Synchronous Machines

Alternators

and

Motors

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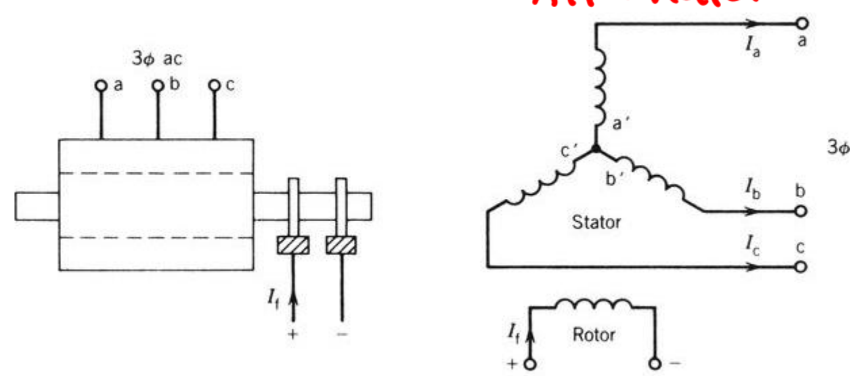
Synchronous Machines

- A Synchronous machine rotates at a constant speed in the steady state
- The rotating air gap field and the rotor in the synchronous machine rotate at the same speed, called the synchronous speed
- Synchronous machines are used primarily as Generators of electrical power
- Synchronous Generators or Alternators
- A synchronous machine is a doubly excited machine
- Its rotor (field winding) poles are excited by a DC current and its stator (armature) windings are connected to the AC supply
- The air gap flux is the resultant of the fluxes due to both rotor current and stator current

synchronous Alternator



Synchronous Alternators (Generators)

- 3-phase synchronous generators are the primary source of all the electrical energy we consume
- Large machines generating electrical power at hydro, nuclear, or thermal power stations
- Converts mechanical power to AC electrical power, in power ranging up to 1500 MVA
- The source of mechanical power is prime mover and may be a diesel engine, a steam turbine, a water turbine or any similar device
- For high speed machines, the prime movers are usually Steam Turbines employing fossil or nuclear energy resources
- Low speed machines are often driven by Hydro-turbines that employ water power for generation

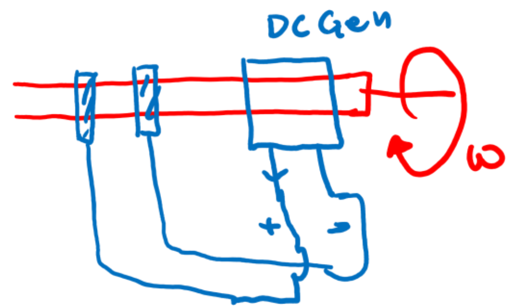
Synchronous Alternator

Types of Synchronous Alternators

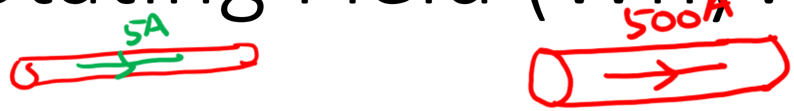
- Synchronous generators are built with either a stationary or a rotating DC magnetic field
- According to the arrangement of the field and armature windings, Synchronous machines may be classified as rotating-armature type or rotating field type
  stationary field type   stationary armature type
- Stationary field or Rotating-Armature Type:
  - the armature winding is on the rotor and the field system is on stator
  - The salient poles create DC field, which is cut by the rotating armature.
  - The armature consists of a 3-phase winding whose terminals are connected to three slip-rings mounted on the shaft. A set of brushes, sliding on the slip rings, enables the armature to be connected to an external 3-phase load
  - v, f
  - The armature is driven by a prime mover and as it rotates, a 3-phase voltage is induced, whose value depends on the speed of rotation and on the DC exciting current in the stationary poles. The frequency of the induced voltage depends on the speed and the number of poles on the field
- Stationary field generators are used when power output is less than 5 kVA

Types of Synchronous Alternators

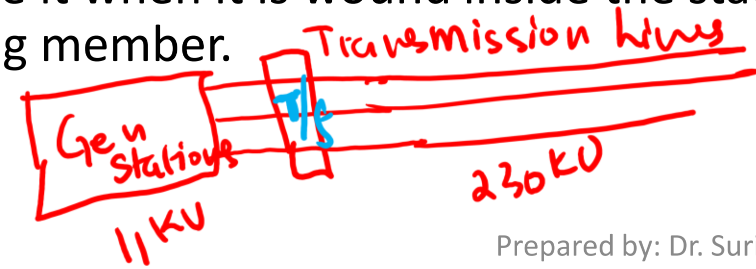
- Rotating-Field or Stationary Armature Type: the armature winding is on the stator and the field system is on the rotor
  - Stator – 3-phase winding in which the AC emf is generated is directly connected to the load, no slip-rings and brushes required
  - Rotor – field winding excited by a DC generator, usually mounted on the same shaft



Synchronous Alternator – Stationary Armature or Rotating Field (Why?)



- Large power capacity generator requires thicker conductors in its armature winding to carry high currents and to minimize copper losses. Deeper slots are required to house thicker conductors. Because the stator can be made large enough with fewer limitations, it inadvertently becomes the preferred member to house the armature conductors
- As the output of a synchronous generator is of alternating type, the armature conductors in the stator can be directly connected to the transmission line. This eliminates the need for slip rings for AC power output.
- As most of the heat is produced by the armature winding, an outer stationary member can be cooled more efficiently than an inner rotating member
- As the induced emf in the armature winding is quite high, it is easier to insulate it when it is wound inside the stationary member rather than the rotating member.



Synchronous Alternator - Construction

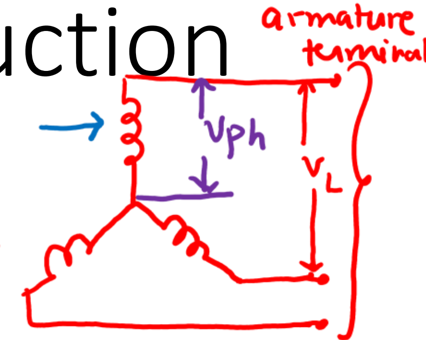
- Stator: the stator, also known as the armature, of a synchronous machine is made of thin laminations of highly permeable (μ) steel in order to reduce the core losses. The stator laminations are held together by a stator frame. The frame may be made from cast iron. The frame is designed not to carry the flux but to provide mechanical support to the machine. The inside of the stator contains a set of slots that carry 3-phase armature windings. The armature winding is always connected in WYE and the neutral is connected to ground. The induced emf in large machines is in kv with a power handling capability in MVA.

Synchronous Alternator - Construction

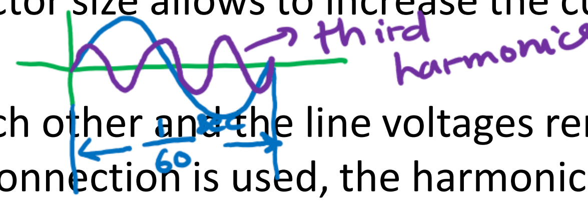
- Stator:

$V_{ph} = \frac{V_L}{\sqrt{3}} = 0.58\, V_L$

= 58% of the line voltage



- A WYE connection is preferred to a DELTA connection because
  - The voltage per phase is only $1/\sqrt{3}$ or 58% of the voltage between the lines. The highest voltage between the stator conductor and the grounded stator core is only 58% of the line voltage. The amount of insulation required in the slots is less and therefore the conductor size (cross-section) can be increased. A larger conductor size allows to increase the current and power output from the machine. MVA / VA



  - With a WYE connection, harmonics (third) cancel each other and the line voltages remain sinusoidal under all load conditions. When a DELTA connection is used, the harmonic voltages do not cancel, but add up. As the DELTA is closed on itself, they produce a third harmonic circulating current, which increases the I^2R losses.

- The line voltage of a synchronous generator depends on its kVA rating. The greater the power rating, the higher the voltage. However, the nominal line-to-line voltage generally do not increase beyond 25 kV because the increased slot insulation take up valuable space at the expense of the copper conductors.

Synchronous Alternator - Construction

- Number of Poles:
  - The # of poles on a synchronous generator depends on the speed of rotation and frequency of the produced voltage?
  - For example, a stator conductor that is successively swept by the N and S poles of the rotor. If a positive voltage is induced when an N pole sweeps across the the conductor, a similar negative voltage is induced when the S pole sweeps by. So, every time a complete pair of poles crosses the conductor, the induced voltage goes through a complete cycle. The alternator frequency then is given by:

$$f = \frac{PN}{120}$$

$$N_s = \frac{120f}{P}$$

  - f – frequency of the induced voltage (Hz)
  - P – no of poles on the rotor
  - N – speed of the rotor (RPM)

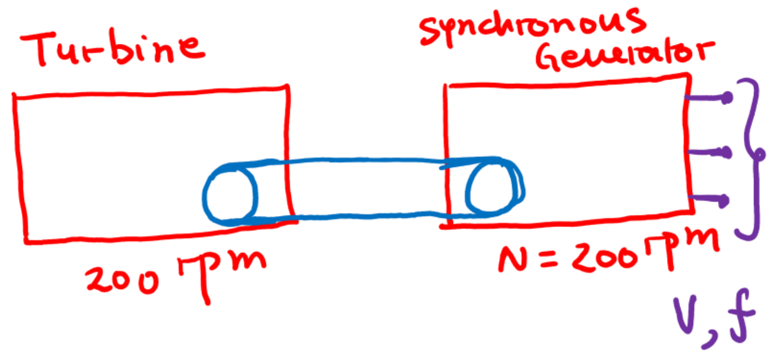
Synchronous Alternator - Construction

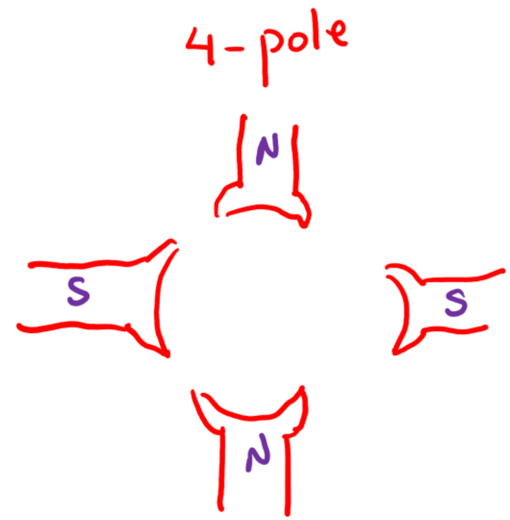
- Number of Poles:
  - Example: A hydraulic turbine turning at 200 rpm is connected to a synchronous generator. If the induced voltage has a frequency of 60 Hz, how many poles does the rotor have?

$$N_s = \frac{120 f}{P}$$

$$f = \frac{PN}{120}$$

$$P = \frac{120 \times 60}{200} = 36 \text{ poles}$$





36 Poles, or 18 pairs of N and S poles

Synchronous Alternator - Construction

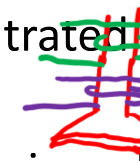
- Rotor: the rotor is rotated at synchronous speed by a prime mover. The rotor has as many poles as the stator, and the rotor winding carries DC current so as to produce the constant flux per pole.
- Synchronous generators are built with two types of rotors:
  - Cylindrical rotor
  - Salient-pole rotor

Synchronous Alternator - Construction

- Salient-Pole Rotor:
  - driven by low-speed hydraulic turbines

$$P = \frac{120f}{N}$$

  - For producing a frequency of 50 or 60 Hz, large # of poles are required on the rotor
  - Large diameter to house large number of poles
  - Salient poles are mounted on a large circular steel frame which is fixed to a revolving vertical shaft. Salient poles have concentrated winding and a non uniform air gap



→ DC field wdg
→ squirrel cage winding (Damper wdg)

  - In addition to DC field winding, a squirrel cage winding is embedded in the pole faces. No current flows through squirrel cage winding under normal conditions. For sudden load changes, rotor speed fluctuates away from synchronous speed, this induces voltage in squirrel cage winding and large current flows through it. This current reacts with the stator produced magnetic field, producing forces which dampen the oscillation of the rotor. Squirrel cage winding is also called DAMPER winding

Synchronous Alternator - Construction

@ $f = 60\,Hz$

P	N
2	3600
4	1800
6	1200
8	900

$\frac{^{30}\cancel{120} \times \cancel{60}\ 30}{\cancel{8}\ \cancel{4}}$

$P = \frac{120f}{N}$

- Cylindrical Rotor:
  - driven by high-speed steam turbines
  - To generate a frequency of 50 or 60 Hz, small # of poles are required. But, the least # of poles possible is 2 and that fixes the highest possible speed. On a 60Hz system, highest possible speed is 3600 rpm. The next lower speed is 1800 rpm corresponding to a 4 pole machine.
  - Steam-turbine generators has 2 or 4 poles
  - It is made of a smooth solid forged steel cylinder with a number of slots on its outer periphery. These slots are designed to accommodate the field winding
  - Winding is distributed and there is a uniform air gap
  - Rotors are long and small in diameter
  - High speed produces strong centrifugal forces, which put an upper limit on the diameter of the rotor

Synchronous Alternator – Field excitation

source to supply DC current to the field winding

- Field excitation: objective is to provide
  - Stable AC terminal voltage
  - Respond to sudden load changes, in order to maintain system stability
- Field excitation: two DC generators are used
  - Main exciter
  - Pilot exciter
- Main exciter provides the field current to the filed of the synchronous generator through brushes and slip rings. Exciter voltage ranges 125 V - 600 V. It is regulated automatically by a control signal produced by the pilot exciter.
- Brushless excitation: 3 phase stationary field generator + rectifier. DC output from the rectifier is fed into the field of the synchronous generator.

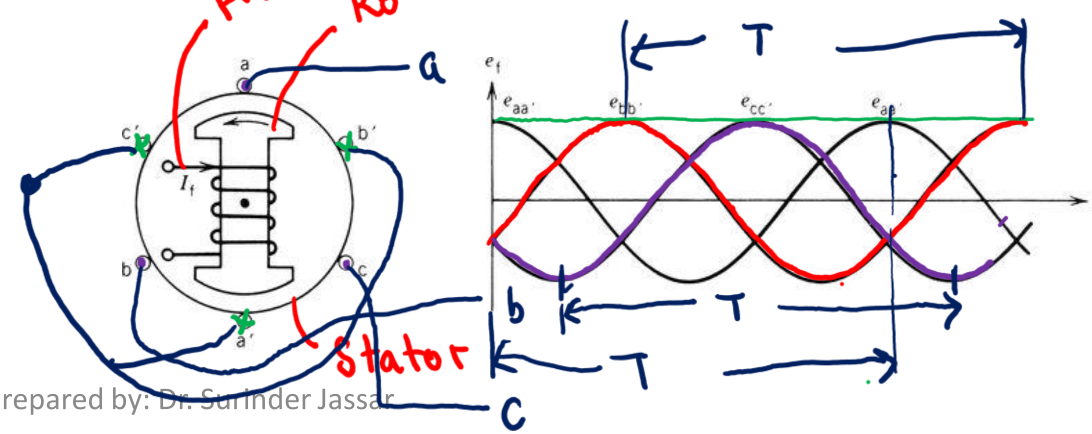
Synchronous Alternator - Operation

- Rotor of the generator is driven by a prime mover
- A DC current is flowing in the rotor winding which produces a rotating magnetic field within the machine. This field is called excitation field because it is produced by excitation current
- The rotating magnetic field induces a three-phase voltage in the stator winding of the generator. These induced voltages have the same magnitude but are phase displaced by 120^0.
- The rotor speed and frequency of the induced voltage are related by: $N = \frac{120f}{P}$
  - N – rotor speed in rpm
  - P - # of poles
  - f – frequency of the induced voltages (Hz)

$e_{aa'} = v_{aa'}$

$f = \frac{1}{T}$

$v = V_m \cos(\omega t \pm \delta)$



Induced AC Voltage

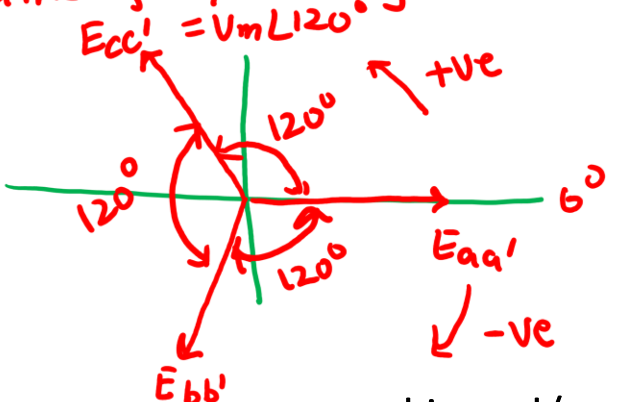
coils [winding]

$E_a = E_0 = K_a \Phi \omega$

$\rightarrow \left.\begin{matrix} aa' \\ bb' \\ cc' \end{matrix}\right\}$ armature/stator

- In three coils, each of N turns, placed around the rotor magnetic field, the induced voltage in each coil is of the same amplitude, and displaced in phase by 120^0.

same frequency



$e_{aa'} = V_m \cos \omega t$ $\qquad E_{aa'} = V_m \angle 0°$

$$e_{aa'} = N\phi\omega \cos \omega t$$

$$e_{bb'} = N\phi\omega \cos\left(\omega t - 120^0\right) \quad = V_m \angle -120°$$

$$e_{cc'} = N\phi\omega \cos\left(\omega t - 240^0\right) \quad = V_m \angle -240° = V_m \angle 120°$$

- ω – rotor speed in rad/sec
- N - # of turns in each phase of the stator winding
- ϕ – flux due to the current flowing through the field winding (Wb)

Induced AC Voltage

$V_m = N\phi\omega$

$V_{rms} = \frac{V_m}{\sqrt{2}} = \frac{N\phi\omega}{\sqrt{2}}$

$= k\phi\omega$

peak voltage

$$E_{\max} = N\phi\omega = N\phi 2\pi f = 2\pi N\phi f$$

RMS voltage

$$E_A = \frac{2\pi}{\sqrt{2}} N\phi f = \sqrt{2}\pi N\phi f$$

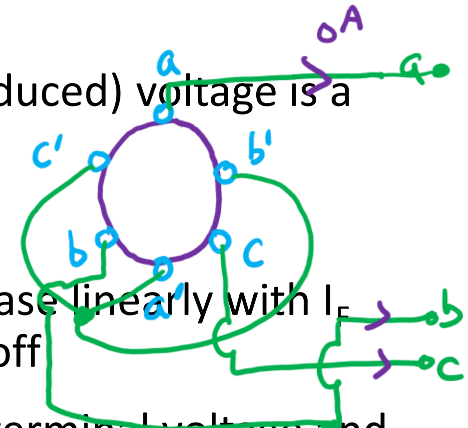
- Amplitude of internally generated stator voltage is:

$$E_o = E_A = k\phi\omega$$

- k is the constant representing the construction of the machines, ϕ is the flux and ω is the rotational speed in rad/sec

Induced AC Voltage

- As the flux depends on the field current, internal generated (induced) voltage is a function of the rotor field current
- Initially, the voltage increases linearly with the field current
- As the field current is further increased, the flux does not increase linearly with I_F because of the saturation of the magnetic circuit and E_A levels off
- If the machine terminals are kept open, E_A will be same as the terminal voltage and can be measured using a voltmeter
- Curve is known as Open-circuit characteristics (OCC) or magnetization characteristics or No-load Saturation curve of the synchronous machine



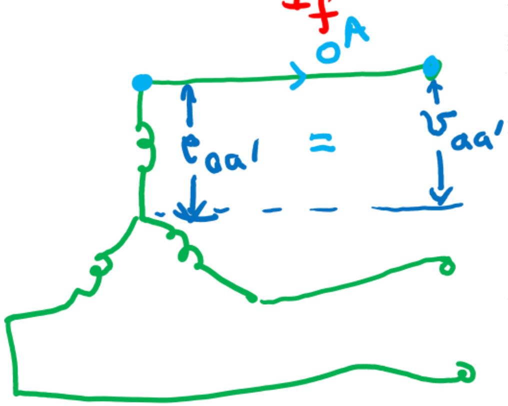
$E_A = K \phi \omega$

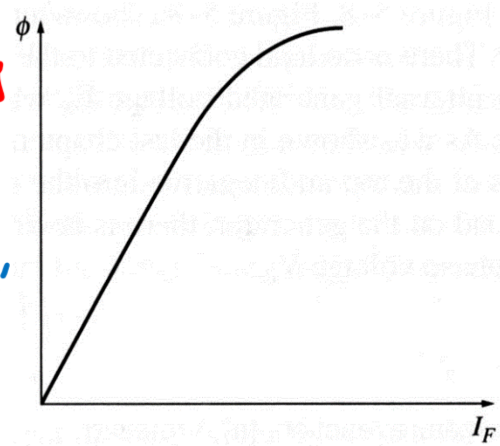
constant

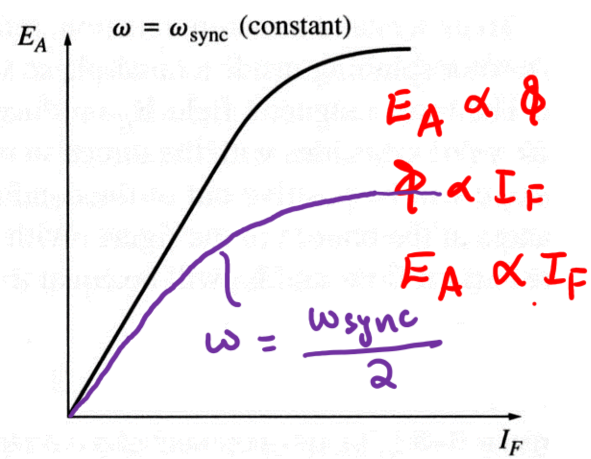
constant

$E_A = K \phi \omega$

produced by I_f

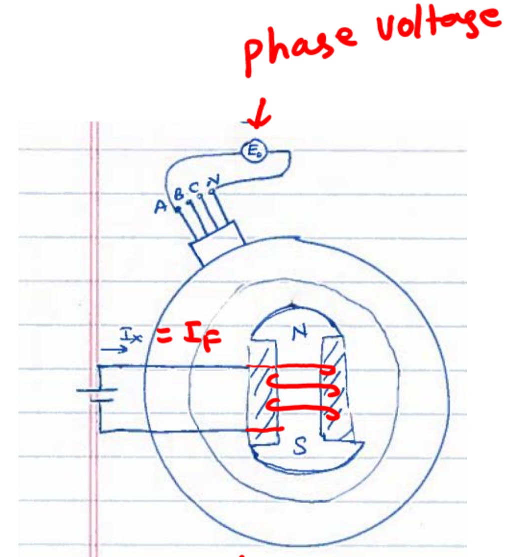


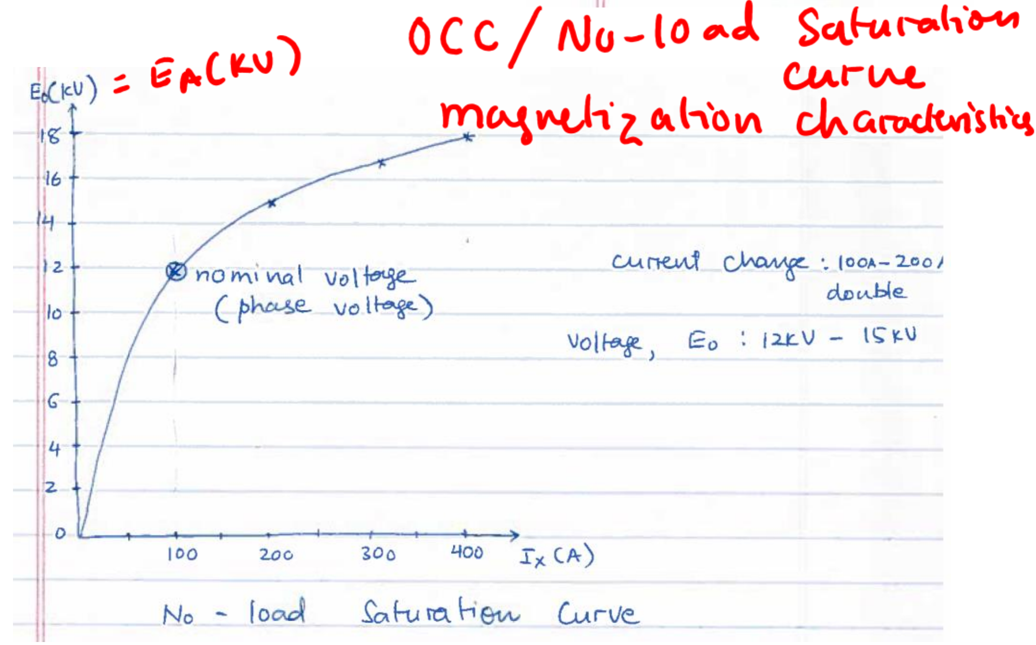




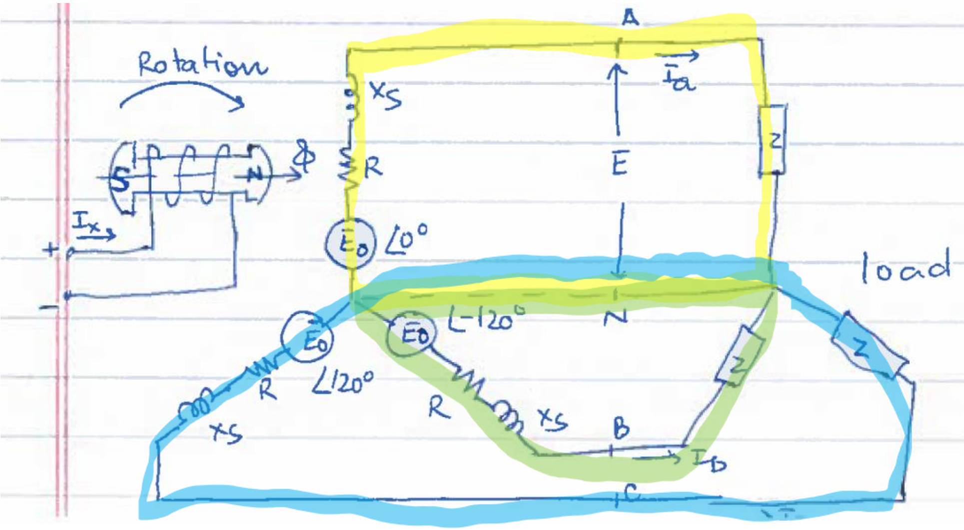
No Load Saturation Curve

- Consider a 2 pole synchronous alternator operating at no load
- Variable exciting current I_X produces the flux in the air gap
- The leads from 3-phase, Y connected stator are brought out to terminals A, B, C, N
- Gradually increase the exciting current I_X and observe the AC voltage E_o between terminals A and N
- For small values of I_X, the voltage E_o increase in direct proportion to the exciting current
- As the material begins to saturate, the voltage rises much less for the same increase in I_X



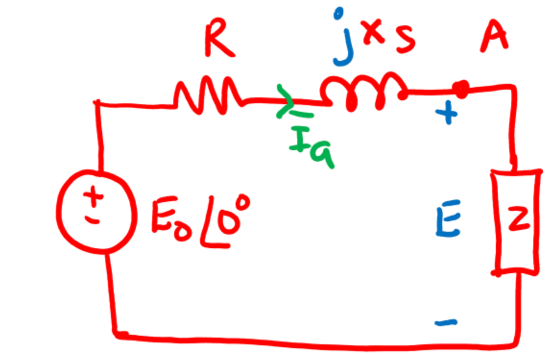


Equivalent Circuit model of a Synchronous Alternator



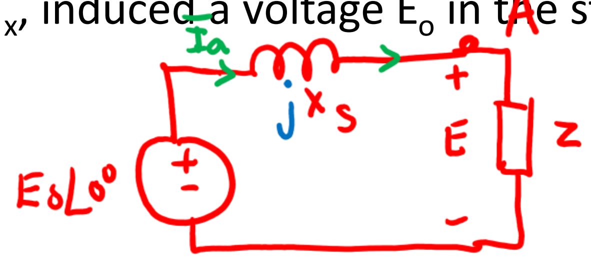
3-phase balanced system

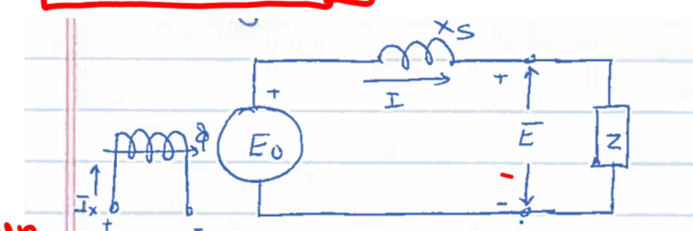
Z is same in each phase



$X_s >> R \rightarrow$ ignore R

- One phase of a WYE connected motor
- The flux ϕ created by the DC exciting current I_x, induced a voltage E_o in the stator
- E_o varies with the DC excitation





$R = R_a \rightarrow$ armature winding resistance

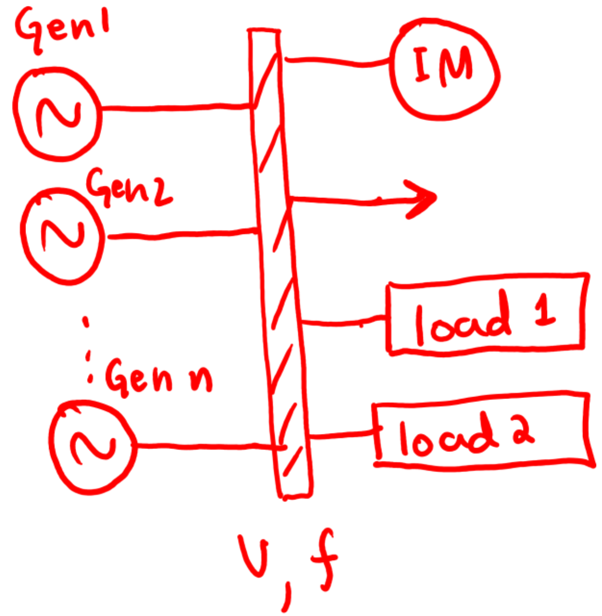
$X_s \rightarrow$ armature winding reactance [synchronous reactance]

$E_o \rightarrow$ internally induced armature voltage

$E \rightarrow$ armature terminal voltage

Synchronous Alternator Under Load

- Two types of loads to be considered:
  1. Isolated loads: supplied by a single generator
  2. The infinite bus



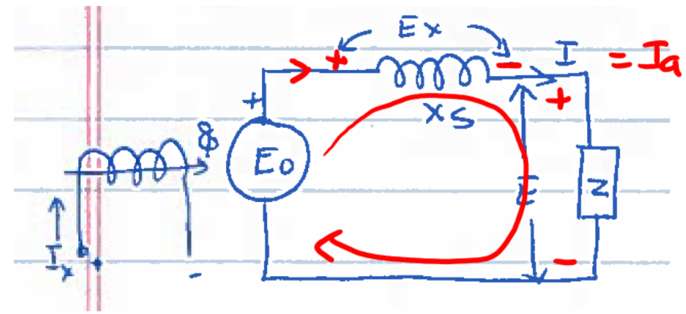
Synchronous Alternator Under Load

$\cos\theta \rightarrow$ phase angle of the impedance $\bar{Z}$

↳ phase angle b/w E and I

- Isolated Loads: lagging or leading power factor load

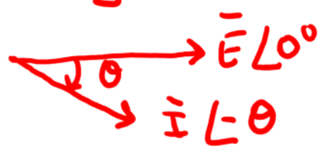
I lags behind E I leads E



KVL $\Rightarrow -\bar{E}_0 + (\bar{I}(jx_s)) + \bar{E} = 0$

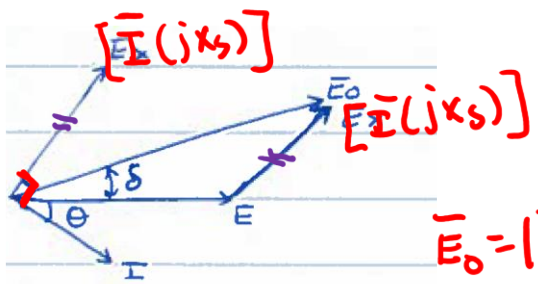
$$\bar{E}_0 = \bar{E} + [\bar{I}(jx_s)]$$

$$\bar{E} = |\bar{E}|\angle 0^\circ$$



$$\bar{E}_0 = \bar{E} + [\bar{I}(jx_s)]$$

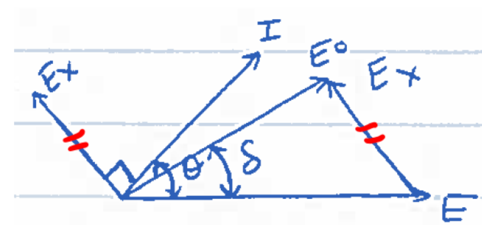
$$\bar{I} = |\bar{I}|\angle\theta$$



$$\bar{E}_0 = |\bar{E}_0|\angle\delta$$

Lagging power factor load

$$|\bar{E}_0| > |\bar{E}|$$



Leading power factor load

$$|\bar{E}_0| < |\bar{E}|$$

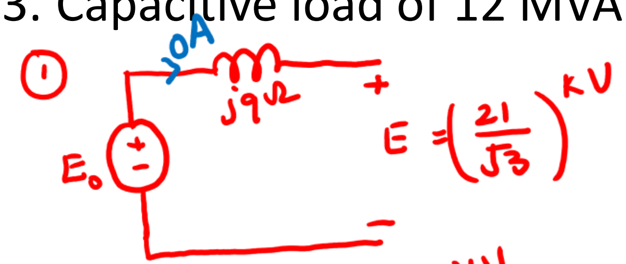
Synchronous Alternator: Example

X_s

A 36 MVA, 20.8 kV, 3-phase alternator has a synchronous reactance of 9 Ω and a nominal current of 1 kA. The no load saturation curve giving the relationship between E_o and I_X is given below. If the excitation is adjusted ($I_x = I_F$) so that the terminal voltage remains fixed at 21 kV (E), calculate the exciting current (I_x) required and draw the phasor diagram for the following condition:

1. No load
2. Resistive load of 36 MW
3. Capacitive load of 12 MVAR

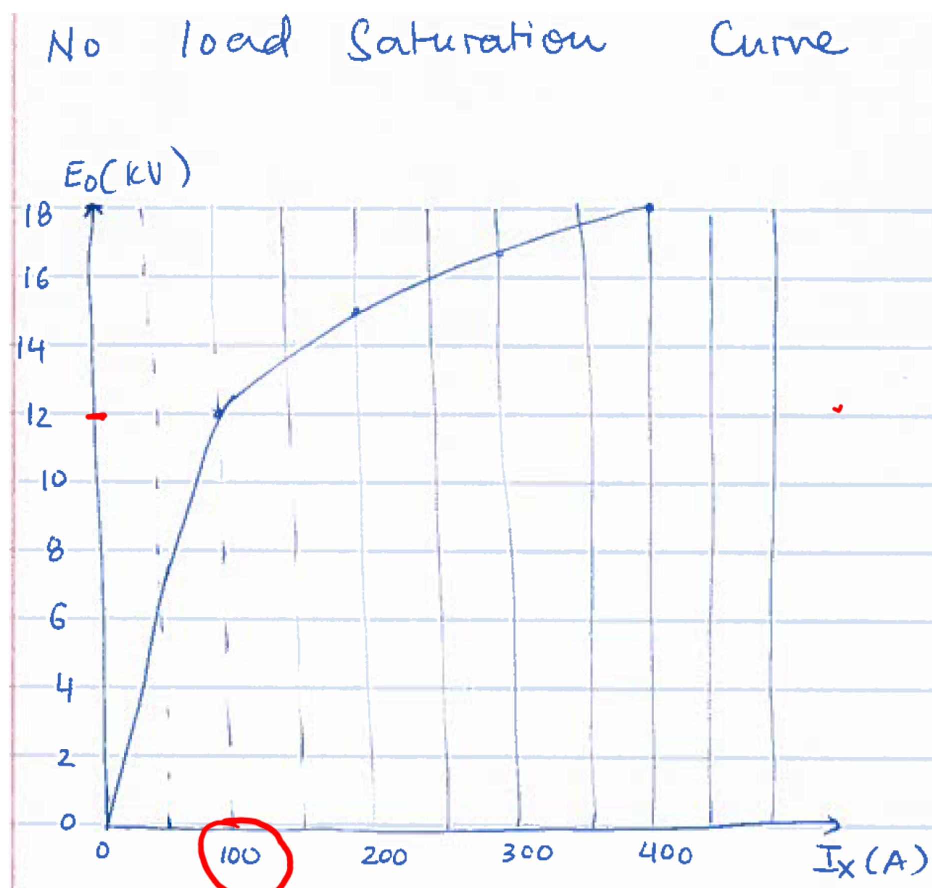
①



$E_o = \frac{21}{\sqrt{3}}$ kV $= 12$ kV

from the graph

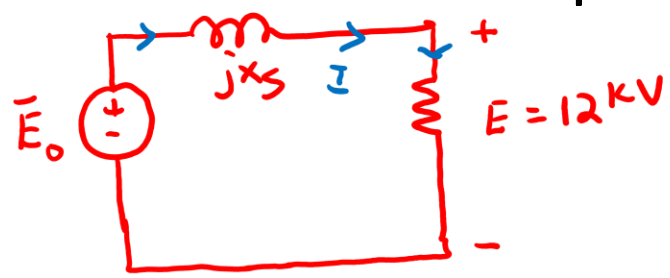
$E_0 = 12$ kV, $I_x = 100$ A



Synchronous Alternator: Example

Resistive load of 36 MW 3-phase

Capacitive load of 12 MVAR



$I = \frac{12^{MW}}{12^{kV}} = 1^{kA}$

$P = \frac{36}{3} = 12^{MW}$

$P = VI$

$\bar{E}_o = \bar{E} + [\bar{I}\,(jx_s)]$

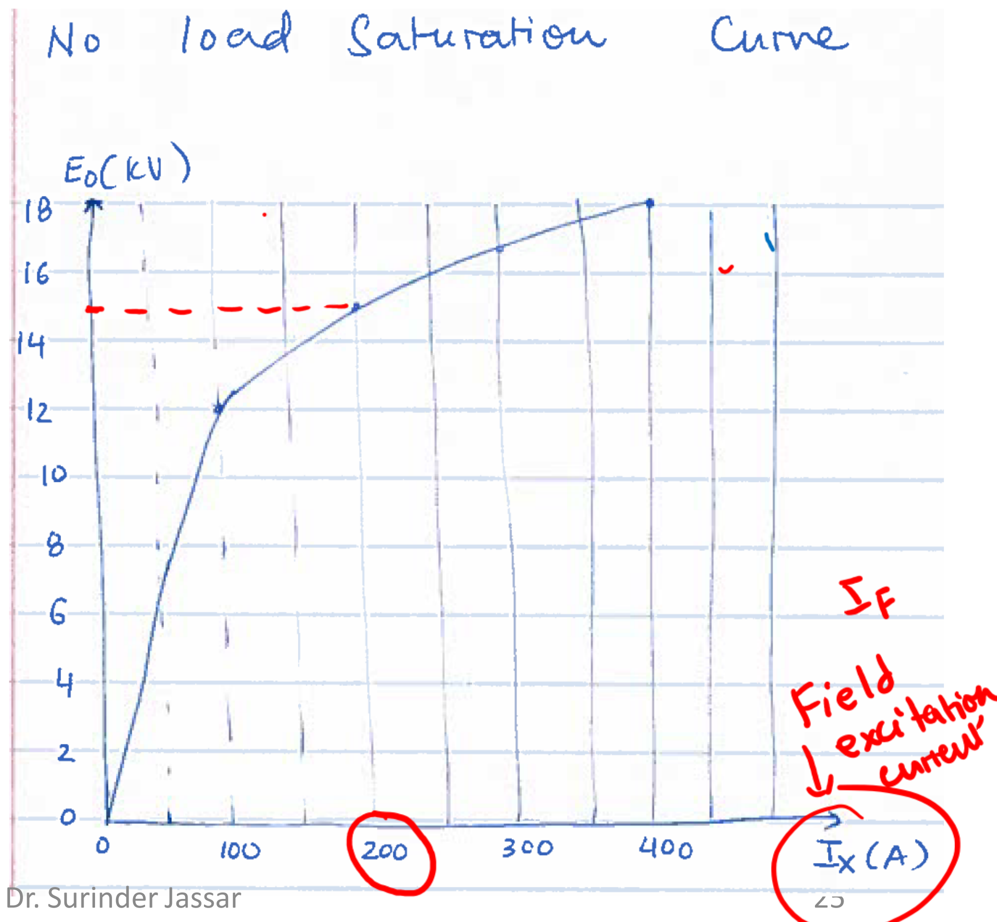
$\bar{E} = 12\angle 0^\circ \text{ kV}$

$\bar{I} = 1\angle 0^\circ \text{kA}$

$\bar{E}_o = [12\angle 0^\circ]^{kV} + [(1\angle 0^\circ)(j9)]^{kV}$

$\bar{E}_o = 15\angle 36.9^\circ \text{kV}$

from the graph $\begin{cases} E_o = 15^{kV} \\ I_x = 200^{A} \end{cases}$

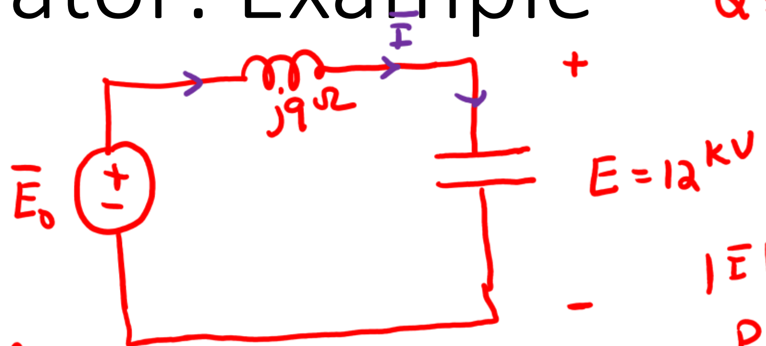


Synchronous Alternator: Example

$Q_{3\text{-}ph} = 12$ MVAR

$Q = \frac{12}{3} = 4$ MVAR

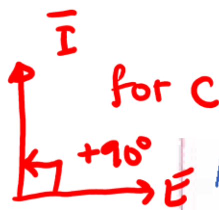
Capacitive load of 12 MVAR



$$\bar{E}_0 = \bar{E} + [\bar{I}(jX_s)]$$

$|\bar{I}| = \frac{4 \text{ MVAR}}{12 \text{ kV}} = \frac{1}{3}$ kA

$\bar{E} = 12\angle 0^\circ$ kV



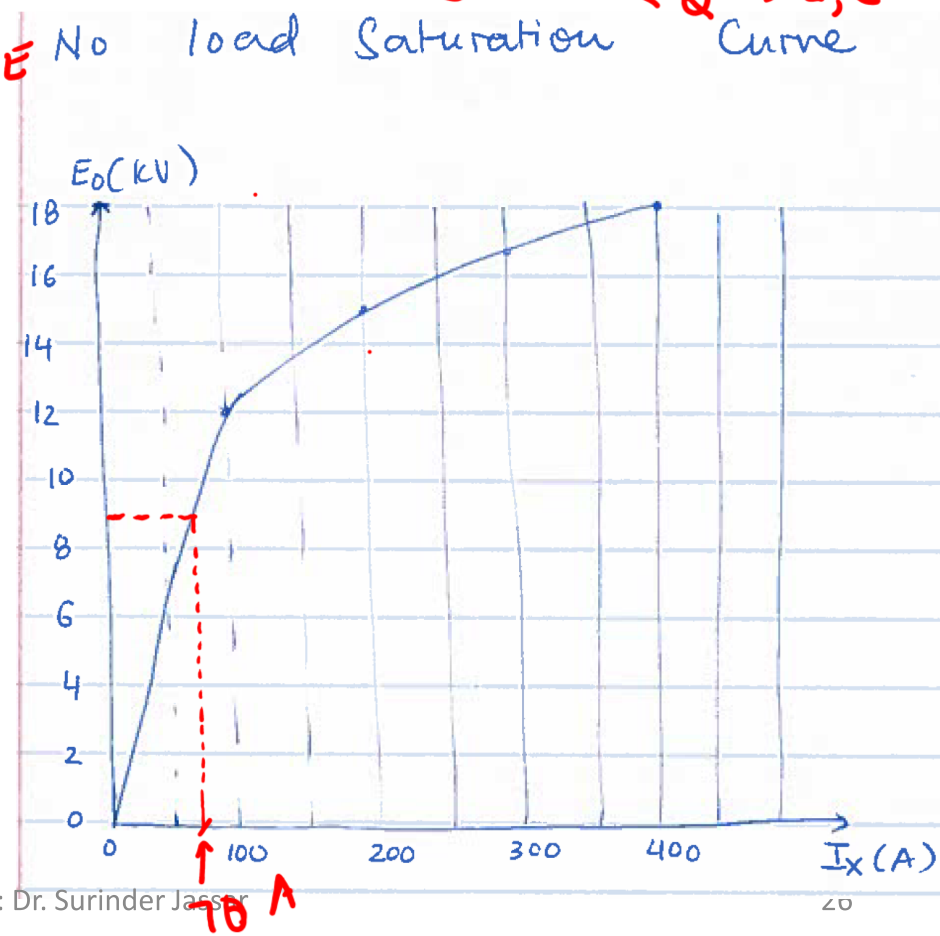
$S = VI$ < P → R; Q → L, C

$\bar{I} = \frac{1}{3}\angle 90^\circ$ kA

$$\bar{E}_0 = [12\angle 0^\circ]^{kV} + [(\tfrac{1}{3}\angle 90^\circ)(j9)]^{kV}$$

$$\bar{E}_0 = 9\angle 0^\circ \text{ kV}$$

from the graph: $E_0 \simeq 9$ kV, $I_x \simeq 70$ A



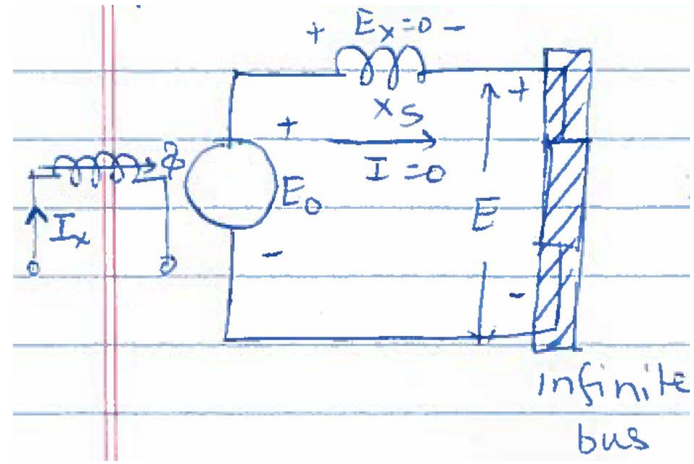
Synchronous Alternator Under Load – Infinite Bus

- An infinite bus imposes its voltage and frequency on all the generators connected to its terminals
- A generator connected to an infinite bus becomes part of the network comprising hundreds of other generators that deliver power to thousands of loads
- Then, what determines the power delivered by a particular generator
- Two parameters can vary as voltage and frequency are constant

1. Exciting current, I_X
2. Mechanical torque exerted by the turbine

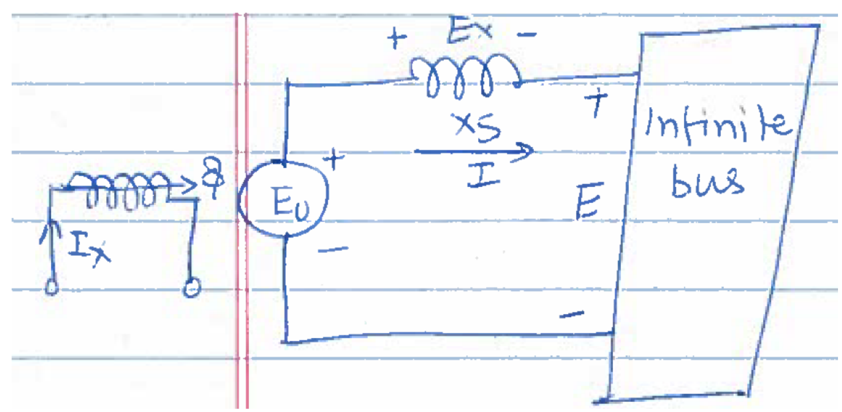
Synchronous Alternator Under Load – Infinite Bus

Effect of Varying the exciting current, I_X



Although the generator is connected to the system, it delivers no power

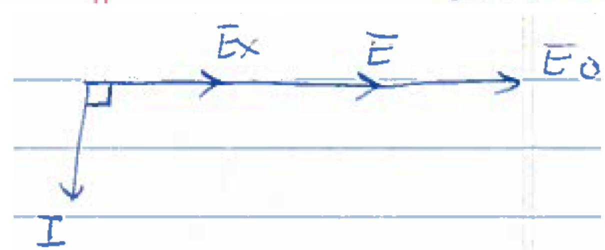
FLOAT on the line



As I_X increases, the E_o increases

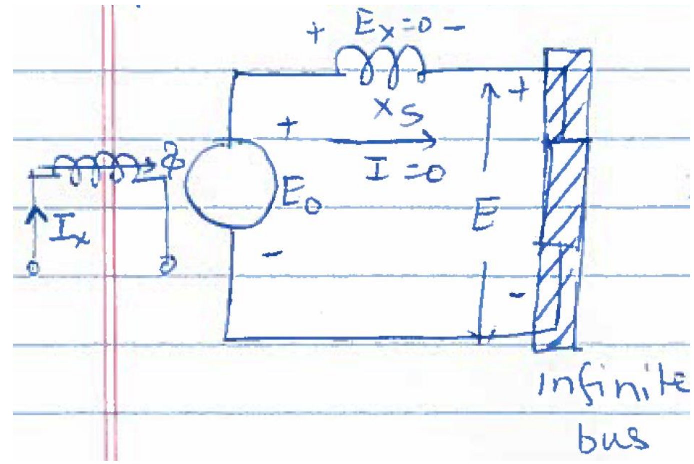
The generator supplies reactive power to the infinite bus. The reactive power increases as the Dc exciting current increases

Over Excited Generator



Synchronous Alternator Under Load – Infinite Bus

Effect of Varying the exciting current, I_X



Although the generator is connected to the system, it delivers no power

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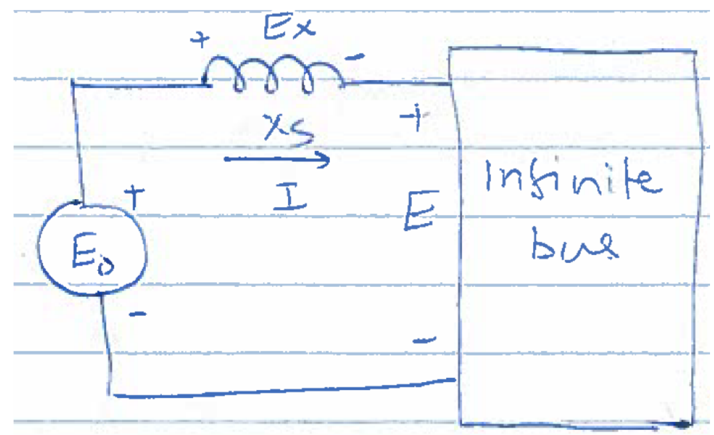
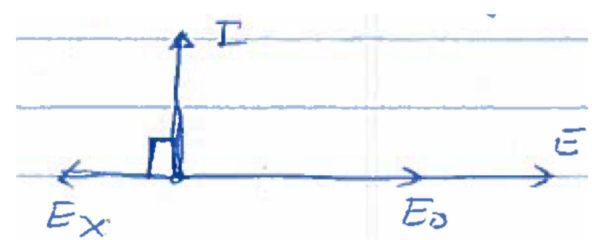


As I_X decreases, the E_o decreases

I leads E by 90^0

The generator see the system as a capacitor and draws reactive power from the infinite bus.

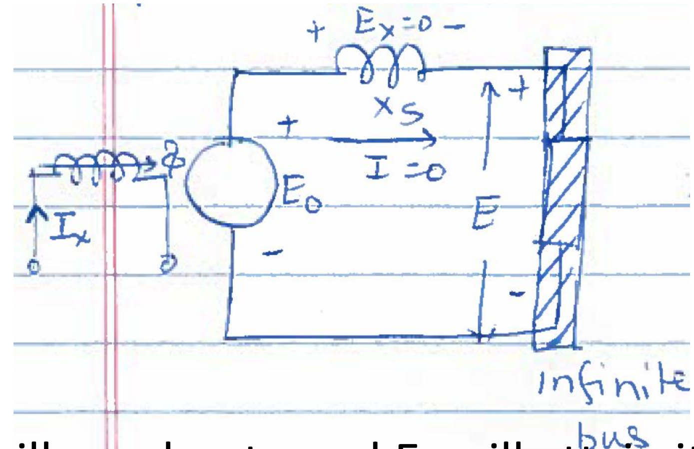
Under Excited Generator



Synchronous Alternator Under Load – Infinite Bus

Effect of varying the mechanical torque

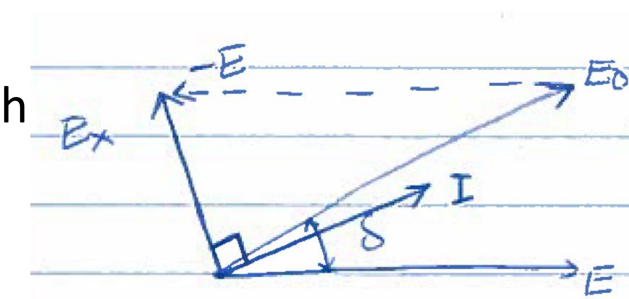
The generator is FLOATING on the line



As the mechanical torque increased, the rotor will accelerate and E_o will attain its maximum value a little sooner

E_o will slip ahead of E by an angle of δ

E_o = E, but $E_X = E_o - E$ will be non zero because of th



en E_o and E

I is almost in phase with E

Generator feeds active power into the system

As the mechanical power supplied by the turbine becomes equal to the Electrical power delivered to the system the rotor will cease to accelerate

Synchronous Alternator Under Load

The active power delivered by the Generator is:

$$P = \frac{EE_o}{X_s} sin\delta$$

P – active power, per phase (W)

E_o – induced line to neutral voltage (Volts)

E – terminal voltage per phase (Volts)

X_s – synchronous reactance, per phase (Ω)

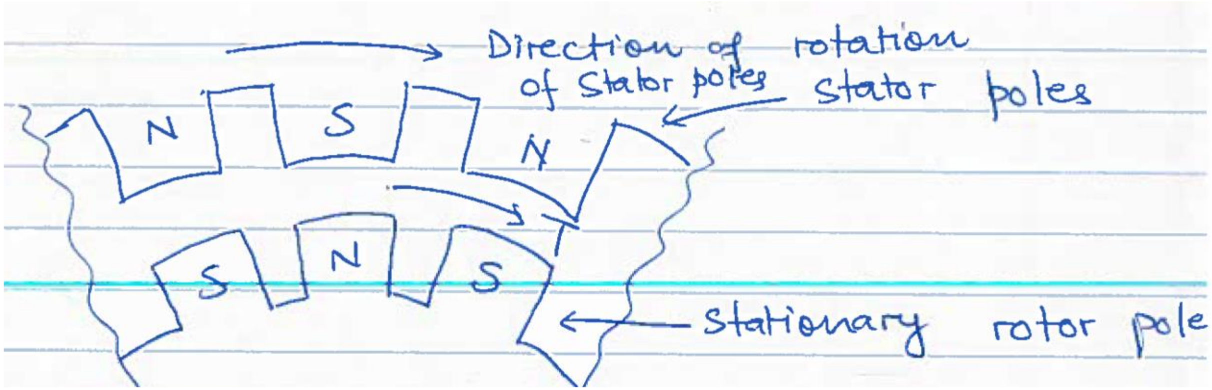
δ – torque angle between E_o and E (degrees)

Synchronous Alternator: Example

A 3-phase alternator has a synchronous reactance of 6 Ω and the excitation voltage E_o of 3 kV per phase. Calculate the line to neutral voltage E for a resistive load of 8 Ω and draw the phasor diagram.

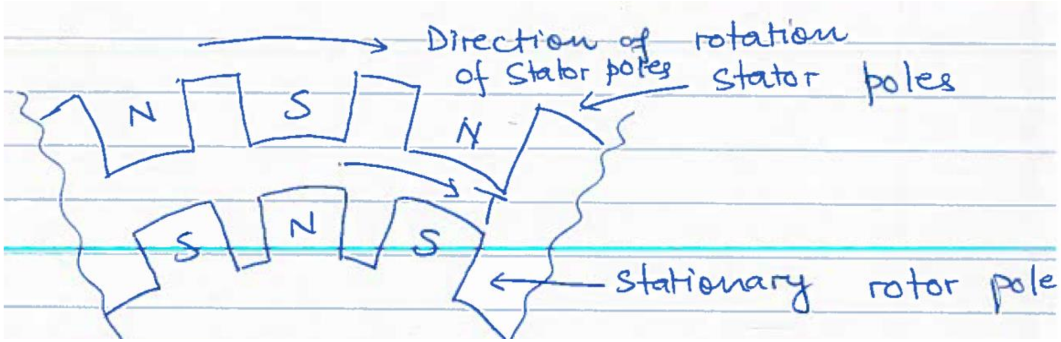
Starting a Synchronous Motor

- Field winding on the rotor is connected to a DC source. Current flowing through the field winding will set up stationary magnetic poles of alternate North and South
- Armature winding is laid out in the stator and is connected to a balanced 3-phase source.
- 3-phase currents flowing in the armature winding produce a rotating magnetic field rotating at synchronous speed. There will be moving North and South poles established in the stator



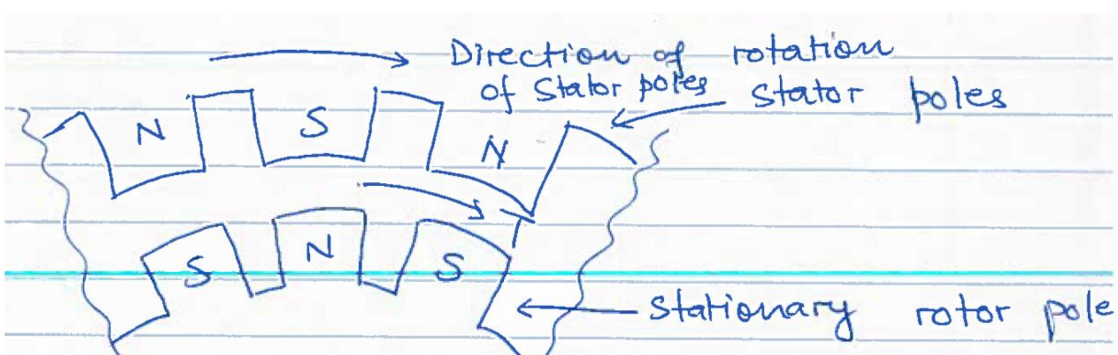
Starting a Synchronous Motor

- At any location in stator there will be a North pole at some instant of time and that will become a South pole after a time period corresponding to half a cycle i.e. = 1/(2f), where f is the supply frequency
- Consider stationary South pole in the rotor is aligned with the North pole in the stator winding at a particular instant of time as shown in the Figure below
- These two poles get attracted and try to maintain this alignment.
- Rotor poles try to follow the stator pole – Torque produced is in CW direction
- However, rotor cannot move instantaneously due to its mechanical inertia, it needs sometime to move



Starting a Synchronous Motor

- In the meantime the stator pole would quickly (half a cycle) change its polarity and becomes a South pole
- Force of attraction will no longer be present and instead like poles experience a force of repulsion – Torque will be produced in CCW direction.
- This condition will not last longer either as the stator pole would again change to North pole after a time of (t = 1/2f).
- Rotor will experience an alternating force which tries to move it CW and CCW at twice the frequency of supply
- Time = (1/2f) is small in comparison to the mechanical time constant of the rotor.



Starting a Synchronous Motor

- Rotor cannot move in any direction and continues to be stationary

- Conclusion: A Synchronous motor cannot be started from a standstill by applying ac to the stator. When ac is applied to the stator a high speed RMF appears around the stator. This RMF rushes past the rotor poles so quickly that the rotor is unable to get started. It is attracted first in one direction and then in the other and hence no starting torque.

- Synchronous motor is NOT self starting
- Synchronous Motor has NO Starting Torque

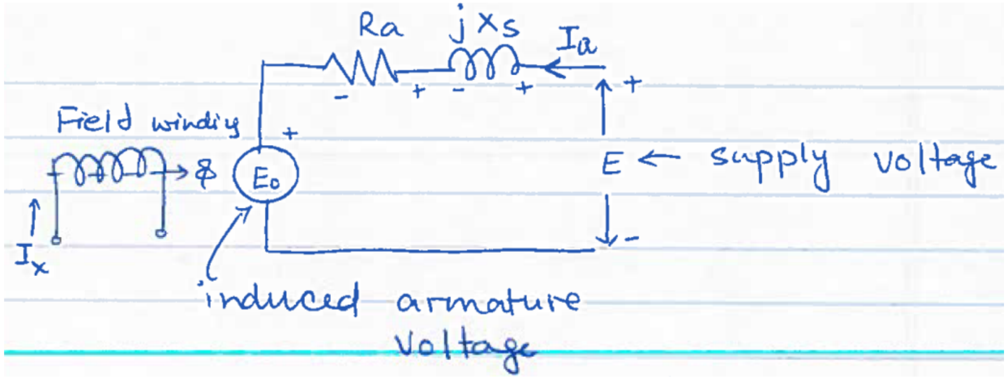
Improvement of starting torque

1. Reducing the supply frequency – if the rotating magnetic field of the stator in a synchronous motor rotates at a low enough speed, there will be no problem for the rotor to accelerate and to lock in with the stator's magnetic field. The speed of the stator magnetic field can then be increased to its rated operating speed by gradually increasing the supply frequency **f** up to its normal 60 Hz value

2. Start as an Induction Motor – additional winding (resembling the cage of an Induction motor) is mounted on the rotor. This winding is known as Damper winding. To start the motor, the field winding is left unexcited. Now, when armature winding terminals are connected to AC supply, the motor will start as an Induction Motor because the currents are induced in the damper winding to produce torque. The motor will speed up and reach synchronous speed. The rotor is closely following the stator poles. Now if the rotor poles will be excited by the field current from the DC source, they will be locked to the stator poles. At synchronous speed the damper winding has no part to play.
3. Apply reduced Stator voltage
4. Very large synchronous motors (20 MW and more) are brought to speed by using an auxiliary motor called PONY motor.

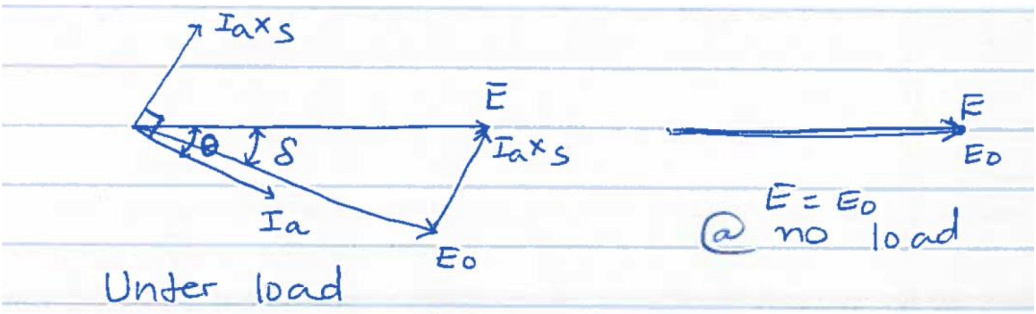
Equivalent Circuit model of a Synchronous Motor

- One phase of a WYE connected motor
- The flux ϕ created by the DC exciting current I_x, induced a voltage E_o in the stator
- E_o varies with the DC excitation



Equivalent Circuit model of a Synchronous Motor

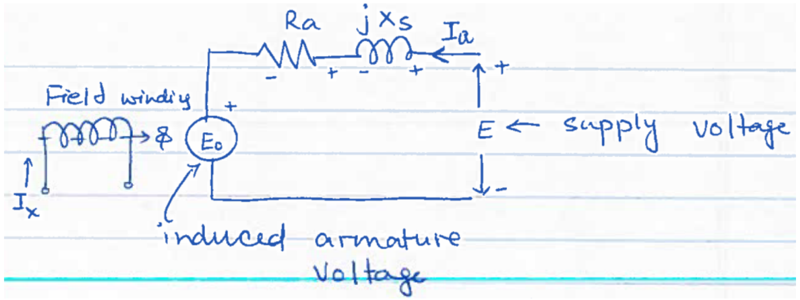
- The rotor and stator poles are aligned at no load, E_o = E and are in phase and I_a = 0
- When a mechanical load is applied to the shaft, the motor will start to slow down. The rotor poles will start to fall behind the stator poles. Due to this mechanical shift, E_o reaches its maximum value a little later than before. E_o will be δ degrees behind E. The mechanical shift between the rotor and stator poles produces an electrical phase shift δ between E_o and E. δ is called "Power angle" or "Torque angle" or "Load angle"
- Current I_a is nearly in phase with E, the motor absorbs active power. This power is entirely transformed into mechanical power except for small copper and iron losses in the stator



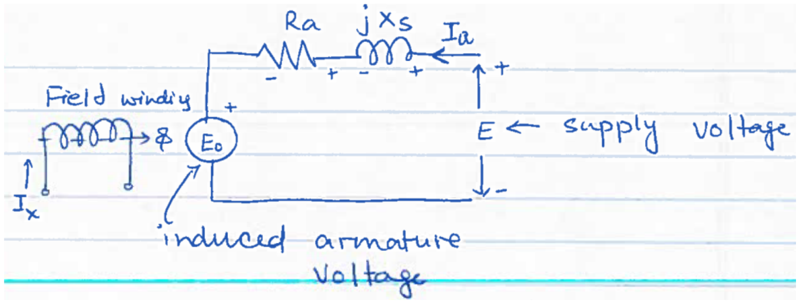
Synchronous Motor: Example

A 500 Hp, 720 rpm synchronous motor connected to a 3980 V, 3-phase line generates an excitation voltage E_o of 1790 V (line –to-neutral) when the DC exciting current is 25 A. The synchronous reactance is 22 Ω and the torque angle between E_o and E is 30^0. Calculate:

1. The AC line current I_a
2. The power factor of the motor
3. The approximate hp developed by the motor



Synchronous Motor: Example



Synchronous Motor: Power and Torque

When a synchronous motor operates under load, it draws active power from the line

$$P = \frac{E E_o}{X_s} sin\delta$$

P – mechanical power of the motor, per phase (W)

E_o – induced line to neutral voltage (Volts)

E – Line to neutral voltage of the source (Volts)

X_s – synchronous reactance, per phase (Ω)

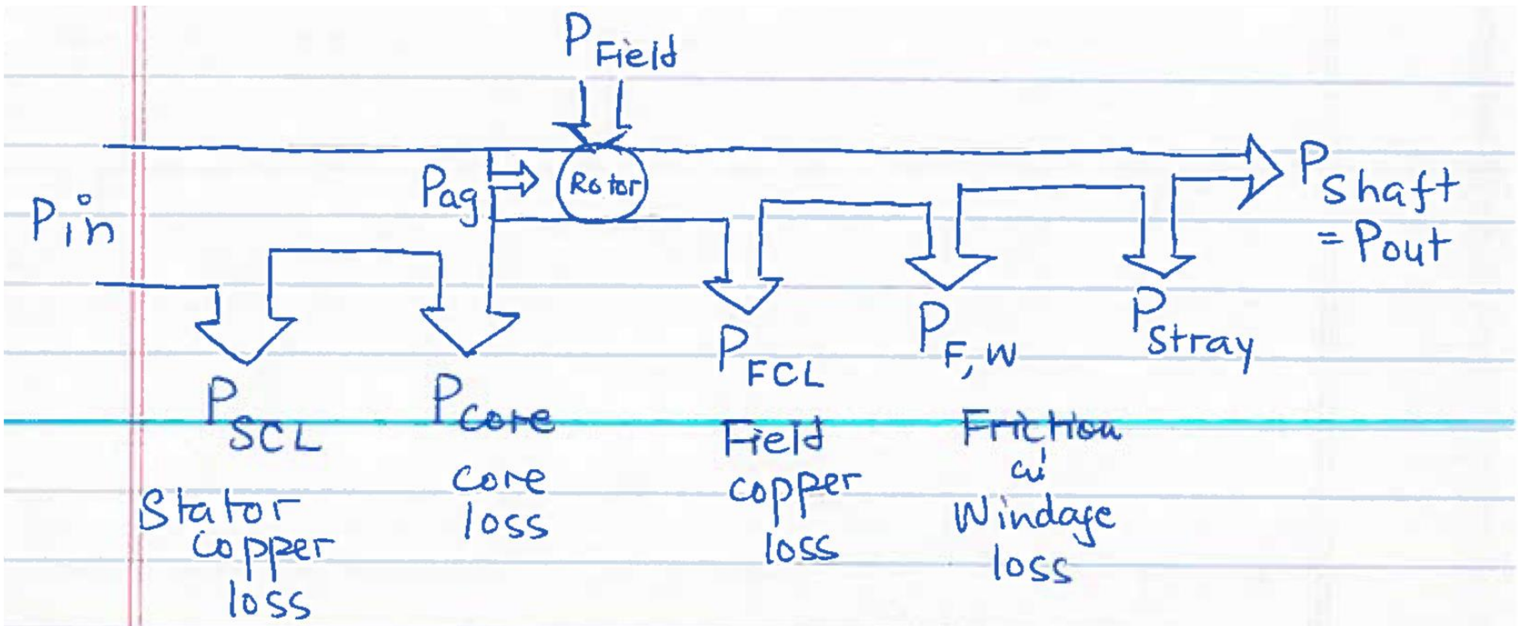
δ – torque angle between E_o and E (degrees)

Torque is directly proportional to the mechanical power because the rotor speed is fixed

$$T = \frac{9.55P}{N_s}$$

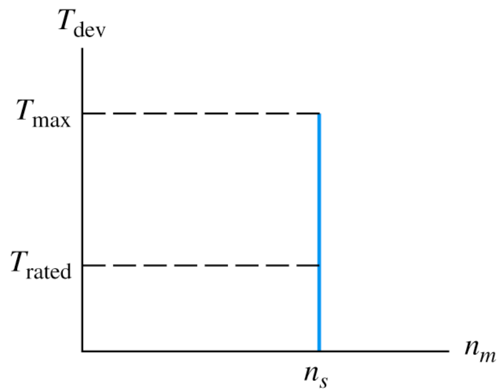
T – torque per phase (N-m)

Synchronous Motor: Losses and Efficiency



$$\eta = \frac{P_{shaft}}{P_{in} + P_{field}} \times 100\% = \frac{P_{shaft}}{P_{shaft} + P_{loss}}$$

Torque versus Speed



The motor speed is locked to the supply frequency

Speed remains constant regardless the load

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

Speed regulation of synchronous motors is 0%

Synchronous Motor: Example

A 6600 V, 3-phase, Y-connected synchronous motor draws a full-load current of 80 A at 0.8 p.f. (leading). The per phase armature resistance and synchronous reactance are 2.2 Ω and 22 Ω, respectively. If the stray loss of the machine are 3200 W, Calculate:

1. The induced armature voltage (line to line value) [E_o = 8594.97 V]
2. The output power [P_{out} = 86.18 kW]
3. The efficiency [93.79%]

Synchronous Motor: Example

Synchronous Motors steady state operation – Effect of Load changes

Initially, the synchronous motor operates with a leading power factor (capacitive) load

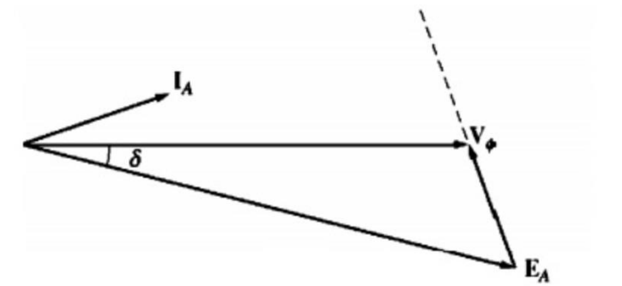
When, the load on the motor increases, the rotor slows down and the power or torque angle δ increases

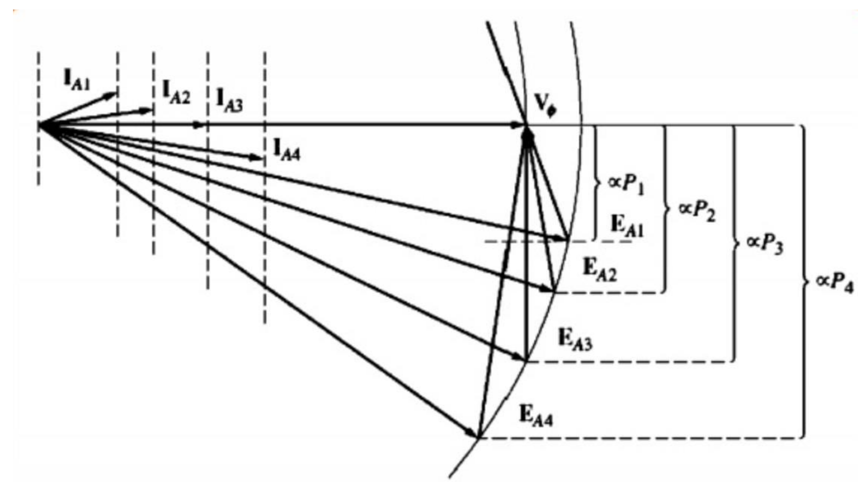
With increase in torque angle, the induced torque will increase

Increase in induced torque will speed up the rotor up to the synchronous speed

So, the motor will operate at synchronous speed with increased torque angle

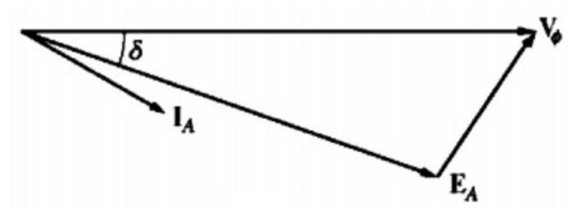
The terminal voltage and frequency supplied to the motor are constant, the magnitude of the induced armature voltage must remain constant ($E_o = k\phi\omega$ and the field current is constant) with the load changes





Synchronous Motors steady state operation – Effect of field current changes

Initially, the synchronous motor operates with a lagging power factor (inductive) load



When, the field current is increased with constant load, the induced armature voltage, E_A will increase.

The power output of the motor remains constant as the load on the shaft is not changing

The speed will remain constant

The terminal voltage and frequency supplied to the motor are constant

As P is constant, $I_a\cos\theta$ and $E_A\sin\delta$ will remain constant

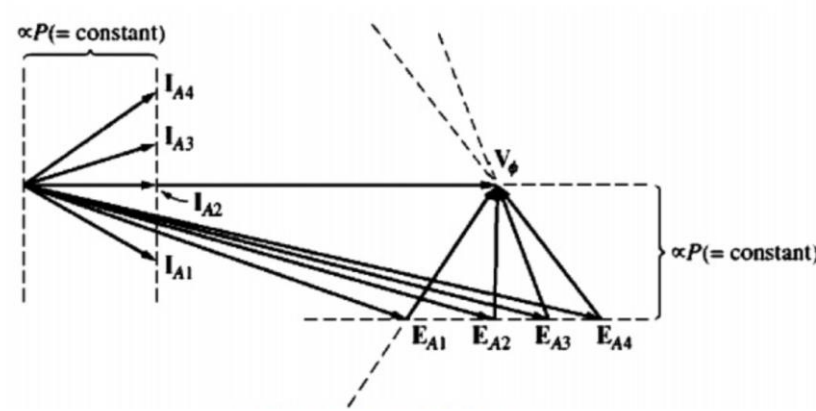
With increase in field (excitation) current, the motor operation changes from lagging power factor to unity power factor and then to leading power factor

It changes from a circuit that absorbs reactive power (inductive) to a circuit that provides reactive power (capacitive)

Under-excited to over-excited motor

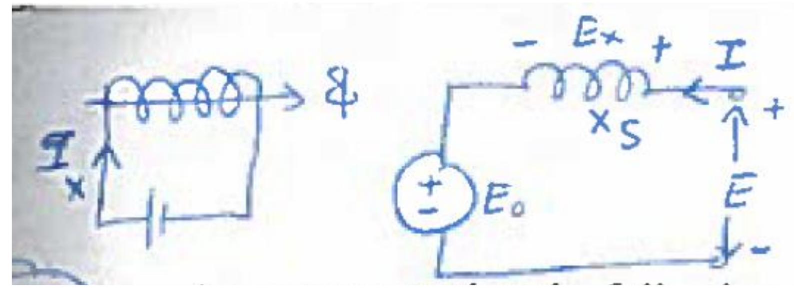
The over-excited motor behaves like a Capacitor

By varying the field excitation, the synchronous motor can absorb or deliver reactive power



Synchronous Motors: Example

A 3-phase, Y-connected synchronous motor has the following parameters, per phase:

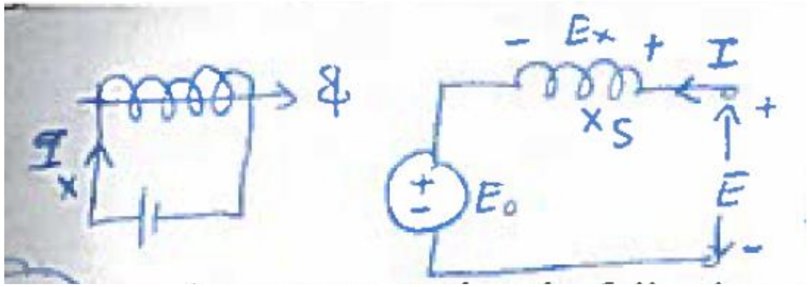


$E = 2.4$ kV; $E_o = 3$ kV, $X_s = 2\ \Omega$, $I = 900$ A

Draw the phasor diagram and calculate:

1. Torque angle [36.9^0]
2. Active power, per phase [2.16 MW]
3. Power factor of the motor [1]
4. Reactive power absorbed or delivered, per phase [0]
5. Calculate the line current and the new torque angle if the mechanical load is suddenly removed. Also calculate the new reactive power absorbed (or delivered) by the motor, per phase [300 A, 720 kVAR (delivered)]

Synchronous Motors: Example



Synchronous Motors: Example

A 4000 hp, 6.9 kV, 60 Hz, 3-phase, Y-connected synchronous motor has per phase synchronous reactance is 10 Ω. The motor operates at full-load with a leading power factor of 0.89. If the efficiency is 97%, Calculate:

1. Apparent power of the motor [3457 kVA]
2. The AC line current [289 A]
3. The value of E_o, per phase [5889 V]
4. The total reactive power supplied to the electrical system [1569 kVAR]
5. The approximate maximum power the motor can develop, without pulling out of step in hp [9150 hp]

if the power factor is required to be adjusted to unity, Calculate:

1. The induced voltage E_o required, per phase [4741 V]
2. The new torque angle [32.8^0]

Synchronous Motors: Example