EN304- ELECTRICAL ENERGY SYSTEMS

Department of Energy Science and Engineering

This is only reading material (not class lecture slides)

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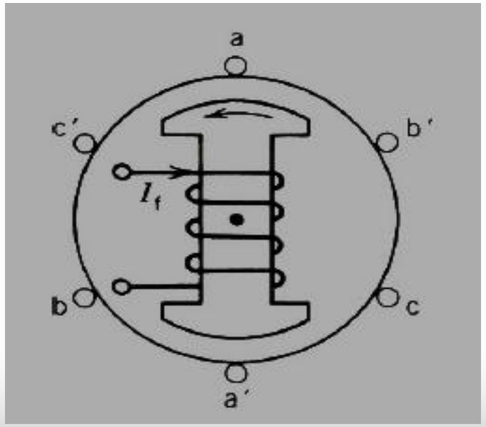
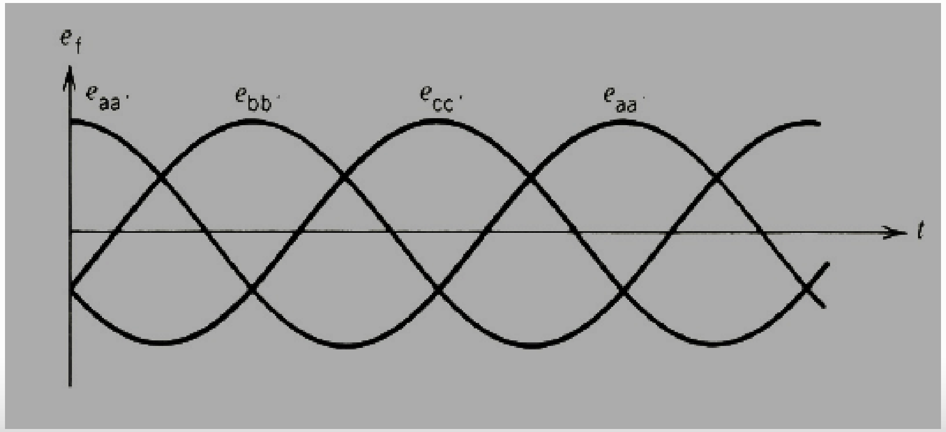
SLIDE DECK 3: SYNCHRONOUS MACHINES

Synchronous machine: Introduction

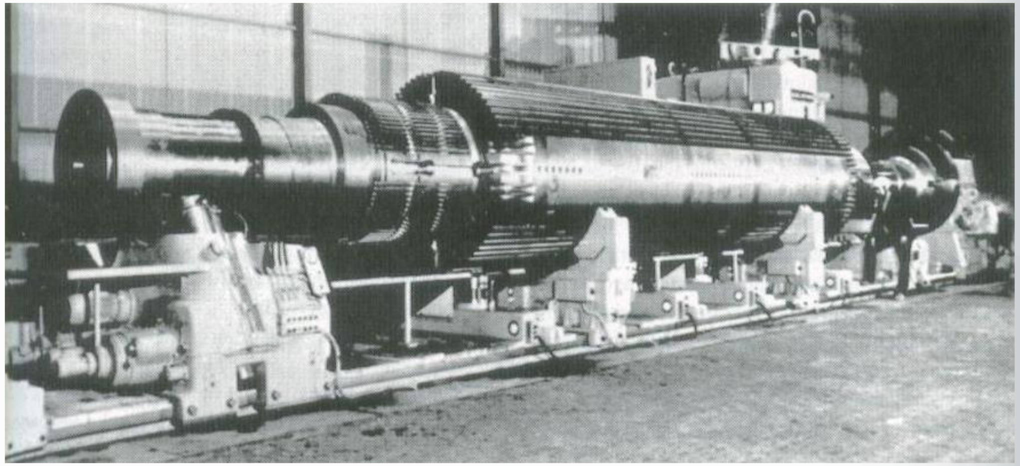
- A synchronous machine, whether it is a generator or a motor, operates at **synchronous speed,** that is, at the speed at which the magnetic field created by the field coils rotates.
- The main components of the synchronous machine are the stator and the rotor.
  - The **stator** core assembly of a synchronous machine is almost identical to that of an induction motor. The stator core provides a high permeability path for magnetism. The stator core is comprised of thin silicon steel laminations and insulated by a surface coating minimizing eddy current and hysteresis losses generated by alternating magnetism.
  - The **rotor** has a winding called the field winding, which carries direct current. The field winding on the rotating structure is normally fed from an external dc source through slip rings and brushes.
- The synchronous speed is given by $N_s = \frac{120\,f}{P}$, where f is the electrical frequency and P is the number of poles.





Synchronous Generator

- Synchronous generators or alternators are used to convert mechanical power derived from steam, gas, or hydraulic-turbine to ac electric power
- Synchronous generators are the primary source of electrical energy we consume today
- Large ac power networks rely largely on synchronous generators



Construction:

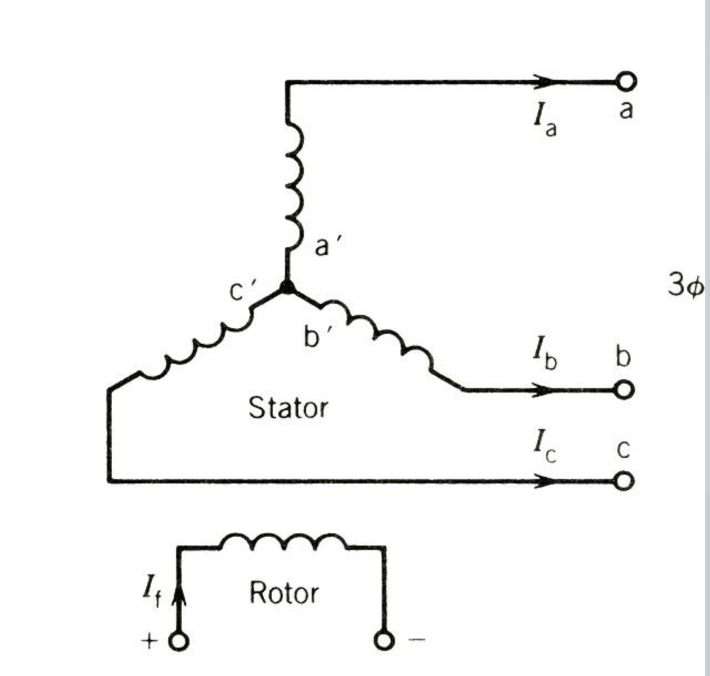
- Basic parts of a synchronous generator:

1) Rotor -dc excited winding
2) Stator -3-phase winding in which the ac emf is generated

Construction

Stator:

- The stator is similar in construction to that of a induction motor
- Distributed ac winding
- Absorbs ac power- Motor
- Delivers ac power – Generator



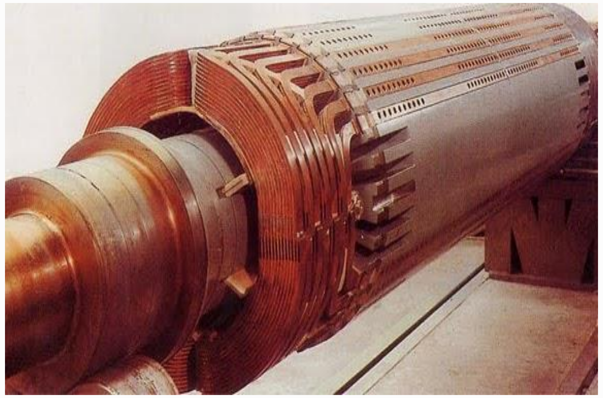
Rotor:

- The rotor can be Salient or Non-Salient (cylindrical rotor)
- Concentrated dc winding
- Always absorbs dc power whether Motor or Generator
- Therefore, synchronous machine is a doubly excited machine:
- Armature winding => AC source
- Field winding => DC source

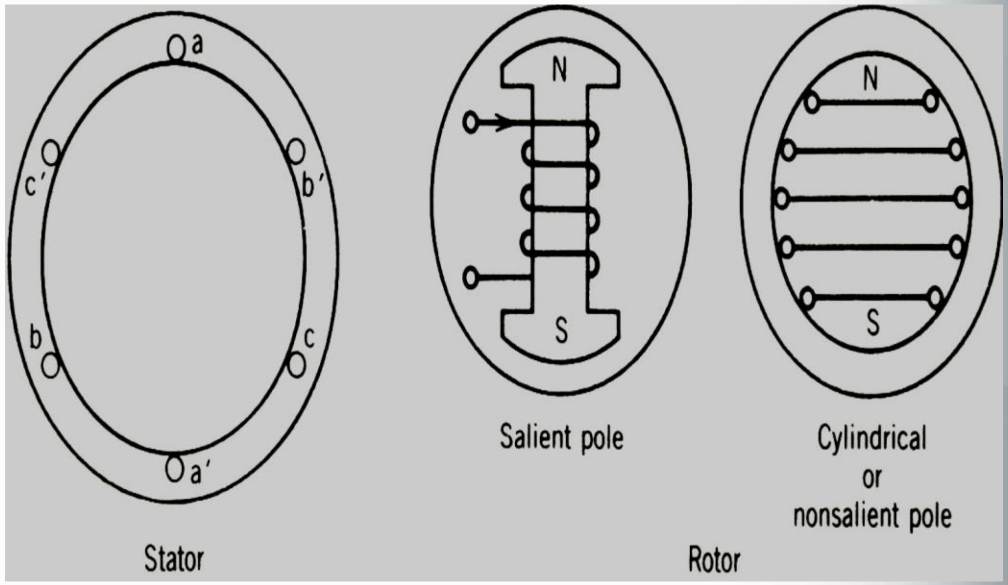
Type of Rotors

Two types of rotors are used in the design of synchronous generators, the **cylindrical** rotor and **a salient-pole** rotor. The rotor is rotated at the synchronous speed by a prime mover such as a steam turbine. The rotor has as many poles as the stator, and the rotor winding carries dc current so as to produce constant flux per pole.

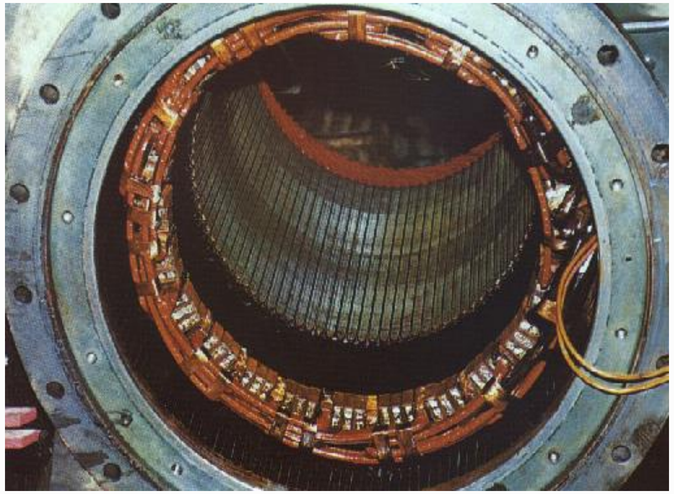
Salient rotor



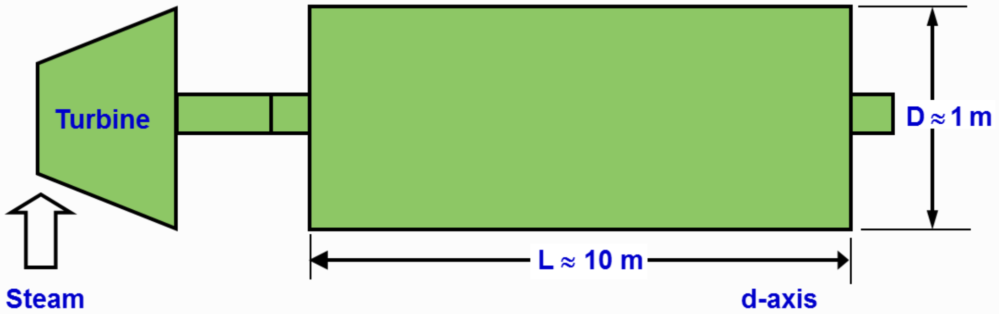
Cylindrical rotor



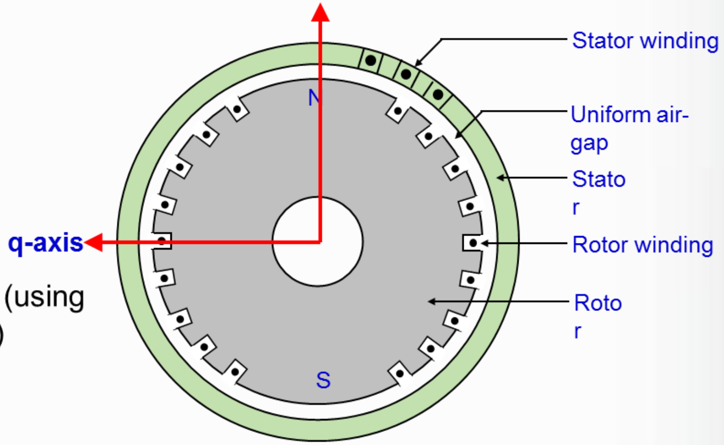
Construction contd..



Stator



- High speed
- 3600 r/min ⇒ 2-pole
- 1800 r/min ⇒ 4-pole
- Direct-conductor cooling (using hydrogen or water as coolant)
- Rating up to 2000 MVA



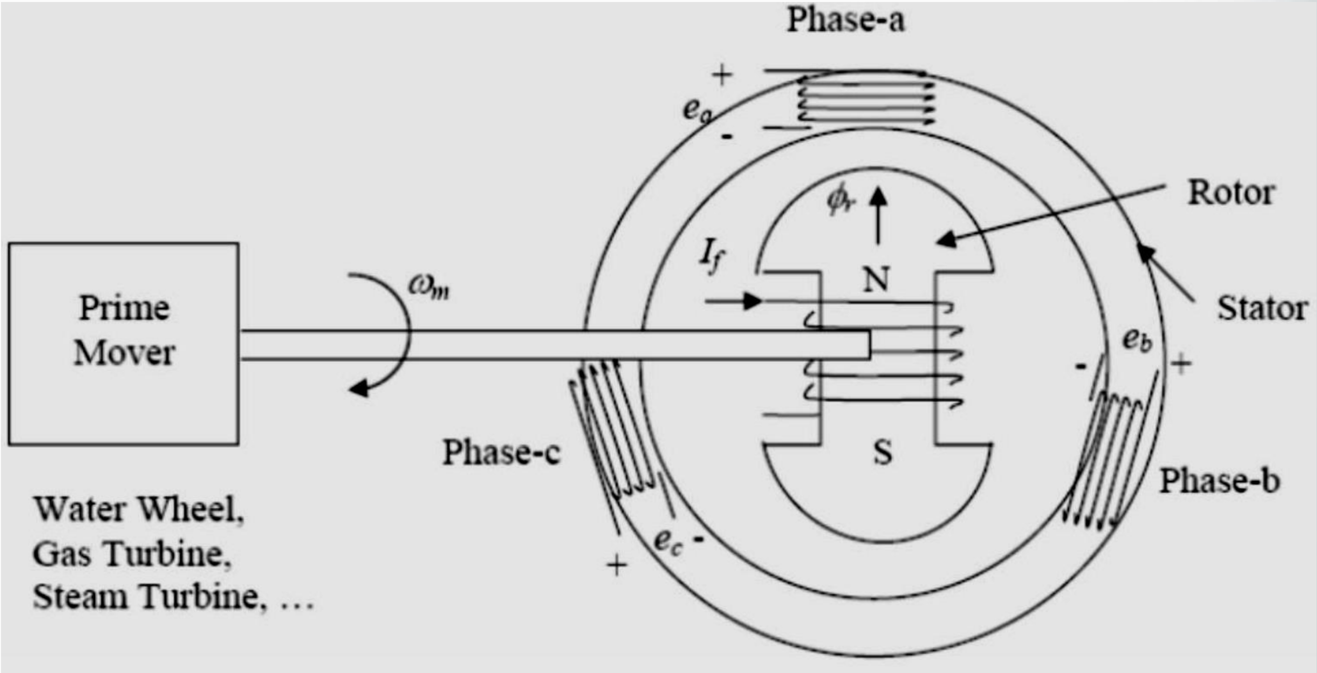
Turbogenerator

Operation principle

Rotor of generator is driven by a prime mover

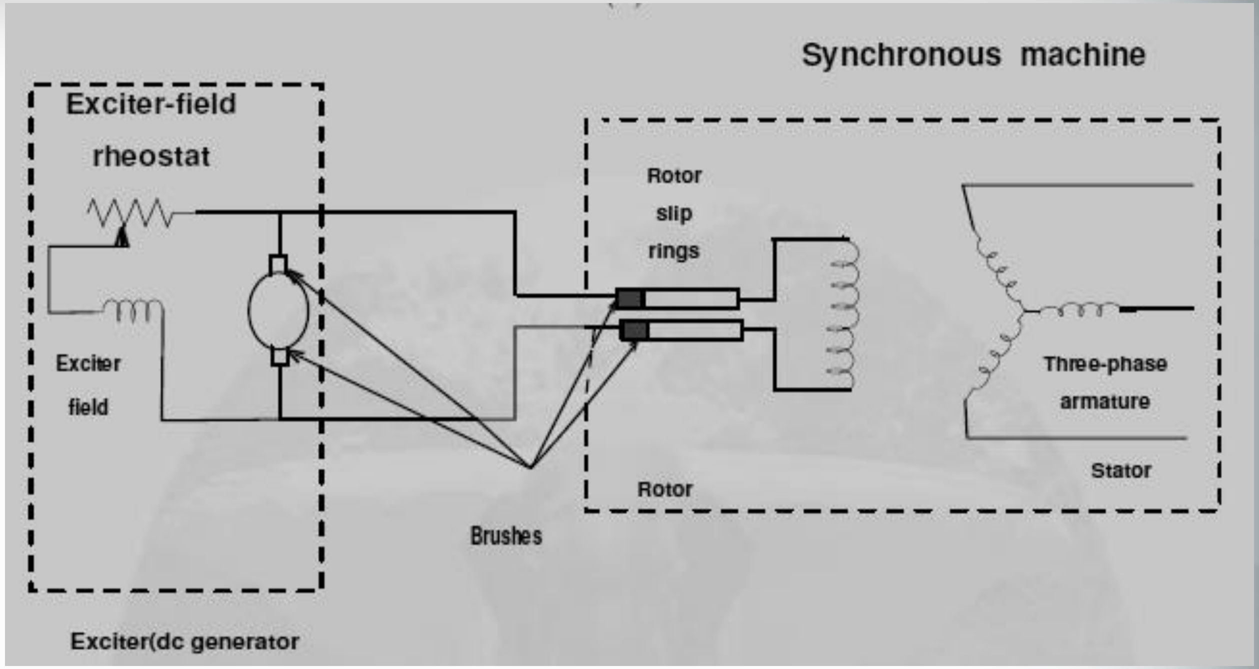
A dc current is flowing in the rotor winding which produces a rotating magnetic field (RMF) within the machine

The rotating magnetic field induces a three-phase voltage in the stator winding of the generator



Excitation Systems for Synchronous Machine

- Three methods of excitation
  - Slip rings link the rotor's field winding to an external dc source
  - dc generator exciter
    - a dc generator is built on the same shaft as the ac generator's rotor
    - a commutator rectifies the current that is sent to the field winding
  - brushless exciter
    - An ac generator with fixed field winding and a rotor with a three phase circuit
    - Diode/SCR rectification supplies dc current to the field windings



- Adjustment of field current can be either automatic or manual based on complexity of system it is connected to
- Voltage is up to 125V for 50kW system and higher voltage for higher system rating

Electrical Frequency and Generated Voltage

- Electrical frequency produced is synchronized to the mechanical speed of rotation of a synchronous generator:

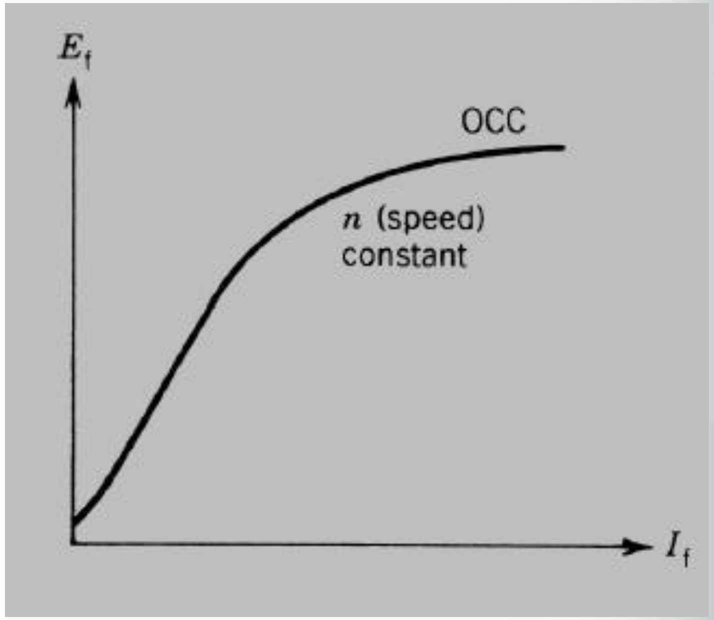
$$f_e = \frac{Pn_m}{120}$$

Where,
f_e= electrical frequency in Hz
P = number of poles
n_m= mechanical speed of the rotor, in rev/min

- The generated voltage of a synchronous generator is given by

$$E_f = 4.44 N_c BAf$$
$$E_f = K_c \phi f$$

Where,
Φ= flux in the machine (function of I_f)
f = electrical frequency
K_c= synchronous machine constant
N_c = number of turns,
B= flux density,
A = cross sectional area of the magnetic circuit



Synchronous machine: Open Circuit Characteristic

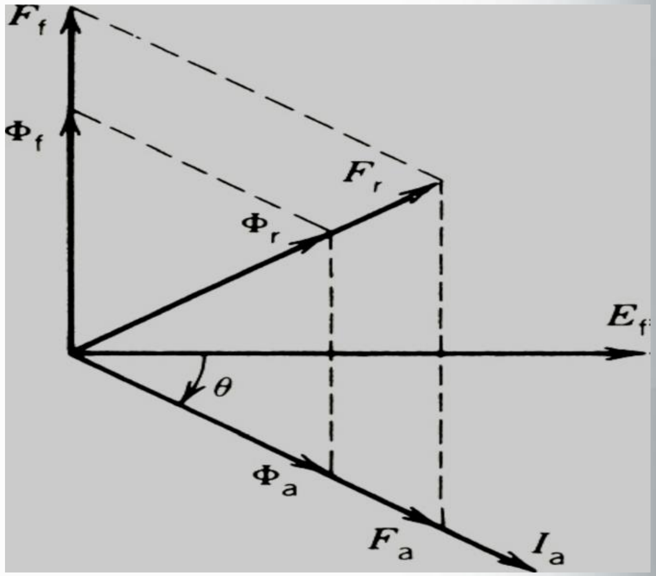
- The excitation voltage, $E_f = 4.44\, \phi_f\, N\, K_w$

  ϕ_f is the flux per pole due to the excitation current I_f

  N is the number of turns in each phase

  K_w is the winding factor

- The excitation voltage is proportional to the machine speed and excitation flux, and the excitation flux in turn depends on the excitation current I_f. The variation of the excitation voltage with the field current is shown in open-circuit characteristic (OCC).



If the stator terminals of the machine are connected to a three phase load, stator current I_a will flow. The frequency of I_a will be the same as that of the excitation voltage E_f. The stator currents flowing in the three phase windings will also establish a rotating field in the air gap. The net air gap flux is the resultant of the fluxes produced by rotor current I_f and stator current I_a, $\phi_r = \phi_f + \phi_a$

Synchronous reactance

- The internal voltage E_f produced in a machine is not usually the voltage that appears at the terminals of the generator

- That difference occurs due to the following factors:

i. Armature reaction: The distortion of the air-gap magnetic field by the current flowing in the stator
ii. The self-inductance of the armature coils.
iii. The resistance of the armature coils.
iv. The effect of salient-pole rotor shapes.

Synchronous reactance

Therefore the terminal voltage is given by:

$$V_t = \underbrace{E_f}_{\text{Generated voltage}} - \underbrace{j\,\omega M_s I_a}_{\text{Drop due to Armature reaction}} - \underbrace{j\,\omega L_s I_a}_{\text{Drop due to armature self reactance}} - \underbrace{I_a R_a}_{\text{Drop due to armature coil resistance}}$$

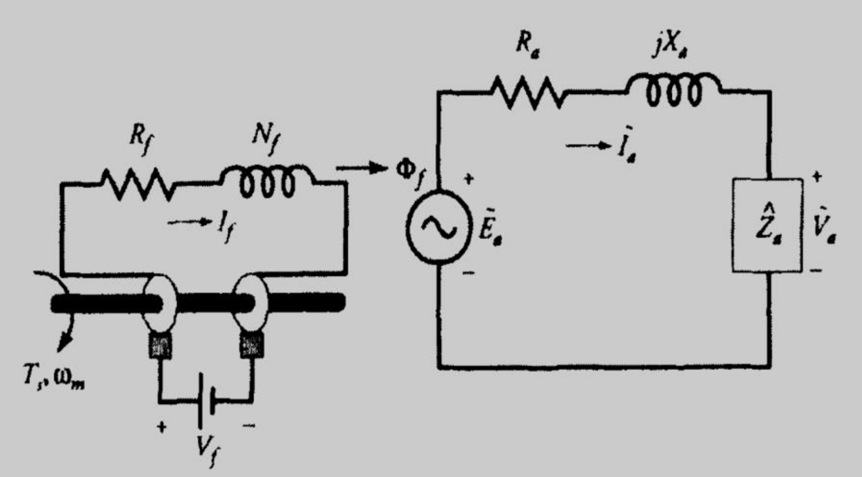
$$X_s = \omega(M_s + L_s)$$

Where X_s is called synchronous reactance

Synchronous generator: equivalent circuit

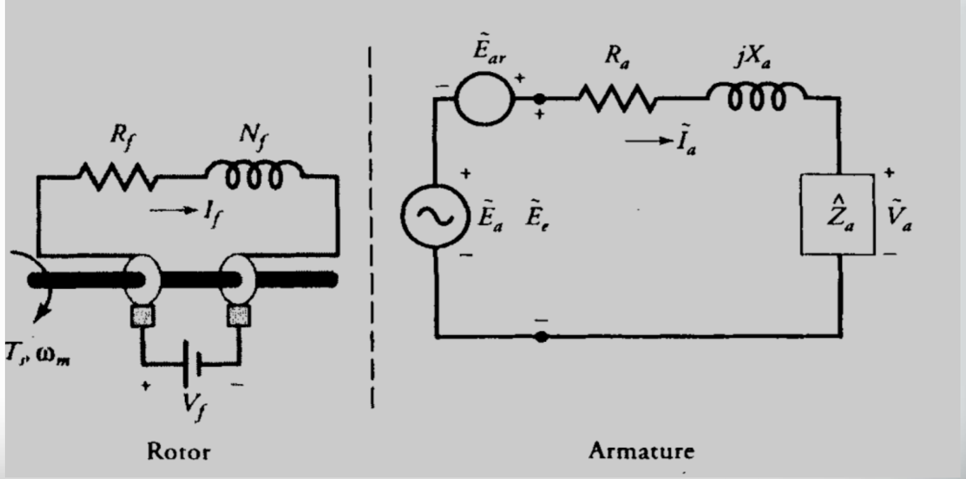
- The equivalent circuit of synchronous generator, neglecting the armature reaction,

  $\tilde{V}_a$= terminal voltage
  $\tilde{I}_a$= armature current
  $\tilde{E}_a$= induced armature voltage
  R_a= per-phase armature winding resistance
  X_a= per-phase armature winding leakage reactance
  R_f= rotor winding resistance
  N_f= the effective field winding turns
  V_f= excitation voltage
  I_f= excitation current



- The equivalent circuit of synchronous machine with considering the armature reaction,

  $\tilde{E}_{ar}$= armature reaction voltage



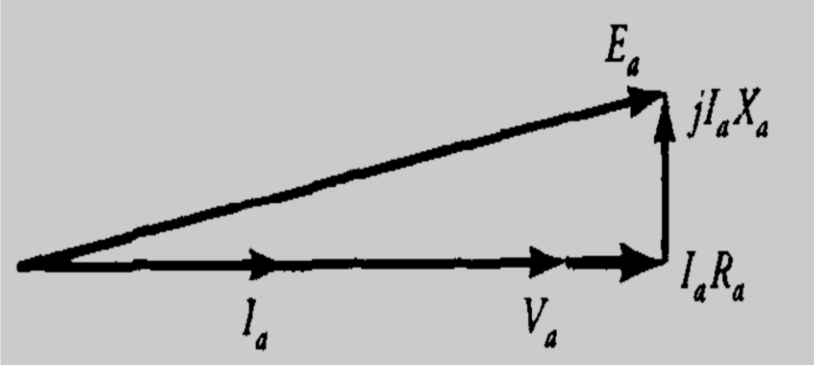
Synchronous generator: phasor diagram

- From the equivalent circuit, the synchronous machine terminal voltage is given by,

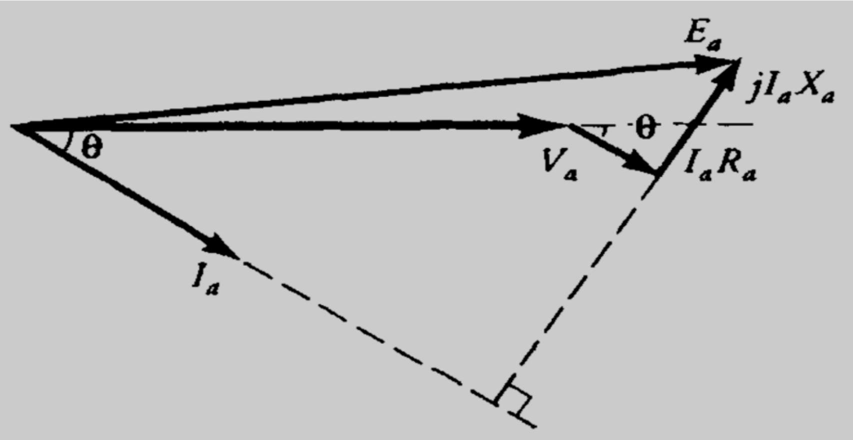
$$\tilde{V}_a = \tilde{E}_a - \tilde{I}_a(R_a + jX_a)$$

- Consequently, the phasor diagram of the synchronous machine can be drawn for unity, lagging and leading load power factor as follows,

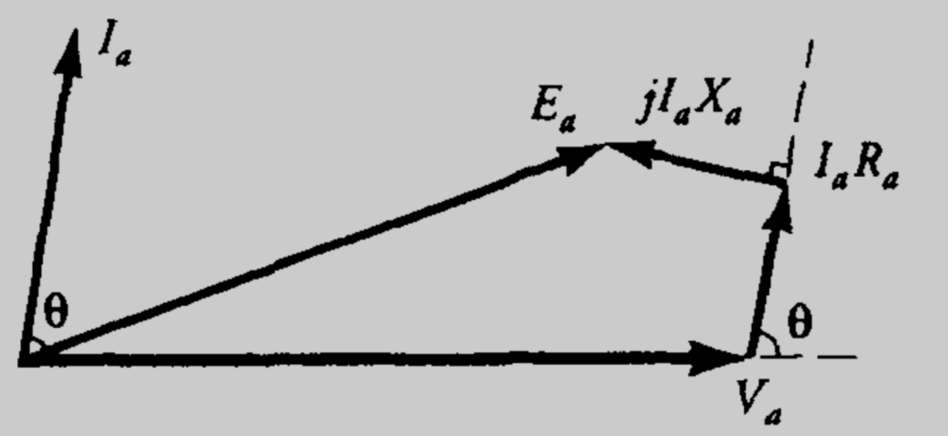
Resistive load



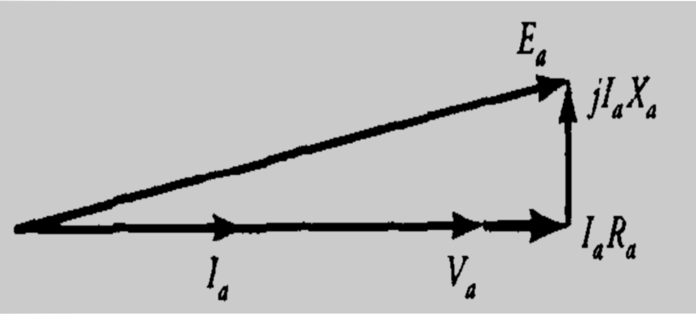
Inductive load



Capacitive load

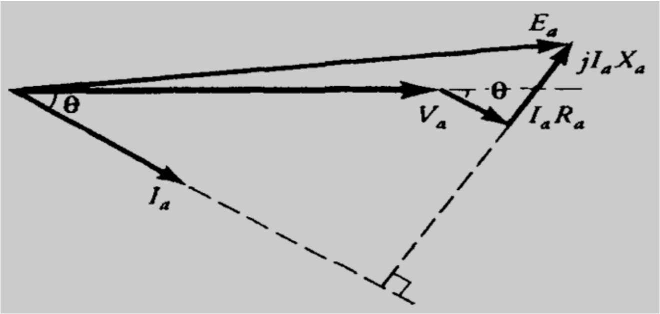


Synchronous generator: phasor diagram



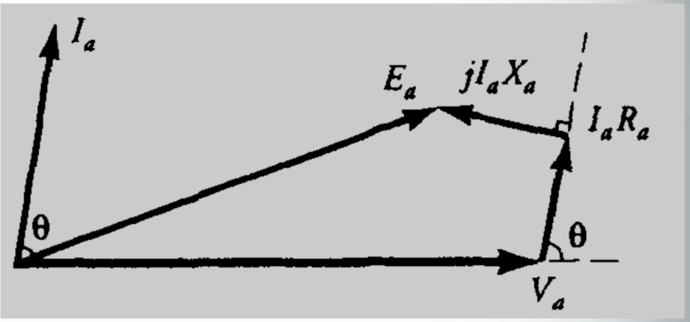
Phasor diagram of a cylindrical-rotor synchronous generator, for the case of unity power factor

$|V_t|=|E_f|\cos\delta$ for normal excitation



Phasor diagram of a cylindrical-rotor synchronous generator, for the case of lagging power factor

$|V_t|<|E_f|$ for over-excited condition



Phasor diagram of a cylindrical-rotor synchronous generator, for the case of leading power factor

$|V_t|>|E_f|$ for under-excited condition

Synchronous generator: Power flow

- The mechanical power input to the generator is

$$P_{inm} = T_s\,\omega_s$$

Where T_s and ω_s are the synchronous torque and rotational speed.

- The total input power include excitation power,

$$P_{in} = T_s\omega_s + V_f I_f$$

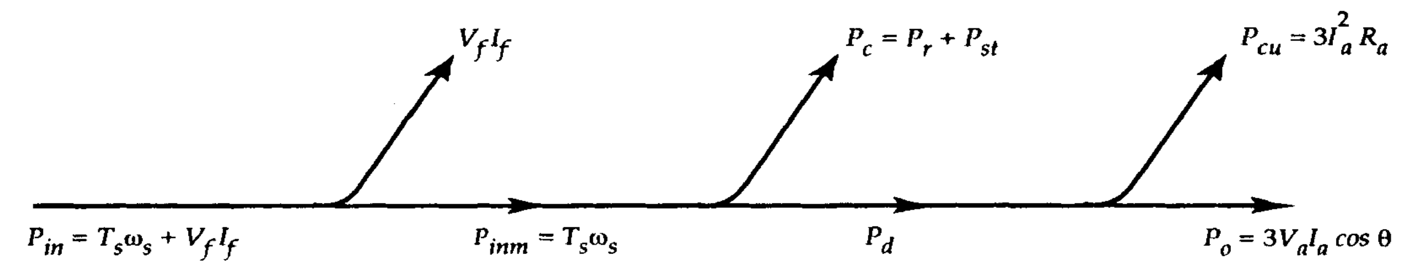
- The total constant loss P_c consists of two main components, rotational loss P_r and stray loss P_{st}.
- The cupper loss in the stator is given by, $P_{cu} = 3\,I_a^2 R_a$.
- The output power is given by,

$$P_o = 3V_a I_a \cos\theta.$$

- The overall synchronous machine efficiency is given by,

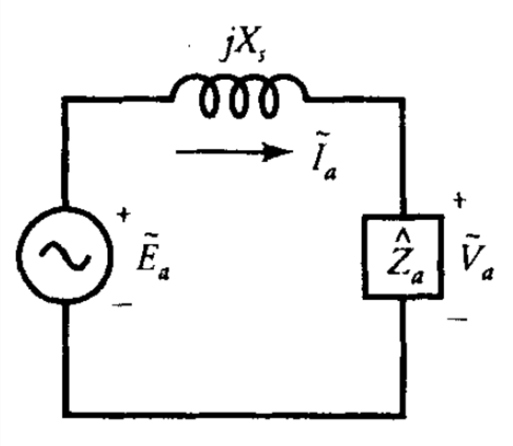
$$\eta = \frac{P_o}{P_{in}} = \frac{3V_a I_a \cos\theta}{3V_a I_a \cos\theta + 3\,I_a^2 R_a + P_c + V_f I_f}$$

The power flow diagram of synchronous generator

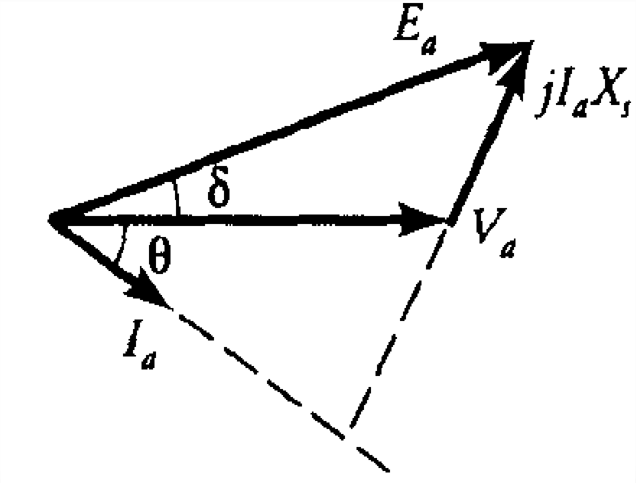


Power Characteristic

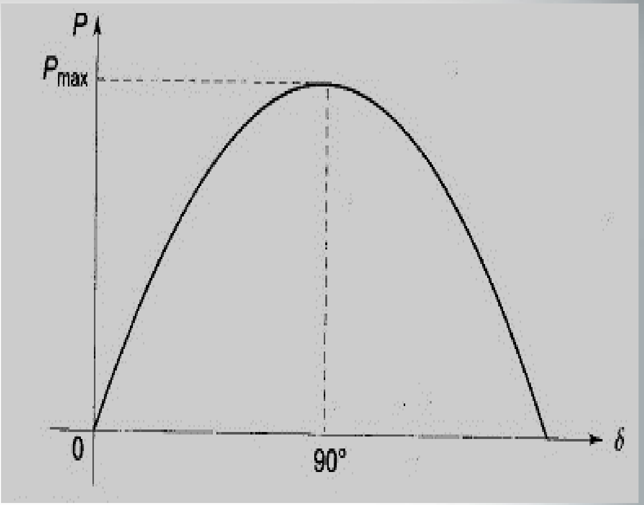
- The per-phase armature-winding resistance of a synchronous generator is usually very small and can be neglected in comparison with its synchronous reactance. Hence, the approximate equivalent circuit is given as follows,



- The corresponding phasor diagram for lagging load,



Power Characteristic



- From the phasor diagram, $\tilde{V}_a = \tilde{E}_a - \tilde{I}_a\, jX_s$

$$\tilde{I}_a = \frac{\tilde{E}_a - \tilde{V}_a}{X_s} = \frac{E_a \sin\delta}{X_s} - j\frac{E_a\cos\delta - V_a}{X_s}$$

- Thus, the real coordinate of the armature current,

$$I_a\cos\theta = \frac{E_a\sin\delta}{X_s}$$

- Consequently, the approximate active power generated by synchronous machine,

$$P_o = 3V_a I_a\cos\theta$$
$$= \frac{3V_a E_a}{X_s}\sin\delta$$

- Thus, the approximate active power output of the generator varies as $\sin\delta$, where δ is the angle from V_a to E_a, δ is called the power angle.

Where $P_{max} = \frac{3V_a E_a}{X_s}$.

Power Characteristic

- The imaginary part of armature current,

$$I_a \sin\theta = \frac{E_a \cos\delta - V_a}{X_s}$$

Consequently, the approximate reactive power generated by synchronous machine,

$$Q_o = 3V_a I_a \sin\theta$$

$$= \frac{3V_a E_a}{X_s}\cos\delta - \frac{3{V_a}^2}{X_s}$$

- Voltage regulation of synchronous generator,

$$VR\% = \frac{E_a - V_a}{V_a} \times 100$$

Real and reactive power control

- Complex power delivered by the generator is given by:

$$S = P + jQ = V_t I_a^* = |V_t||I_a|(\cos\theta + j\sin\theta)$$

- Assuming δ is the angle between E_i *and* V_t:

$\lvert E_i\rvert \cos\delta > \lvert V_t\rvert$	$\lvert E_i\rvert \cos\delta = \lvert V_t\rvert$	$\lvert E_i\rvert \cos\delta < \lvert V_t\rvert$
Over excited	Normal excitation	Under excited

- For Generators, lagging power factor $\Rightarrow$ Over excited
  leading power factor $\Rightarrow$ Under excited

- Over-excited generators and motors $\Rightarrow$ supply reactive power to the system

- Under-excited generators and motors $\Rightarrow$ absorb reactive power from the system

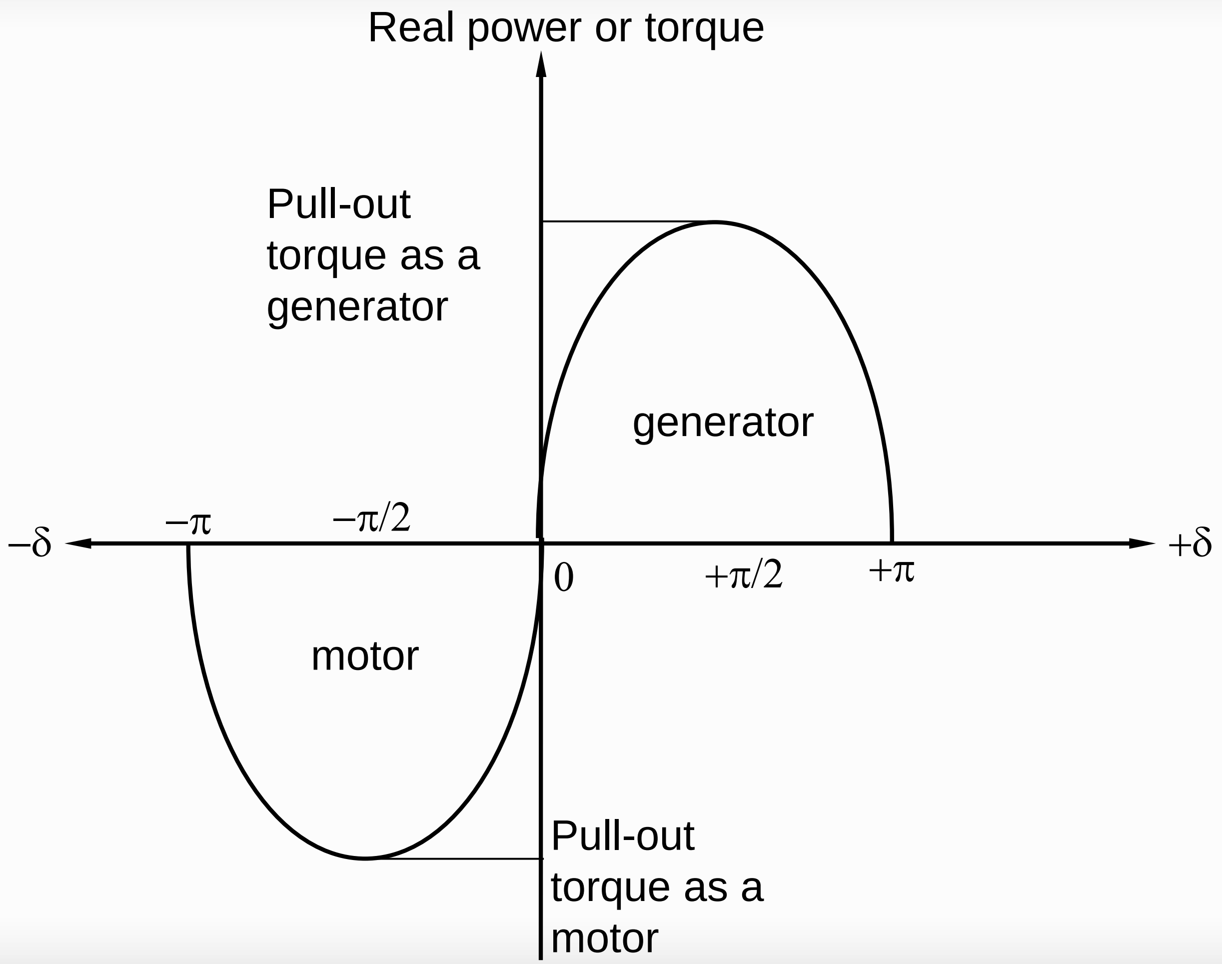
Real and reactive power control

- Reactive power control → Varying I_f
- Active power control → Varying torque imposed on the shaft, by prime mover (generator) or mechanical load (motor)
- Neglecting the armature resistance, I_a can be written as follows: $I_a = \dfrac{|E_i|\angle\delta - |V_t|}{jX_d}$
- Now the complex power delivered is given by:

$$S = P + jQ = V_t I_a^* = \frac{|V_t||E_i|\angle(-\delta) - |V_t|^2}{-jX_d}$$

- Real and reactive power are given by $P = \dfrac{|V_t||E_i|}{X_d}\sin\delta, \quad Q = \dfrac{|V_t|}{X_d}(|E_i|\cos\delta - |V_t|)$
- From the above equations *P* and *Q* are per phase quantities if E_i and V_t are line-neutral values. *P* and *Q* are per total three phase quantities if E_i and V_t are line-line values

Steady-state power-angle characteristic of a synchronous machine (with negligible armature resistance).



Steady-state stability limit

Total three-phase power: $$P = \frac{3V_t E_f}{X_s} sin\delta$$

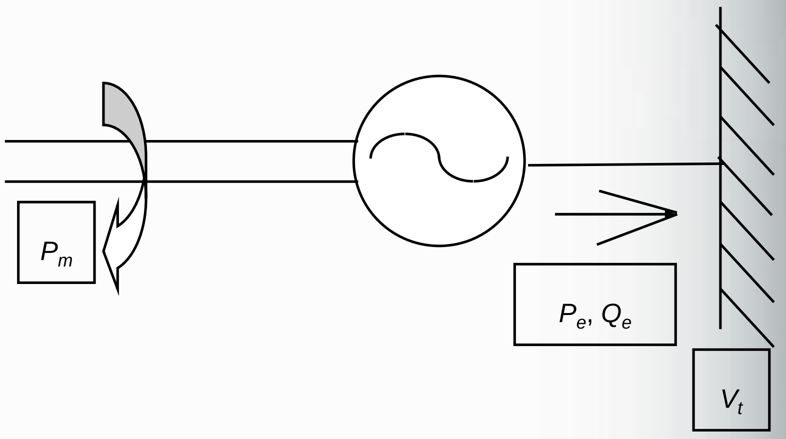
The above equation shows that the power produced by a synchronous generator depends on the angle δ between the V_t and E_f. The maximum power that the generator can supply occurs when δ=90º.

$$P = \frac{3V_t E_f}{X_s}$$

The maximum power indicated by this equation is called *steady-state stability limit* of the generator. If we try to exceed this limit (such as by admitting more steam to the turbine), the rotor will accelerate and lose synchronism with the infinite bus. In practice, this condition is never reached because the circuit breakers trip as soon as synchronism is lost. We have to resynchronize the generator before it can again pick up the load. Normally, real generators never even come close to the limit. Full-load torque angle of 15º to 20º are more typical of real machines.

Concept of the infinite bus

When a synchronous generator is connected to a power system, the power system is often so large that nothing the operator of the generator does will have much of an effect on the power system. An example of this situation is the connection of a single generator to the Indian power grid. Our Indian power grid is so large that no reasonable action on the part of one generator can cause an observable change in overall grid frequency. This idea is idealised in the concept of an infinite bus.



An infinite bus is a power system so large that its voltage and frequency do not vary regardless of how much real or reactive power is drawn from or supplied to it.

Loading capability Curve/diagram of Synchronous Generator

- Loading capability diagram(or operating chart) shows all the normal operating conditions of the round rotor generator connected to an infinite bus on a single diagram
- Assumptions made while constructing the chart:

i. Generator has fixed terminal voltage V_t

ii. Negligible armature resistance

- The following five operating modes are represented on the chart:

a) CONSTANT POWER : Since $|V_t|$ is constant, vertical line m-p at the fixed distance $X_d|I_a| \cos\theta$ from the vertical axis n-o represents a locus of operating points for constant P. The megawatt output of the generator is always positive regardless of the pf of the output

b) CONSTANT REACTIVE POWER: When $|V_t|$ is constant, horizontal line q-m at the fixed distance $X_d |I_a| |\sin\theta|$ from the horizontal axis represents a locus of operating points for constant Q. For unity power-factor operation the Q output of the generator is zero corresponding to an operating point on the horizontal axis o-p. For lagging (leading) power factors the Q output is positive (negative) and the operating point is in the half-plane above (below) the line o-p

Loading capability diagram

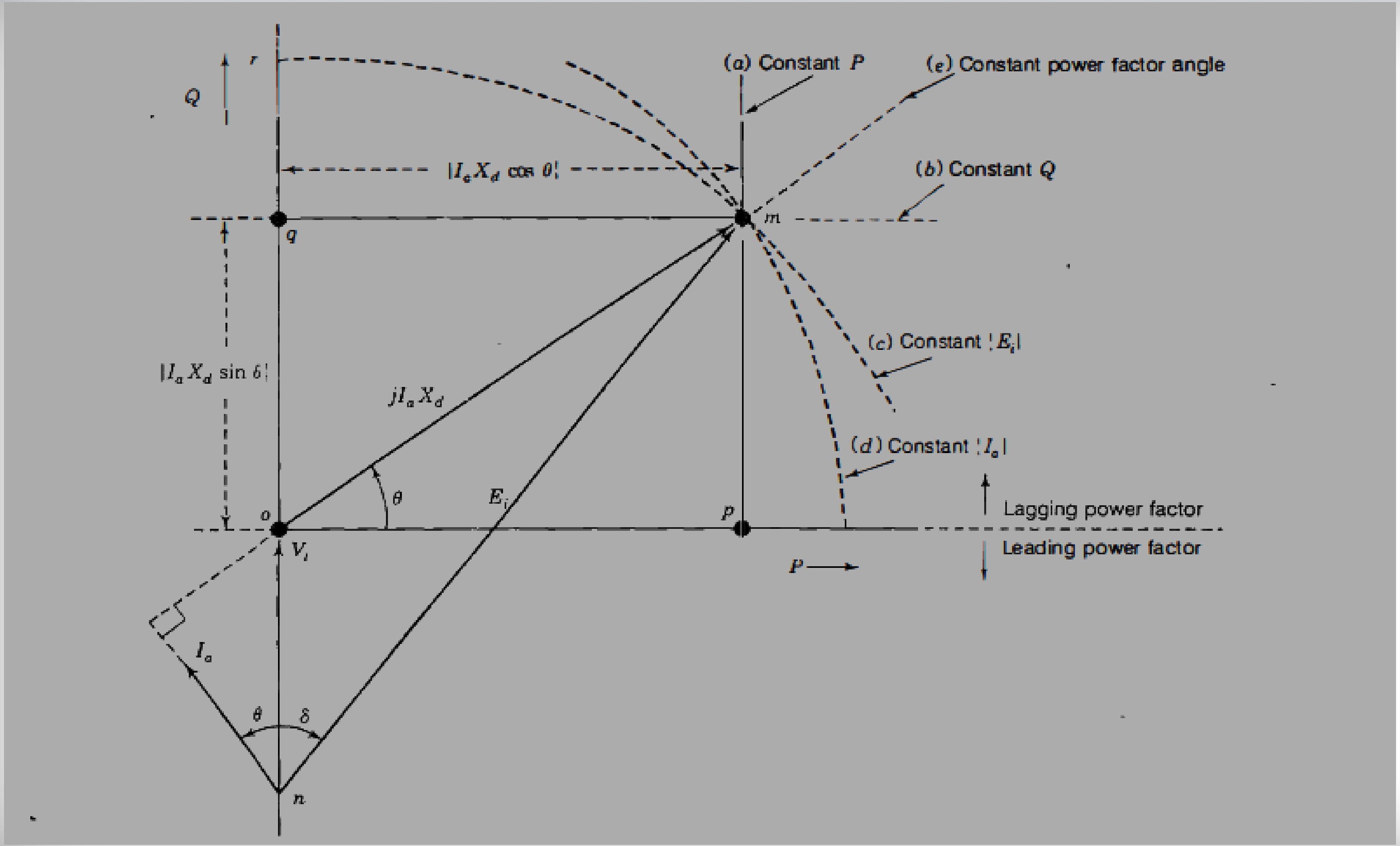


Fig : Phasor diagram showing five loci

a)constant power P
b)constant reactive power Q
c)constant internal voltage $|E_i|$
d)constant armature current $|I_a|$
e)constant pf angle θ

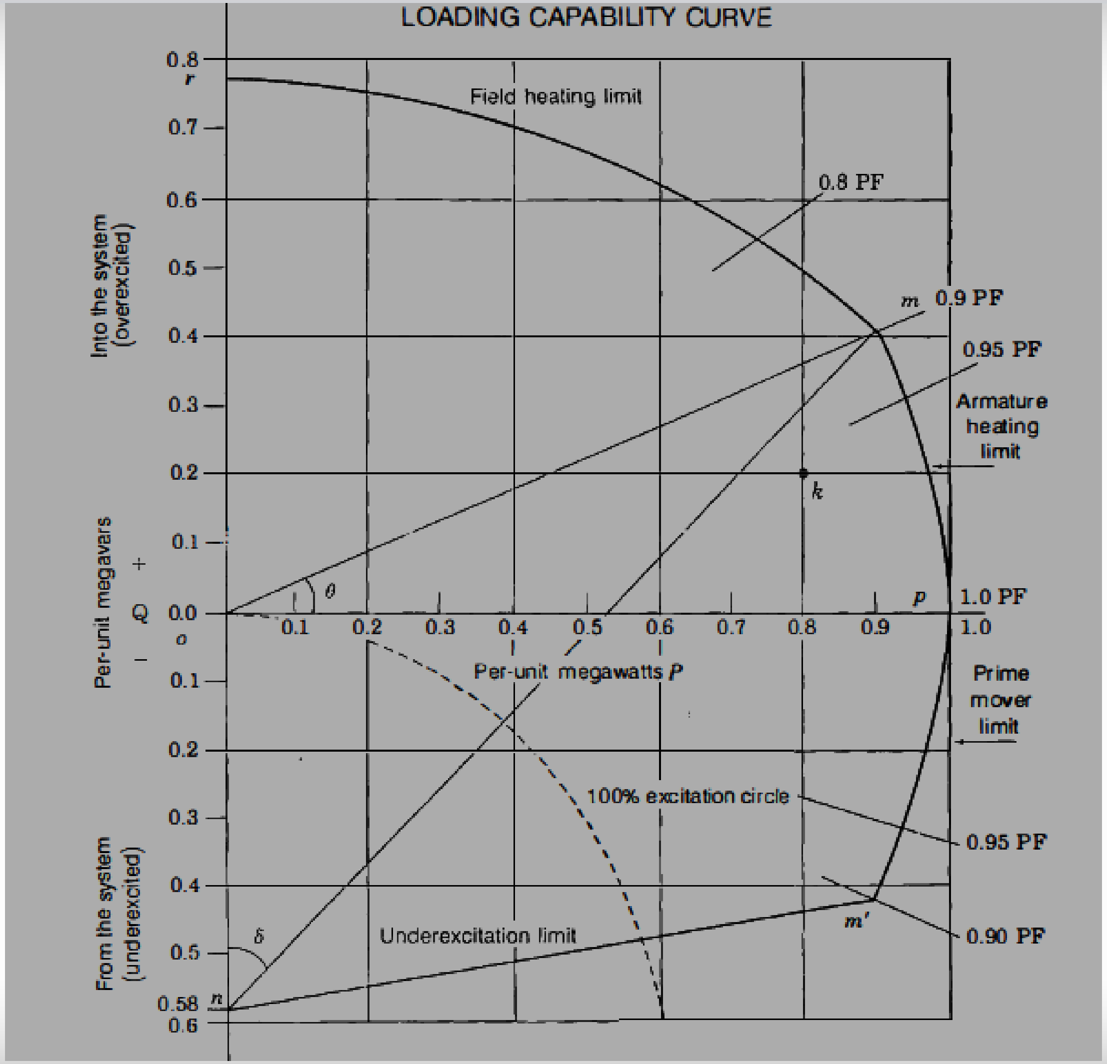
Loading capability diagram

c) CONSTANT EXCITATION IE_iI : The constant excitation circle has point 'n' as center and a radius of length 'n-m' equal to the internal voltage magnitude IE_iI

d) CONSTANT Ii_aI : The circle for constant armature current has point 'o' as center and a radius of length 'o-m' proportional to a fixed value of II_aI. Because IV_tI is fixed, the operating points on this locus correspond to constant megavolt-ampere output (IV_tI II_aI) from the generator

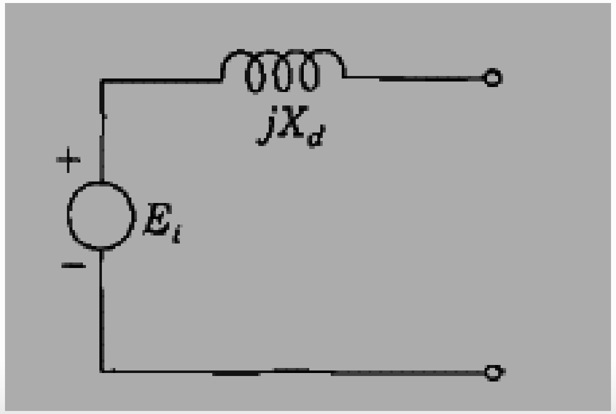
e) CONSTANT POWER-FACTOR ANGLE θ : The radial line o-m corresponds to a fixed power-factor angle θ between the armature current I_a and terminal voltage V_t .The angle θ is for a lagging power-factor load. When θ = 0°, the power factor is unity and the operating point is actually on the horizontal axis o-p. The half plane below the horizontal axis applies to leading power factors

Loading capability curve

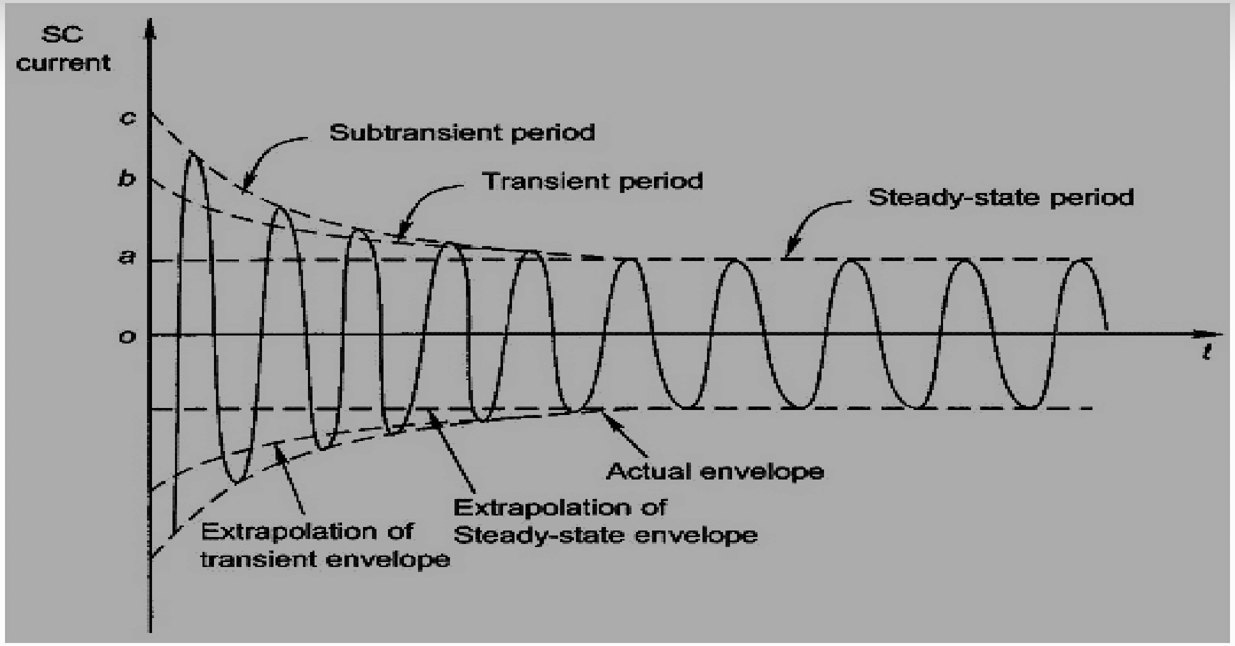


Transient and sub-transient effects

- During a fault the only devices that can contribute fault current are those with energy storage
- Thus the models of generators (and other rotating machines) are very important since they contribute the bulk of the fault current
- Generators can be approximated as a constant voltage behind a time-varying reactance:



Transient and sub-transient effects



The time varying reactance is typically approximated using three different values, each valid for a different time period:

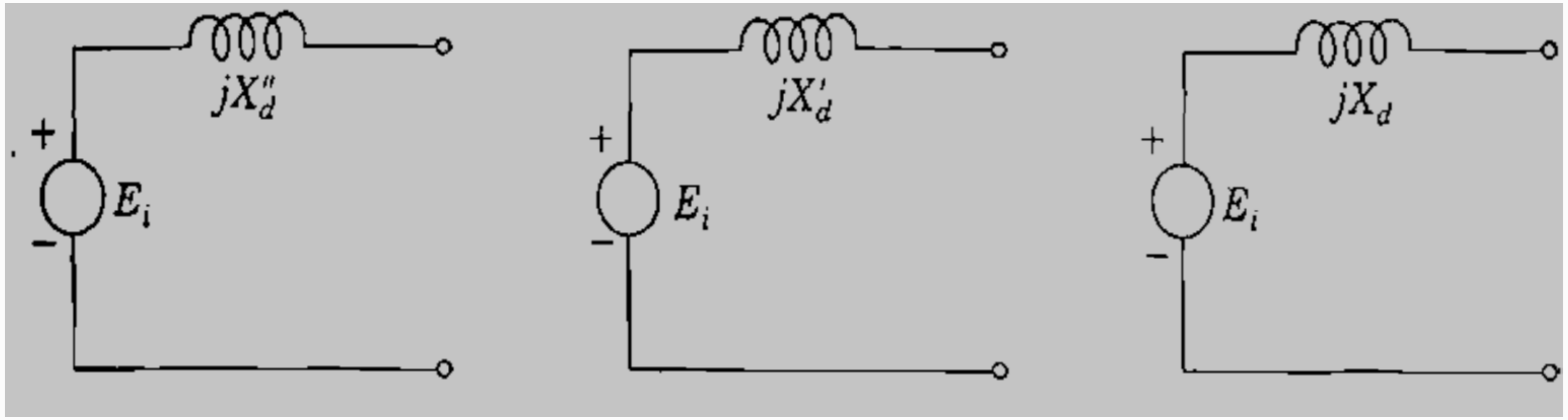
X_d''=Direct axis sub-transient reactance

X_d'=Direct axis transient reactance

X_d=Direct axis synchronous reactance

We can then estimate currents using circuit theory

Equivalent circuits for a Synchronous Generator



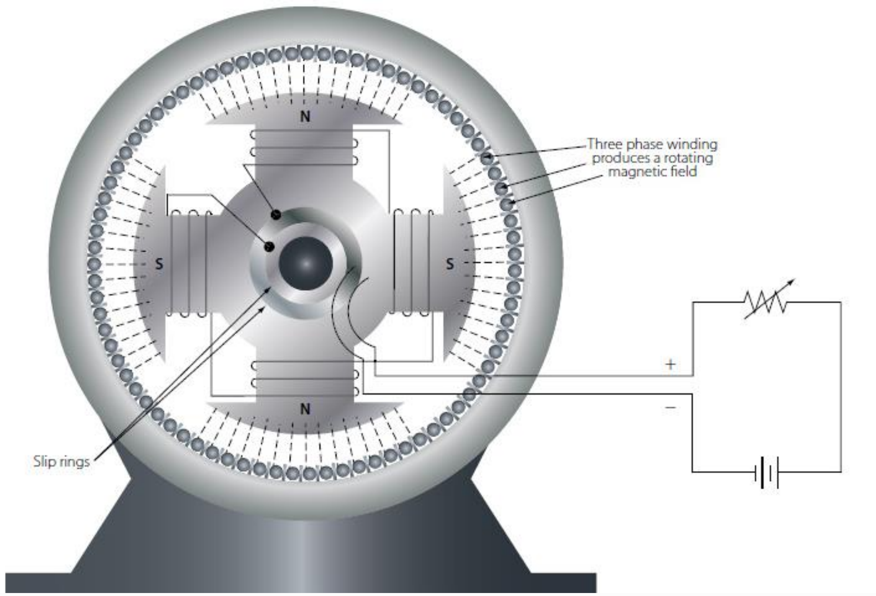
(a) (b) (c)

Equivalent circuits for a synchronous generator with internal voltage E; and

(a) sub-transient reactance; (b) transient reactance ; (c) synchronous reactance

Synchronous motor- Construction

- The construction:
  - The armature of a synchronous motor is exactly the same as that of a synchronous generator.
  - The rotor of the synchronous motor has a field winding that produces the constant flux in the motor in exactly the same fashion as it does in a synchronous generator.



Synchronous motor- Working Principle

- The working principle:

  - As the synchronous speed, depends only upon (a) the frequency of the applied voltage and (b) the number of poles in the machine. In other words, the speed of a synchronous motor ($N_s = \frac{120\,f}{P}$) is independent of the load as long as the load is within the capability of the motor.

  - when connected to the 3-phase supply, a rotating magnetic field is produced. But instead of having a cylindrical rotor with a cage winding, the synchronous motor has a rotor with either a DC excited winding (supplied via slip rings), or permanent magnets, designed to cause the rotor to ‘lock-on’ or ‘synchronise with’ the rotating magnetic field produced by the stator. Once the rotor is synchronised, it will run at exactly the same speed as the rotating field despite load variation, so under constant-frequency operation the speed will remain constant as long as the supply frequency is stable.

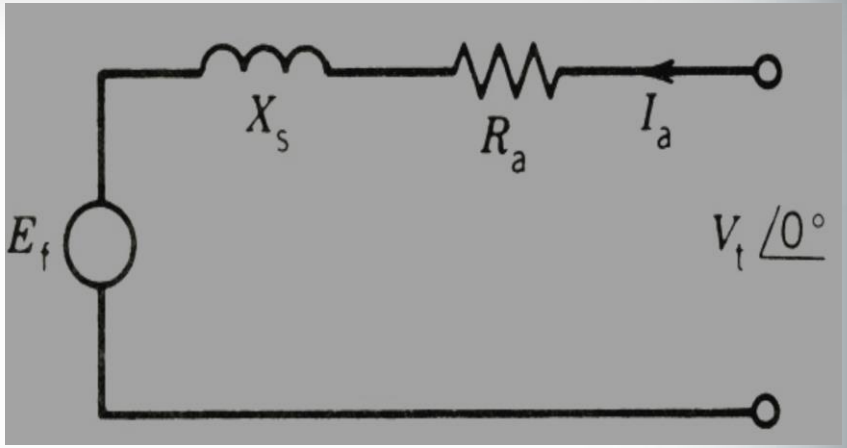
Synchronous motor: equivalent circuit

- The equivalent circuit of the synchronous motor is same as the synchronous generator with changing the armature current direction.

- From the equivalent circuit, the excitation voltage E_f can be expressed by,

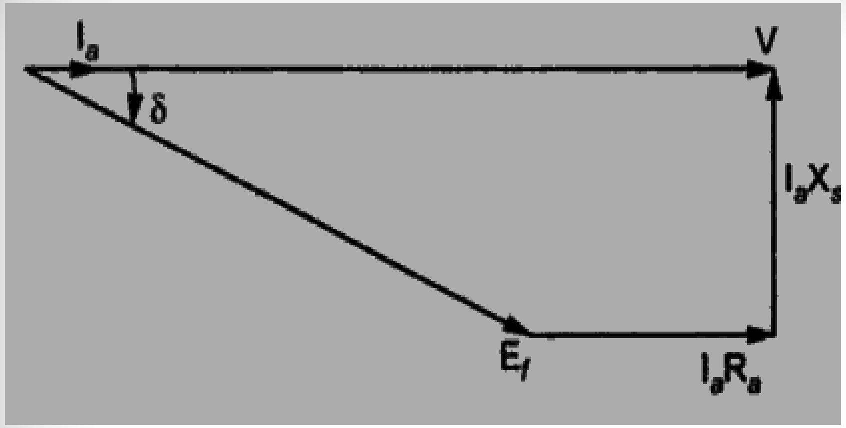
$$\tilde{E}_f = \tilde{V}_a - \tilde{I}_a(R_a + jX_a)$$

- The power factor of the synchronous machine can be controlled to be unity, lagging or leading. This can be done by controlling the excitation current as follows.

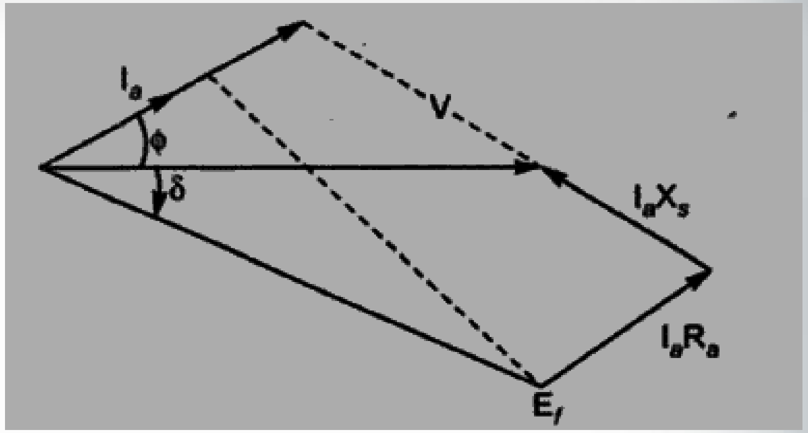


The equivalent circuit of synchronous motor

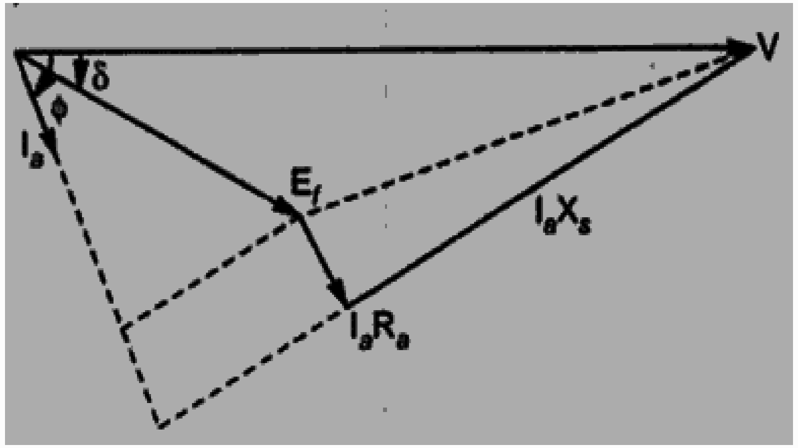
Synchronous motor: phasor diagrams



Unity power factor



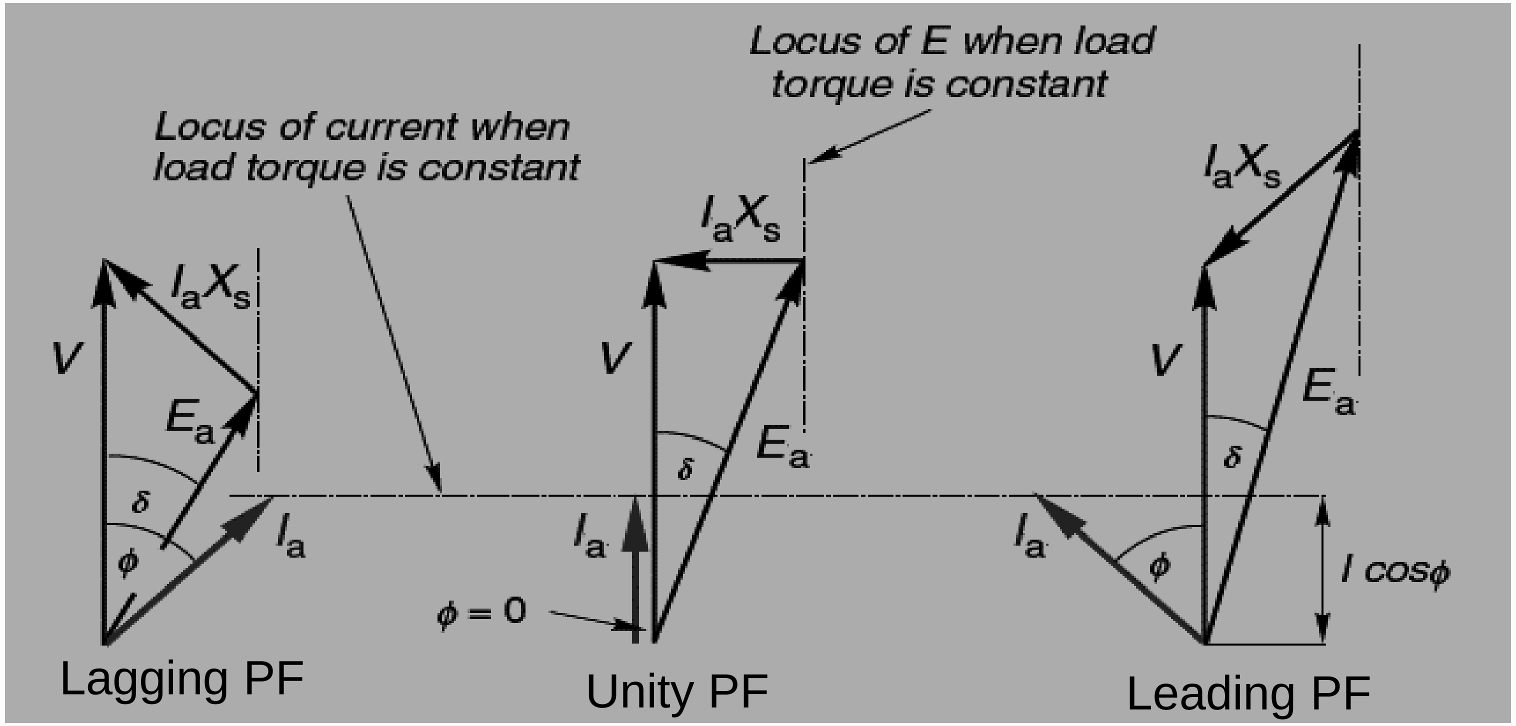
Leading power factor



Lagging power factor

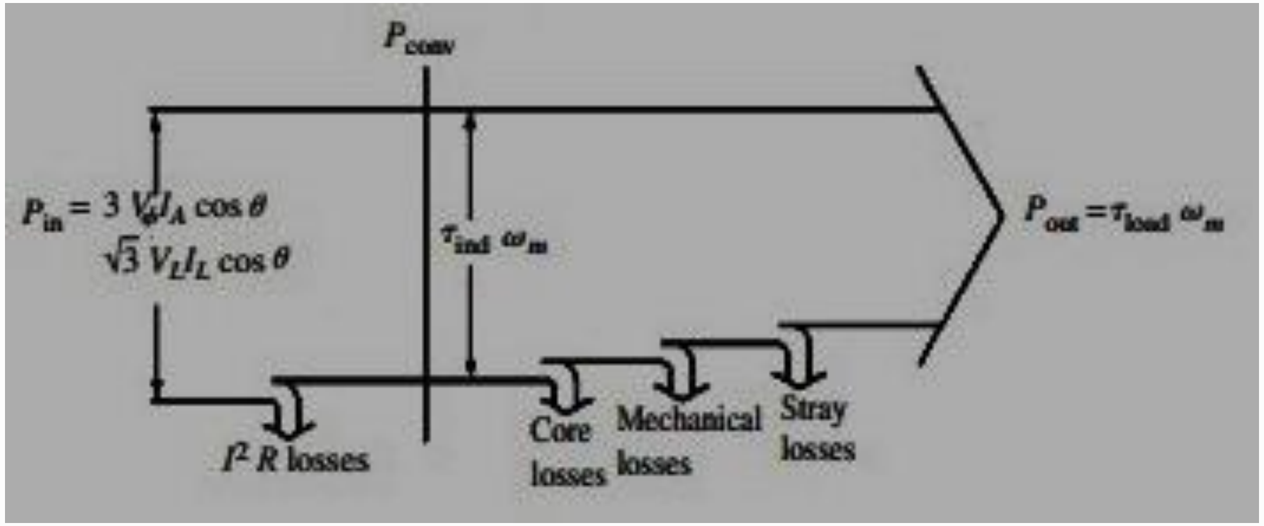
Synchronous motor: phasor diagram

- If we neglect the armature resistance, for the same terminal voltage and power angle, controlling the excitation current changes E_a which consequently changes the armature current phase angle. The following phasor diagram shows how for the same mechanical load, controlling E_a could result in controlling the power factor.



Synchronous motor: power flow

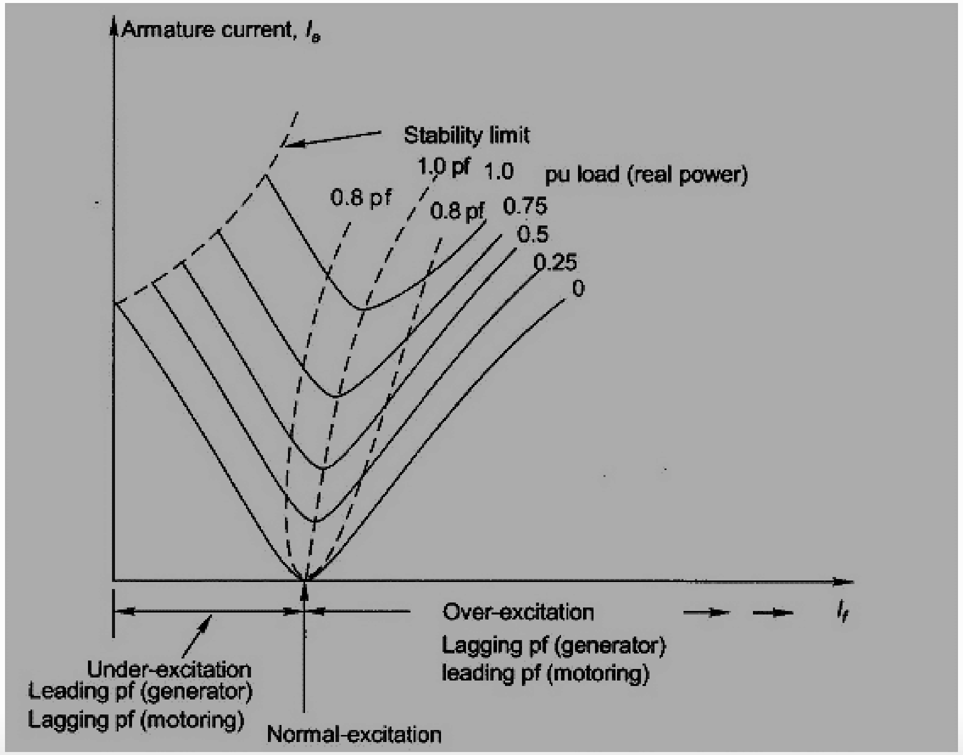
- The same topology of understanding the power flow through synchronous generator can be applied in synchronous motor with taking the reversed power direction into account as the input power of the synchronous motor is electrical power and the output power is mechanical. From the following diagram of load flow through synchronous motor, the motor efficiency can be expressed as,



$$\eta = \frac{P_o}{P_{in}} = \frac{T_{load}\,\omega_m}{3V_a I_a \cos\theta}$$

Synchronous machines: V curves

- For a given real-power loading, the power factor at which a synchronous machine operates, and hence its armature current, can be controlled by adjusting its field excitation. The curve showing the relation between armature current and field current at a constant terminal voltage and with a constant real power is known as a V curve because of its characteristic shape. Note that the following graph is for both operation modes (Generating, Motoring).



Synchronous compensator

- Synchronous compensator is a synchronous motor running without a mechanical load and, depending on the value of excitation, it can absorb or generate reactive power.
- The synchronous compensator during the normal operation consumes small amount of active power to cover the internal losses. While at the same it can supply/consume reactive power.
- Some advantages of the synchronous compensators over the static ones (like capacitors),
    - The flexibility of operation for all load conditions.
    - Being a rotating machine, its stored energy is useful for increasing the inertia of the power system and for riding through transient disturbances, including voltage sags.
    - The high short circuit current that these compensator could contribute during the faults.
- The main disadvantages of synchronous compensators compared with static ones, are the high installation cost and the higher need of maintenance.