# Chapter 6: Synchronous Motors

Synchronous motors are synchronous machines used to **convert electrical power to mechanical power.**

## 6.1. Basic principles of motor operation

The basic principle of synchronous motor operation is that the rotor "chases" the rotating stator magnetic field around in a circle, never quite catching up with it.

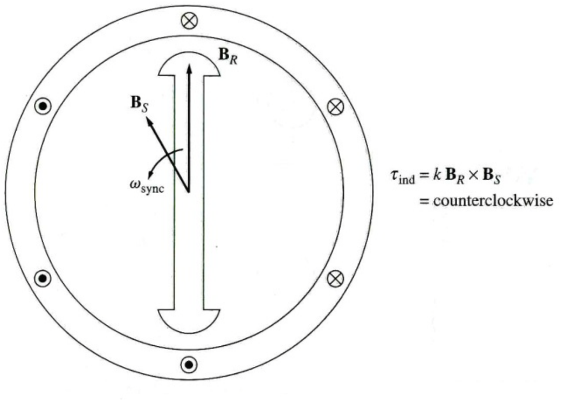
How does it work?

- The rotor field current $I_F$ produces a steady-state magnetic field $\bar{B}_R$
- A three-phase set of voltages applied to the stator produces a three-phase current flow in the winding.
- These currents then produce a uniform rotating magnetic field $\bar{B}_S$.
- Since there are two magnetic fields in the machine,

⇨ $\bar{B}_R$ tends to ________________ with $\bar{B}_S$.
Since $\bar{B}_S$ is rotating, $\bar{B}_R$ will constantly try to catch up, just as the two magnets will tend to line up if placed near each other.

The amount of **torque depends** on the **angle between the two magnetic fields**.

Just like in the induction motor, the rotor "chases" the rotating $\bar{B}_S$ in a circle but never quite catching up with it.




A two-pole synchronous motor.

## 6.2. The speed of rotation of a synchronous machine

Synchronous motors usually supply power to loads that require a **constant speed**.

The motor speed of rotation is locked to the applied frequency, so the

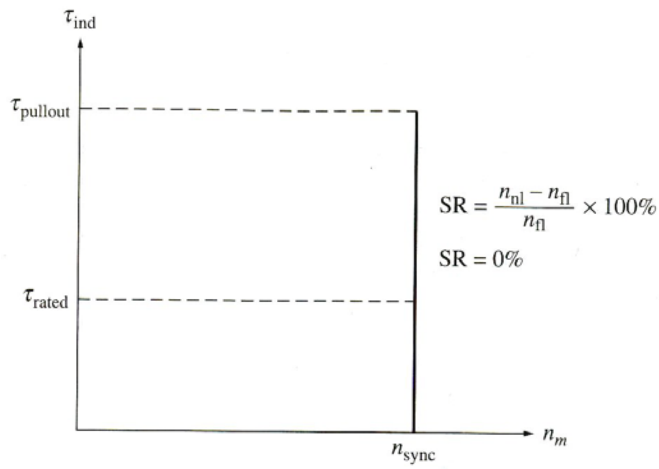
⇨ **motor speed** is **constant** regardless of the load.

Hence, the **rate of rotation of magnetic fields** in the machine is **related to the stator electrical frequency by**:

where $f_e$ = electrical frequency, in Hz
$n_m$ = mechanical speed of magnetic field, in r/min (equals speed of rotor for synchronous machines)
$P$ = number of poles

Hence for a synchronous motor, its **torque speed characteristic is constant speed** as the induced torque increases.

Hence, speed regulation **SR = 0%**.



## 6.3. The equivalent circuit of a synchronous motor

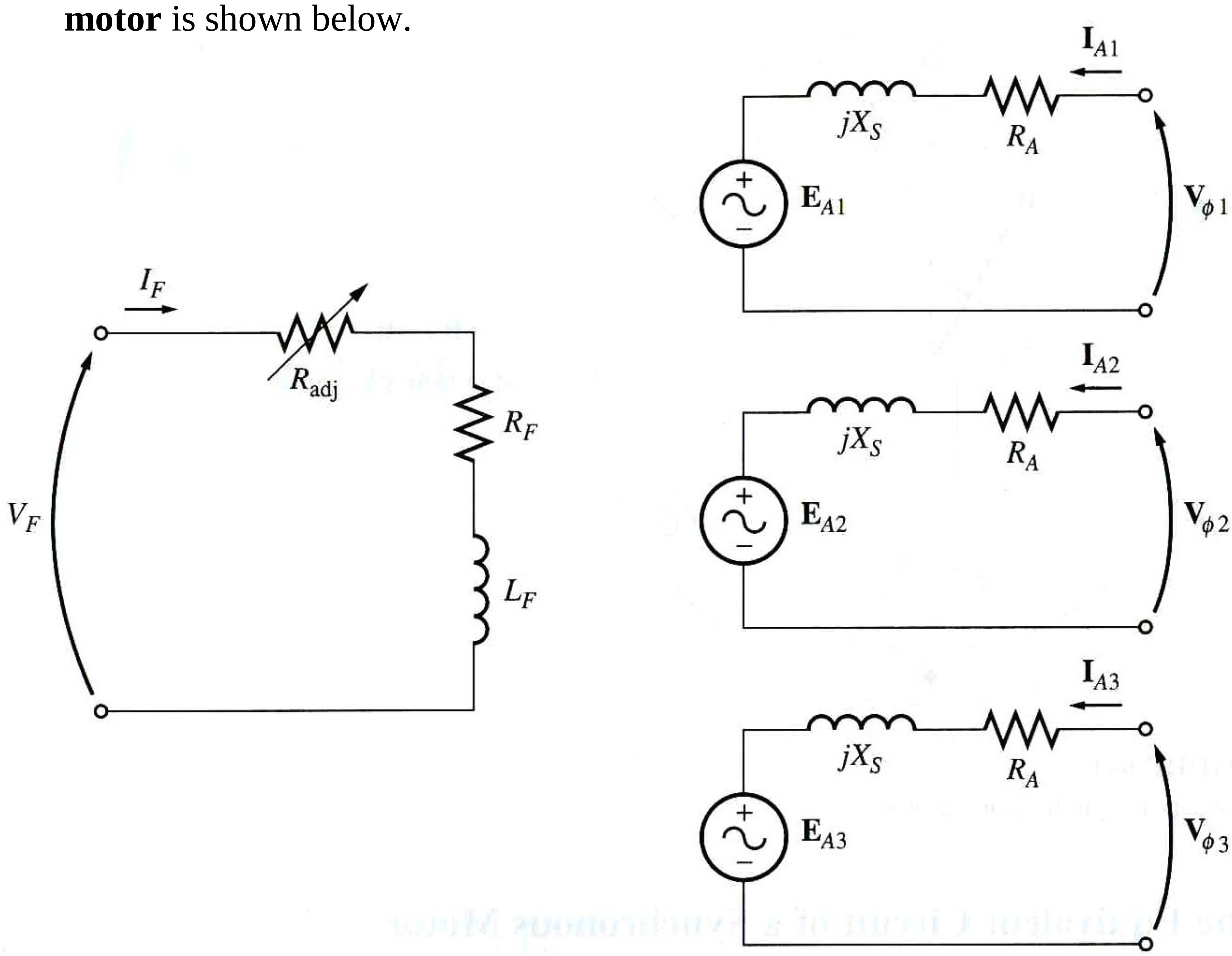
$\bar{E}_A$ = **internal generated voltage** produced in one phase of a synchronous motor.

$\bar{V}_\phi$ = **voltage at the stator winding terminals** of the motor, i.e. input voltage of a phase.

There will be **differences between** $\bar{E}_A$ and $\bar{V}_\phi$ due to:

a) **self-inductance** of the armature coils
b) **resistance** of the armature coils

Therefore, the **full equivalent circuit of a three-phase synchronous motor** is shown below.




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

The **dc power source supplying the rotor field circuit** is modelled by:

- the **coil's inductance $L_F$ and resistance $R_F$** in series.
- an **adjustable resistor $R_{adj}$** that controls the flow of field current.

The **three phases can be either Y- or Δ- connected** with the terminal voltage found using:

$$V_{\mathrm{T}} = \sqrt{3}V_{\phi}$$

$$V_{\mathrm{T}} = V_{\phi}$$

Ideally, the **terminal voltage** for **all three phases** should be **identical** since we assume that the **loads** connected are **balanced**.

This leads to the use of a **per-phase equivalent circuit**:

The **per-phase equivalent circuit** of a three-phase synchronous motor.

## 6.4. <u>The phasor diagram of a synchronous motor</u>

The **phasor diagram** of a synchronous motor is a **graphical representation** of the **current $\bar{I}_{\mathrm{A}}$ and voltages** in the motor which is given by the following voltage equation:

$$\bar{V}_{\phi} = \bar{E}_{\mathrm{A}} + jX_{\mathrm{S}}\bar{I}_{\mathrm{A}} + R_{\mathrm{A}}\bar{I}_{\mathrm{A}}$$

The **reference phasor (assumed to be at angle 0°)** = _______

In **real** synchronous machines,

$$X_{\mathrm{S}} \gg R_{\mathrm{A}}$$

so **$R_{\mathrm{A}}$ is often neglected** in the **qualitative study** of voltage variations. For accurate **numerical** results, $R_A$ must be included.

Assuming a lagging power factor:

In the motor, the quantity of $jX_S\bar{I}_A$ points from $\bar{E}_A$ to $\bar{V}_\phi$. By observing the magnetic firld diagram, in a motor, $\bar{E}_A$ lies behind $\bar{V}_\phi$, and $\bar{B}_R$ lies behind $\bar{B}_{net}$.

## 6.5. The effect of load changes on a synchronous motor

If a load is attached to the synchronous motor's shaft, the motor will develop enough torque to keep **both** motor and load turning at **synchronous speed**.

*What happens when the load is changed?*

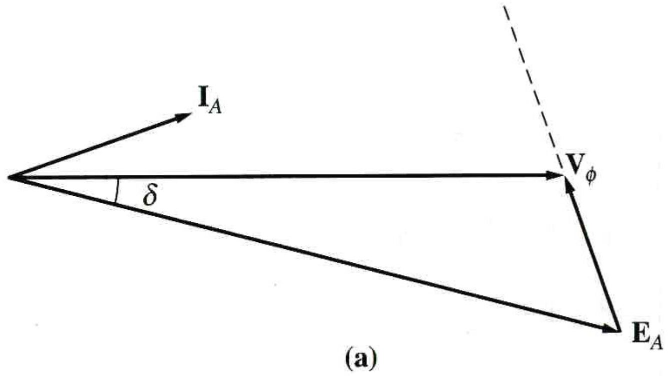
**Assumption:**

- **The field current settings are unchanged.**
- **Synchronous motor operating initially with a leading power factor (as in phasor diagram on next page).**

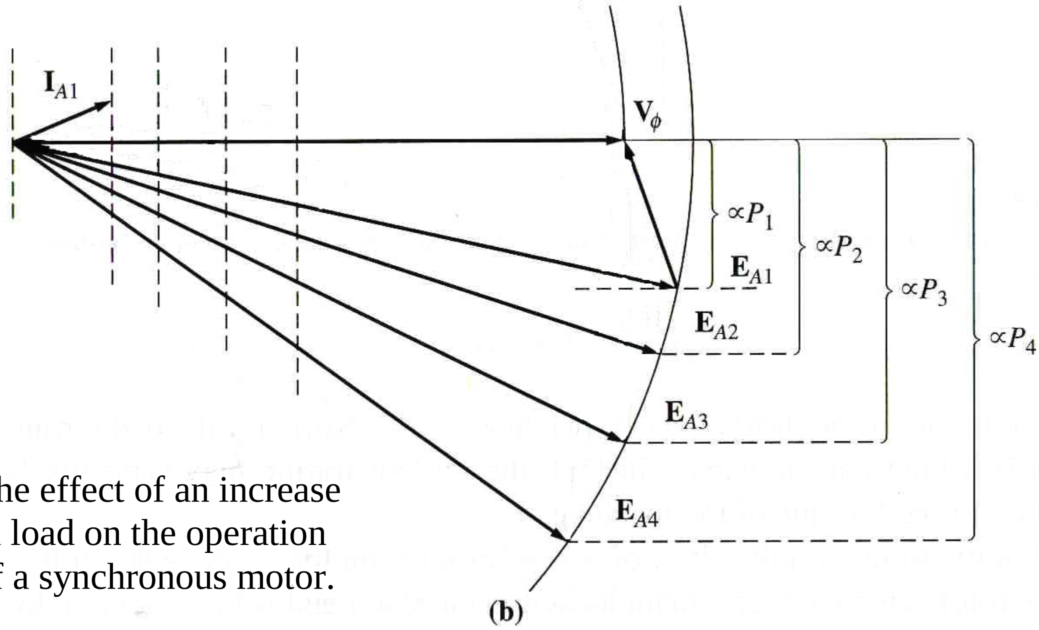
As the load **increases**:

- The rotor will **initially slow down**.
- The **torque angle** $\delta$ becomes **larger** causing an **increase** in **induced torque**.
- This will eventually **speed** the **rotor back up to synchronous speed** but with a **larger torque angle** $\delta$.

The **overall effect** is that the synchronous motor phasor diagram would have a **bigger torque angle** $\delta$ as shown in the next page.




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




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

In terms of the **internal generated voltage** $\bar{E}_\mathrm{A}$,

⇨ Its **magnitude** $|\bar{E}_\mathrm{A}|$ must be_______________ with load changes.

Since the **angle of** $\delta$ **increases**, the distances proportional to **power** ($E_\mathrm{A}$ sin $\delta$ and $I_\mathrm{A}$ cos $\theta$) will **increase** and $\bar{E}_\mathrm{A}$ swings down further (on the curve) with constant magnitude.

The phasor $jX_\mathrm{S}\bar{I}_\mathrm{A}$ must increase to reach from tip of $\bar{E}_\mathrm{A}$ to $\bar{V}_\phi$. Hence, the **armature current** $\bar{I}_\mathrm{A}$ also **increases**. Notice that the **power factor angle** $\theta$ **changes** from leading to lagging.

**Example 6-1 (pg. 353):** A 208-V, 45-kVA, 0.8-PF-leading, Δ-connected, 60-Hz synchronous machine has a synchronous reactance of 2.5 Ω 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 0.80 leading.

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

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

(c) Find $I_A$, $I_L$ and $E_A$ after the load change. What is the new motor power factor?

## 6.6. The effect of field current changes on a synchronous motor

**Assumption:** The synchronous generator is **rotating at synchronous speed with a lagging load** connected to it. **The load remains unchanged.**

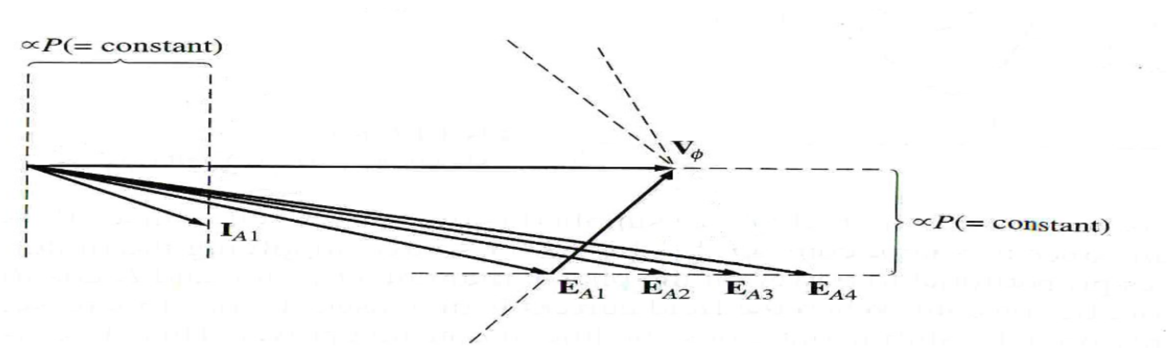
As the field current is **increased**:

- The **magnitude of** $\bar{E}_A$ will **increase**.

- Unfortunately, there are **constraints set** to the machine as such that the **power requirement is unchanged** (power supplied by motor changes only when shaft load changes).

- At the same time, $V_T$ **is kept constant** by the power source supplying the motor.

- Hence, the **distances proportional to power** ( $E_A$ sin $\delta$ and $I_A$ cos $\theta$ ) on the phasor diagram must **remain constant**. Therefore, $\bar{E}_A$ tends to slide across a horizontal limit (i.e. line of constant power) as shown in the phasor diagram below for a lagging power factor load.




The effect of an increase in field current on the operation of a synchronous motor under lagging power factor conditions.

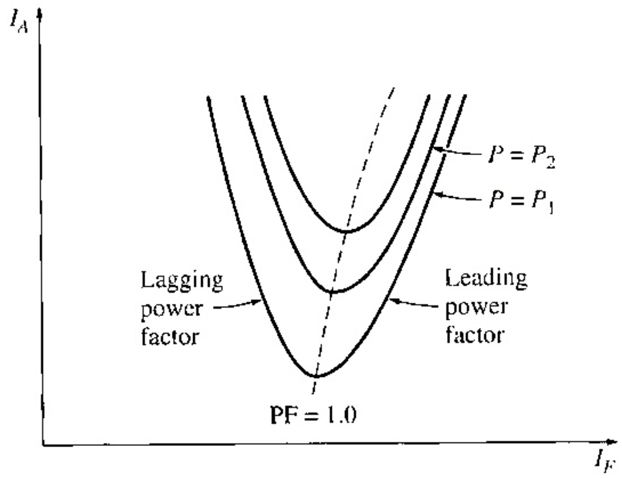
Notice that:

- As $\bar{E}_A$ increases, the magnitude of armature current $\bar{I}_A$ initially decreases and then increases again.
- $\bar{I}_A$ will react to the changes in $\bar{E}_A$ as such that its **angle changes** from a lagging power factor to a leading power factor.

| | **Armature current, $\bar{I}_A$** | **Motor acting like:** | **Reactive power *Q*** |
|---|---|---|---|
| **Low $\bar{E}_A$** | Lags $\bar{V}_\phi$ | Inductive load | **Consumed** by motor |
| **Medium $\bar{E}_A$** | In phase with $\bar{V}_\phi$ | Purely resistive circuit | - |

| | | | |
|---|---|---|---|
| **High** $\bar{E}_A$ | Leads $\bar{V}_\phi$ | Capacitive load | **Supplied to the system** (i.e. motor is consuming –*Q*) |

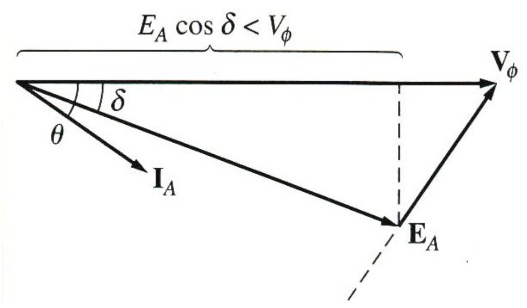
This characteristic can also be represented in the synchronous motor as shown below:




Synchronous motor V curves.

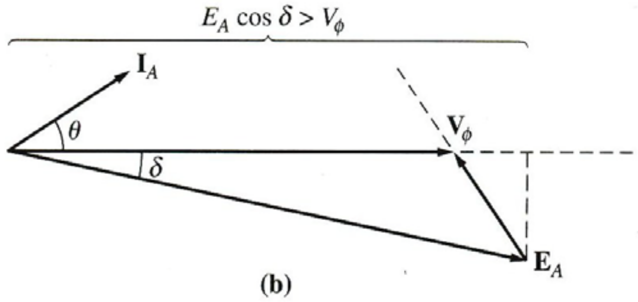
Several V curves are drawn, corresponding to different real power levels. For each curve:

- **Minimum** $\bar{I}_A$ occurs at _____________ power factor (i.e. when **only real power is supplied** by the motor)
- At **any other point**, some **reactive power is supplied to or by** the motor as well as real power.

| | |
|---|---|
| $\boldsymbol{I_F < I_{F,I_A\ min}}$ | ❑ $\bar{I}_A$ lagging<br>❑ motor is ________________ $Q$<br>❑ $E_A \cos\delta < V_\phi$<br>❑ motor is ***underexcited*** (small $I_F$)<br> |

<table>
<tr>
<td>$I_F > I_{F,I_A\,min}$</td>
<td>

- $\bar{I}_A$ leading
- motor is ___________________ $Q$ to the power system
- $E_A \cos\delta > V_\phi$
- motor is ***overexcited*** (large $I_F$)

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This gives a possibility to utilise the synchronous motor as a **power factor correction tool** since varying magnetic field would change the motor from leading to lagging or vice versa.

**Example 6-2 (pg. 357):** The 208-V, 45-kVA, 0.8-PF-leading, Δ-connected, 60-Hz synchronous machine of the previous example is supplying a 15-hp load with an initial power factor of 0.85 lagging. The current $I_F$ at these conditions is 4.0 A.

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

(b) If the motor's flux is increased by 25%, sketch the new phasor diagram of the motor. What are $E_A$, $I_A$ and the power factor of the motor now?

# The synchronous motor and power-factor correction

In a power system, **low power factors means greater losses** in the power lines feeding it.

**Most loads** on a typical power system are **induction motors** with lagging power factors.
Having **one or more leading loads (overexcited synchronous motors)** in the system is useful because:

- It can **supply reactive power *Q*** for the lagging loads instead of using a generator. Hence, reactive power doesn't have to travel over long, high-resistance transmission lines.
- This leads to **reduction** in **transmission line current** and power system **losses are much lower.**
- This enables the use of **lower current rating transmission lines** for a given rated power flow. Hence, **reduces the costs** of the power system significantly.
- In addition, the use of overexcited synchronous motors increases the motor maximum torque and reduces the chance of accidentally exceeding the pullout torque.

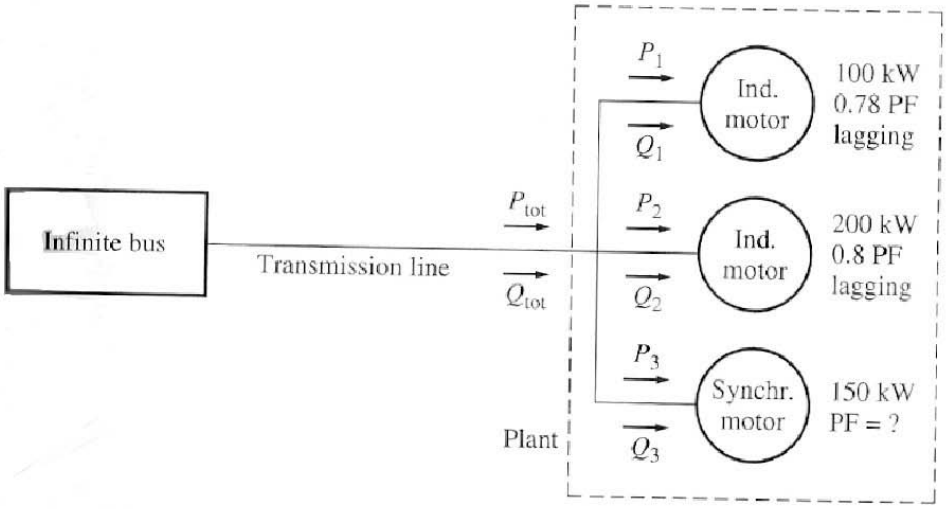
**Power factor correction** – use of synchronous motors or other equipment to increase the overall power factor of a power system.

Hence, if a **synchronous motor** is **incorporated** nearby a load which require reactive power, the synchronous motor may be operated **to inject reactive power,** hence **maintaining stability** and **lowering high current flow** in the transmission line.

**Synchronous motor provides power system correction!**

**Example 6-3 (pg. 360):**

The infinite bus in the figure below 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?

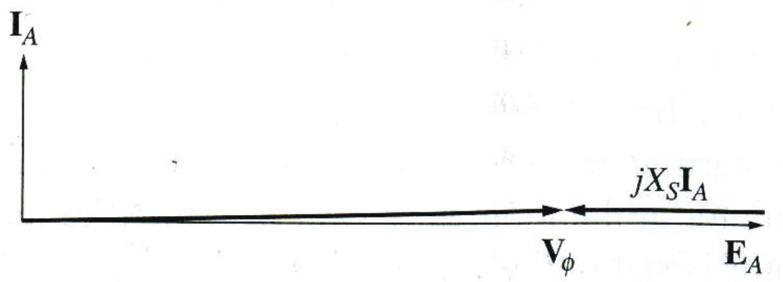
| | Real power (P) | Reactive power (Q) |
|---|---|---|
| Load 1 | | |
| Load 2 | | |
| Load 3 | | |
| Total | | |

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

(c) Assume the transmission line losses are given by $P_{LL} = 3I_L^2R_L$, where LL stands for line losses. How do the transmission losses compare in the two cases?

# The synchronous capacitor or synchronous condenser

- Synchronous motor purchased to drive a load can be operated overexcited to supply reactive power $Q$ for a power system.
- Sometimes a synchronous motor is run without a load, simply for power factor correction only. Hence, at no load, the phasor diagram of a synchronous motor becomes:




No power being drawn from the motor

⇒ the distances proportional to power ($E_A$ sin $\delta$ and $I_A$ cos $\theta$) are zero.

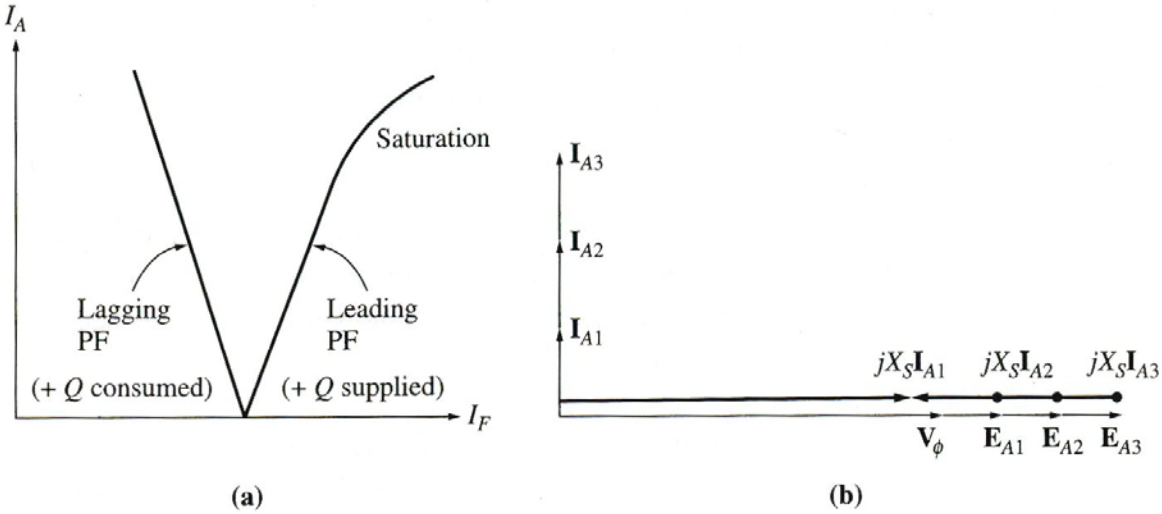
From KVL, $\bar{V}_\phi = \bar{E}_\mathrm{A} + jX_\mathrm{S}\bar{I}_\mathrm{A}$

⇒ the quantity $jX_\mathrm{S}\bar{I}_\mathrm{A}$ points to the left, and therefore the $I_A$ points straight up.

- If $\bar{V}_\phi$ and $\bar{I}_\mathrm{A}$ are examined, the voltage-current relationship looks like that of a capacitor.
- An **overexcited synchronous motor at no load looks like a large capacitor** to the power system.

Synchronous motors are sometimes used solely for PF correction. These machines had shafts that did not even come through the frame of the motor – no load can be connected to them even if one wanted to do so. Such special-purpose synchronous motors were often called *synchronous condensers or synchronous capacitors* (condenser is an old name for capacitor)

The V curve and phasor diagram for a synchronous capacitor is shown:



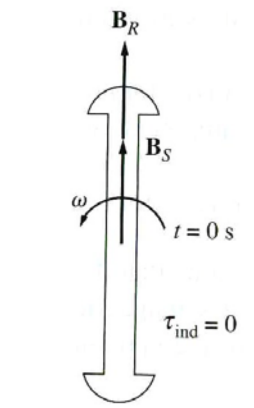
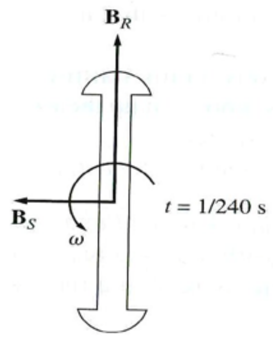
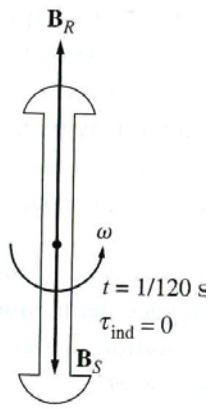
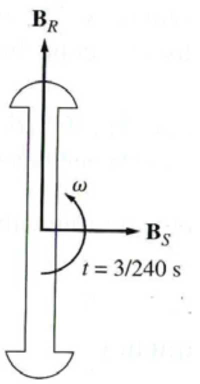

- Since the real power supplied to the machine = 0 (except for
- losses), at unity PF the current $I_A$=0.
- As the field current is increased above unity PF point, the line current (and the reactive power supplied by the motor) increases in a nearly linear fashion until saturation is reached.

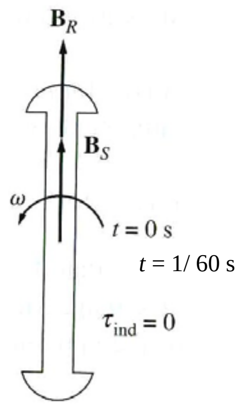
## 6.7. <u>Starting synchronous motors</u>

In explaining the behaviour of a synchronous motor under steady state conditions, the motor was always assumed to be initially turning at synchronous speed.

*But how did the motors get to synchronous speed in the first place since it has no net starting torque?*

To understand the starting problem, refer to the figures below showing a 60-Hz synchronous motor at the moment power is applied to the stator windings. The **rotor is stationary**, therefore the magnetic field $\bar{B}_R$ is **stationary.** The stator magnetic field $\bar{B}_S$ is starting to sweep around the motor at synchronous speed.

| | |
|---|---|
|  | At $t$ = 0 s,<br>o $\bar{B}_R$ and $\bar{B}_S$ are exactly **lined up.**<br>o $\boldsymbol{\tau_{ind} = 0}$**.** |
|  | At $t$ = 1/240 s,<br>o Rotor has barely moved.<br>o $\bar{B}_S$ has rotated to the left.<br>o $\bar{B}_R$ and $\bar{B}_S$ are 90° apart**.**<br>o $\boldsymbol{\tau_{ind}}$ = maximum in **counterclockwise direction.** |
|  | At $t$ = 1/120 s,<br>o $\bar{B}_R$ and $\bar{B}_S$ are 180° apart**.**<br>o $\boldsymbol{\tau_{ind} = 0}$**.** |
|  | At $t$ = 3/240 s,<br>o $\bar{B}_S$ has points to the right.<br>o $\boldsymbol{\tau_{ind}}$ = maximum in **clockwise direction.** |

| | |
|---|---|
|  | At $t$ = 1/60 s,<br>o $\bar{B}_{\text{R}}$ and $\bar{B}_{\text{S}}$ are exactly **lined up again.**<br>o $\boldsymbol{\tau_{\text{ind}} = 0.}$ |

Hence, during one electrical cycle, torque direction goes from counterclockwise to clockwise and **average starting torque is zero,** i.e. the synchronous motor **cannot start by itself**.

As a result, the **motor will vibrate heavily and could overheat**.

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

1) **Reduced speed of stator magnetic field** – the aim is to reduce it slow enough as such that the rotor will accelerate and lock in with the stator magnetic field during ½ a cycle.
2) **Use an external prime mover** to accelerate the synchronous motor up to synchronous speed.
3) **Use damper windings or amortisseur windings**.

## Motor starting by reducing electrical frequency

The idea is to let the **stator magnetic field rotate slow** enough as such that the rotor has time to lock on to the stator magnetic field.

After lock on, the speed of stator magnetic fields can be increased to operating speed by gradually increasing $f_e$ to the normal 50- or 60-Hz value.

This is done using **power electronics technology,** i.e. the rectifier-inverter or the cycloconverter which can convert a constant input frequency to any desired output frequency.

When operating at speed lower than rated speed, **the motor terminal voltage must also be reduced** (roughly linearly with applied frequency) to keep the stator current at safe levels.

## Motor starting with an external prime mover

This is a very straightforward method. The steps involved are:

1. Attach the synchronous motor to an external starting motor.
2. Bring the machine up to full speed with the external motor.
3. Then, parallel the synchronous machine with its power system **as a generator**.
4. Then detach the starting motor from the shaft of the machine.
5. Hence, the machine shaft slows down causing the rotor magnetic field $\bar{B}_{\mathrm{R}}$ **to fall behind** $\bar{B}_{\mathrm{net}}$ and the synchronous machine starts to act **as a motor.**
6. Once paralleling is completed, the motor can be loaded down in an ordinary fashion**.**

Most large synchronous motors have **brushless exciters** which can act as the starting motors.

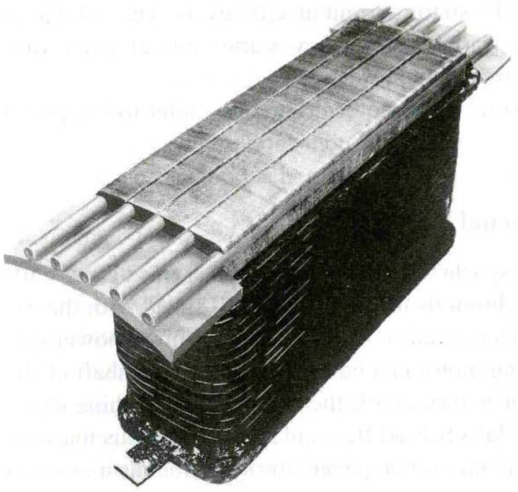
For **many medium-size to large synchronous motors**, starting through an external motor or using the exciter may be the **only option**, because the power systems they are connected to may not be able to handle the large starting currents needed if the amortisseur winding approach is used.

## Motor starting by using amortisseur windings

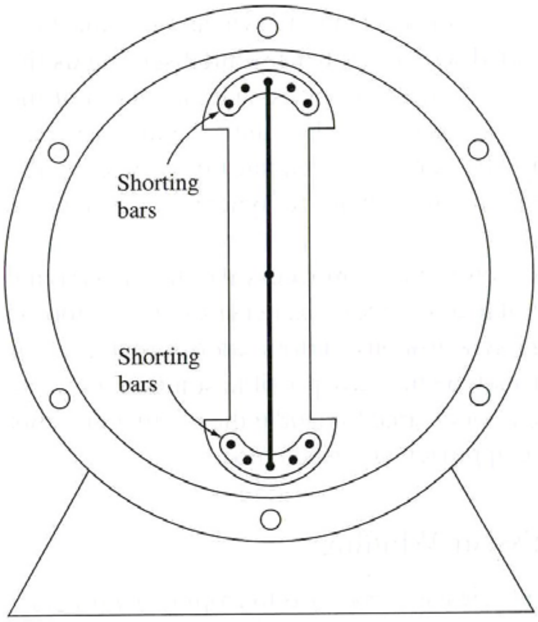
This is the **most popular way** to start a synchronous motor.

Amortisseur (or damper) windings are **special bars** laid into notches carved **in the face** of a synchronous motor's **rotor** which are **shorted at each ends** by a large shorting ring.

A rotor field pole for a synchronous machine showing amortisseur windings in the pole face.



To understand what the amortisseur windings does to the synchronous motor, the simplified salient two-pole rotor shown in the figure below is examined.



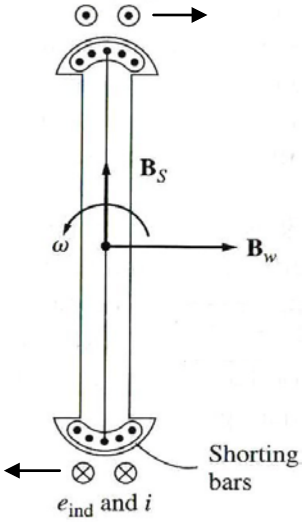

A simplified diagram of a salient two-pole machine showing amortisseur windings.

It shows the shorting bars at the ends of the two rotor pole faces connected by wires. (This is not quite the way normal machines are constructed, but it is useful when used to understand how the windings work.)

**Assumptions:**

- Initially the **main rotor field winding** is **disconnected**.
- A **three-phase set of voltages is applied** to the stator of the machine.

$t = 0$ s

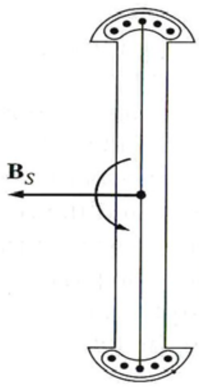
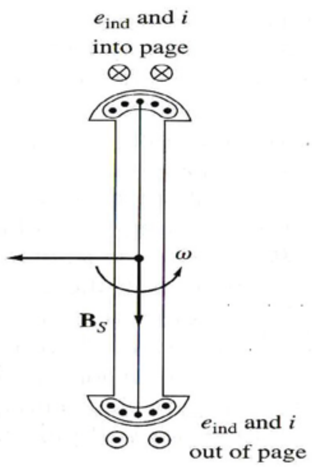
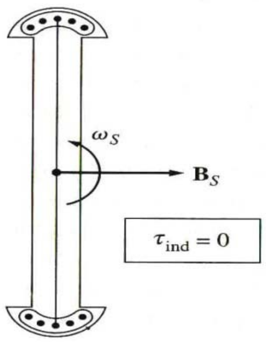



- Assume that  is vertical and sweeps along in a **counterclockwise** direction.
- $\bar{B}_S$ **induces voltage in the bars** of the amortisseur winding given by:

$$e_{\text{ind}} = (\bar{v} \times \bar{B}) \cdot \bar{l}$$

  where $\bar{v}$ = velocity of the bars relative to the magnetic field

- At the top bars, $\bar{v}$ is to the right. Hence, $e_{\text{ind}}$ is out of page.
- At the bottom bars, $\bar{v}$ is to the left. Hence, $e_{\text{ind}}$ is into of page.

| | |
|---|---|
| | o This causes current to flow and **results in a winding magnetic field** $\bar{B}_W$ pointing **to the right**.<br><br>o Thus, **counterclockwise torque** is produced on the bars (and rotor). |
| *t* = 1/240 s<br> | o $\bar{B}_S$ has rotated by 90°**.**<br><br>o The **rotor has barely moved** (it can't speed up in such a short time)<br><br>o $\boldsymbol{e_{ind}}$ **= 0** (because $\bar{v}$ parallel to $\bar{B}$)<br><br>o Thus, no current flows in windings and **induced torque is zero**. |
| *t* = 1/120 s<br> | o $\bar{B}_S$ has rotated by 90° and **rotor still has not moved**.<br><br>o $e_{ind}$ is out of page in bottom bars and is into the page in the top bars.<br><br>o This causes current to flow and **results in a winding magnetic field** $\bar{B}_W$ pointing **to the left**.<br><br>o Thus, **counterclockwise torque** is produced on the bars (and rotor). |
| *t* = 3/240 s<br> | o The condition of the **rotor is exactly as at *t* = 1/240s**, hence **induced torque is zero**. |

Notice that the torque induced is **always unidirectional** and the **net torque is non-zero**, the motor's **rotor speeds up**.

The final effect of this starting method is that the rotor will spin at **near synchronous speed**. Once it is near synchronous speed, the **field windings need to be switched on** to enable the **rotor to lock on to the stator magnetic field**.

In a **real machine**, field windings are **not open-circuited** during starting procedure to **avoid very high voltages** from occurring if they were left open-circuited.

When field windings are short-circuited:

- No dangerous voltages are produced.
- Current will also be induced in them by the rotating $\bar{B}_S$ which contributes **extra starting torque** to the motor.

To summarise, the **procedure required to start a synchronous motor having amortisseur windings** is:

1. **Disconnect field windings** from their dc power source and **short them out**.

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

3. **Connect the dc field circuit to its power source**. After this is done, the **motor will lock into step** at synchronous speed, and **loads may be added** to its shaft.

## The effect of amortisseur windings on motor stability

The advantage of this starting method is that it **tends to dampen out the load or other transients on the machine.**

If rotor speed = $n_{sync}$, no voltage is induced in amortisseur windings.

If rotor speed < $n_{sync}$, voltage is induced in the windings due to relative motion between rotor and stator magnetic field. Hence, current flows in the amortisseur winding and a field is created. This field which interacts with the stator field to produce a torque that tends to speed up the machine.

If rotor speed > $n_{sync}$, a torque is produced that tends to slow down the machine.

Hence, the amortisseur windings may act as a dampening effect to **slow down a fast machines and to speed up slow machines**.