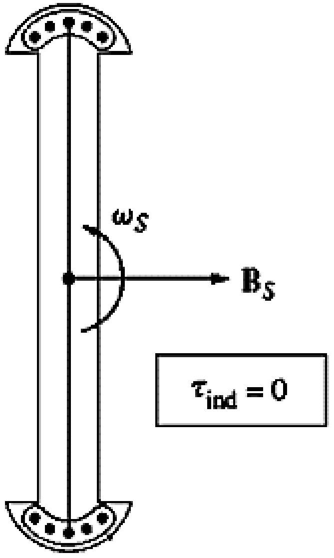
- At **t = 3/(4x60) seconds**, the **stator magnetic field** B_S has rotated **90°** while the rotor has **barely moved** (*it simply cannot speed up in so short a time*).

- At this point, the voltage induced in the damper windings is **zero**, because **v is parallel to B**.

$$e_{ind} = \underbrace{(v \; x \; B)}_{\mathbf{0}}.\, l = 0$$

- With **no induced voltage, there is no current** in the windings, and hence B_w and τ_{ind} are both **zero**.

$$\tau_{ind} = k\underset{\overset{\downarrow}{\mathbf{0}}}{B_w} \; x \; B_S = 0$$



(d) $t = 3/240$ s

How do damper windings operate ?

- Finally we see that the **net induced torque** in the synchronous motor is **not zero**:

$$\tau_{ind(net)} = 0 + \tau_{ind} + 0 + \tau_{ind} \neq 0$$

Both are in ***counterclockwise*** *direction*

- This torque is **unidirectional** (*has only one direction all the time*).
- Because of this **non-zero net torque**, the rotor **speeds up**.

How do damper windings operate ?

- Although the **motor's rotor** will **speed up**, it can **never reach** **synchronous speed**. But why?

- Suppose that the rotor is turning at synchronous speed. Then the speed of the stator magnetic field B_S is the same as the rotor's speed, and there is **no relative motion** between B_S and the rotor.

- If there is **no relative motion**, the **induced voltage** in the windings will be **zero**, the resulting **current** flow will be **zero**, and the winding magnetic field B_w will be **zero**.

- Therefore, there will be **no torque** on the rotor to keep it turning.

- Even though a rotor **cannot speed** up to the **synchronous speed** with **damper windings**, **it can get close to the synchronous speed**.

- Now, the field current can be turned on and applied to the rotor windings.

- After applying the field current, the **rotor speed** will be the **same** as of the **rotating stator magnetic field** B_S (***synchronous speed***)

How do damper windings operate ?

- In summary, if a synchronous motor has **damper** (*amortisseur*) **windings**, it can be started by the following steps:

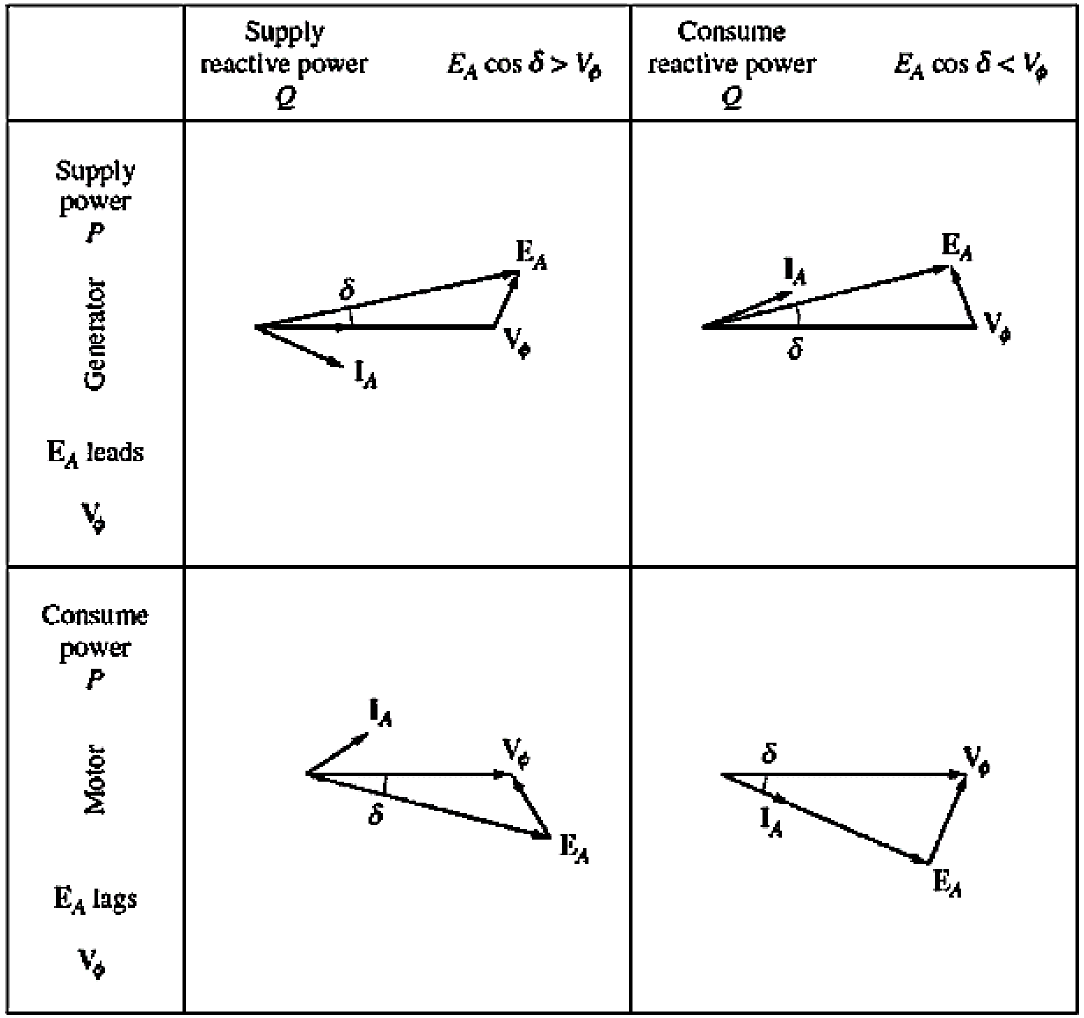
1) Disconnect the field windings from the DC power supply and short them out. (*Shorting will avoid inducing very high voltages at the terminals of the rotor windings*)

2) Apply a three-phase voltage to the stator, and let the rotor accelerate up to near-synchronous speed.

3) The motor should have no load on its shaft , so that its speed can approach synchronous speed as closely as possible.

4) Connect the DC field circuit to its power source. After this is done, the motor will lock into the synchronous speed, and loads may then be added to its shaft.

Comparison of synchronous generators and synchronous motors



	Supply reactive power Q $E_A \cos \delta > V_\phi$	Consume reactive power Q $E_A \cos \delta < V_\phi$
Supply power P Generator $\mathbf{E}_A$ leads $\mathbf{V}_\phi$		
Consume power P Motor $\mathbf{E}_A$ lags $\mathbf{V}_\phi$		

Synchronous motor ratings

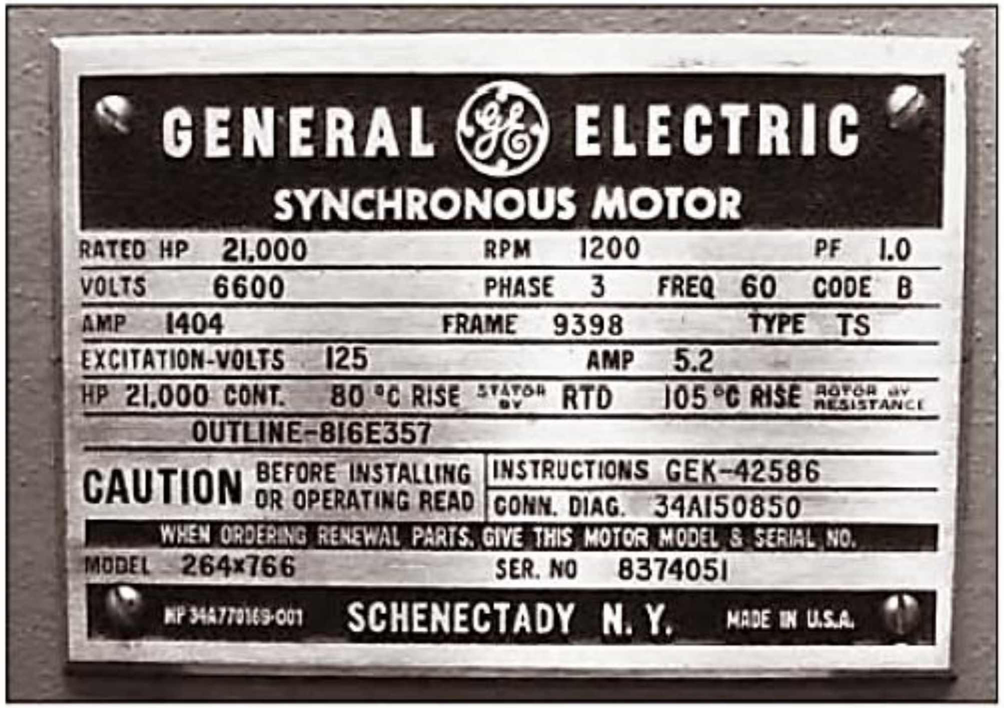
- Since **synchronous motors** are the **same physical machines** as **synchronous generators**, the basic machine ratings are the **same**.

- The one major difference is that a **large** E_A gives a **leading power factor** instead of a **lagging one**.

- Since the output of a **synchronous motor** is **mechanical power**, a **synchronous motor's power rating** is usually given in **horsepower** rather than **kilowatts**.

- In general, **synchronous motors** are **more adaptable** to **low-speed, high-power applications** than **induction motors**.

- **Synchronous motors**, therefore, are commonly used for **low-speed, high-power loads**.



GENERAL ELECTRIC
SYNCHRONOUS MOTOR
RATED HP 21,000 RPM 1200 PF 1.0
VOLTS 6600 PHASE 3 FREQ 60 CODE B
AMP 1404 FRAME 9398 TYPE TS
EXCITATION-VOLTS 125 AMP 5.2
HP 21,000 CONT. 80 °C RISE STATOR BY RTD 105 °C RISE ROTOR BY RESISTANCE
OUTLINE-816E357
CAUTION BEFORE INSTALLING OR OPERATING READ INSTRUCTIONS GEK-42586
CONN. DIAG. 34A150850
WHEN ORDERING RENEWAL PARTS, GIVE THIS MOTOR MODEL & SERIAL NO.
MODEL 264×766 SER. NO 8374051
NP 34A770169-001 SCHENECTADY N. Y. MADE IN U.S.A.

END OF CHAPTER 3

SYNCHRONOUS MOTORS