

Synchronous Machines

Construction

1. Stator - Armature (Same as the stator of an Induction Machine)
2. Rotor - Field Winding (DC Field)

Generator

- ▶ As a generator, this machine is widely used.
- ▶ This is the machine which is used in all conventional power plants.
- ▶ A synchronous generator is called as an Alternator.

Motor

- ▶ Since it runs only at synchronous speed, it is not widely used as a motor but for certain applications like electric clocks.
- ▶ However, it is used to either produce or absorb reactive power.

Construction

1. Stator

- ▶ It is a distributed winding.
- ▶ The windings of each phase are distributed over several slots.
- ▶ Three phase windings are wound 120° (electrical angle) apart in space

2. Rotor

- ▶ It is excited by a DC current.

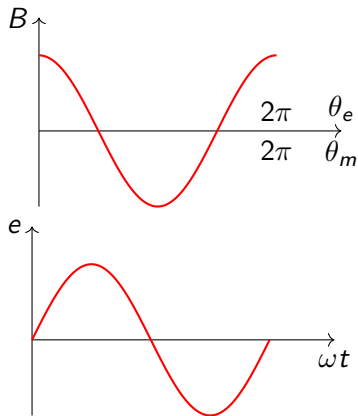
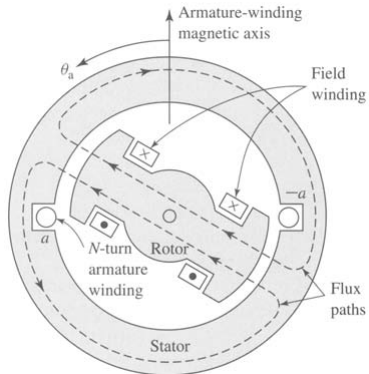
There are two types.

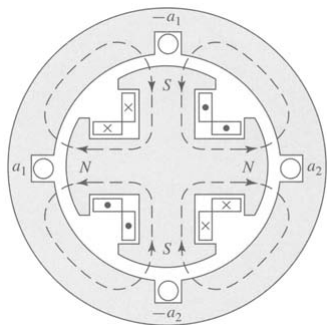
- 2.1 Cylindrical Rotor - used where the turbine speed is high
- 2.2 Salient Pole Rotor - used where the turbine speed is low

Synchronous machine is a doubly excited machine.

We can have field winding placed in stator and armature winding in rotor. This type is called an *inverted synchronous machine*.

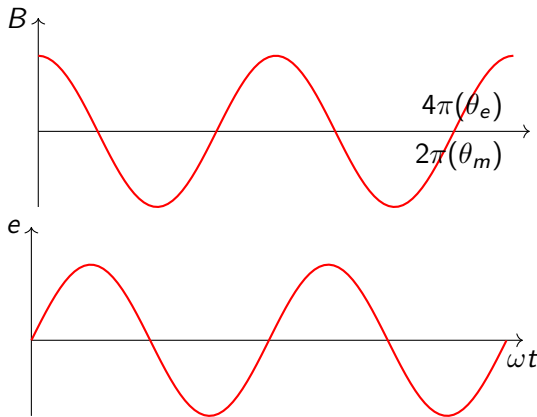
Synchronous Generator

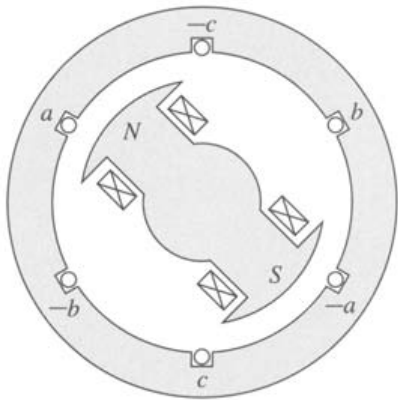




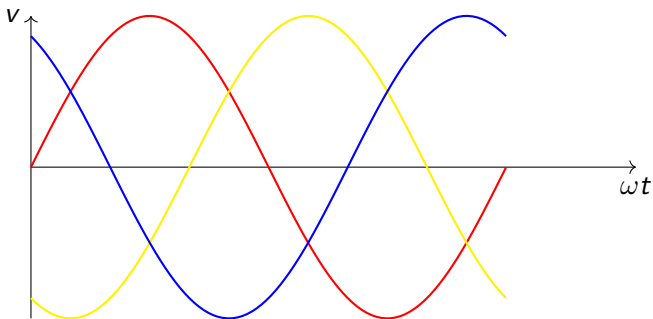
In general

$$\theta_e = \frac{P}{2} \theta_m$$





Source: A. E. Fitzgerald, et.al., "Electric Machinery"



In a 2-pole machine, one revolution makes one cycle of alternating voltage.

In a P-pole machine,

$$1 \text{ revolution/min} \rightsquigarrow \frac{1}{60} \times \frac{P}{2} \text{ cycle/sec}$$

$$N \text{ rpm} \rightsquigarrow \frac{N}{60} \times \frac{P}{2} \text{ cycle/sec}$$

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

The flux linkage with stator coil a is

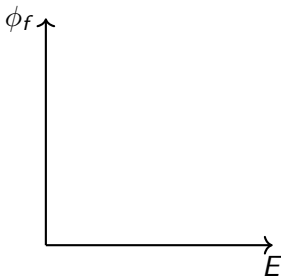
$$\lambda_a = N\phi_f \cos\omega t$$

Where N is the number of turns in each pahse and ϕ_f is the flux per pole due to excitation current I_f . By Faraday's law, the voltage induced in phase a is

$$e_a = -\frac{d\lambda_a}{dt} = \omega N\phi_f \sin\omega t$$

The rms value in voltage is

$$E_a = 4.44fN\phi_f$$



- ▶ The field winding is excited by DC.
- ▶ When the rotor rotates, the field will revolve in the air gap.
- ▶ The revolving field induces an emf in the armature winding placed in the stator.
- ▶ The speed of the field (N) is determined by the frequency of induced voltage.

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

- ▶ Rotor and field due to field winding rotate at the same speed called the synchronous speed.
- ▶ When the stator terminals are connected to a load, a three phase armature current flows out of the machine.
- ▶ When a three phase balanced current flows in the three phase armature winding, a revolving mmf is produced whose speed is

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

- ▶ The field due to armature current also rotates at the synchronous speed in the air gap.
- ▶ Finally the net air gap field is the resultant of field due to I_f and stator current I_a .

$$F_r = F_f + F_a$$

$$\phi_r = \phi_f + \phi_a$$

- ▶ The resultant and component fluxes rotate in the air gap at the same speed.

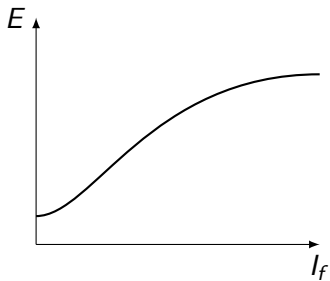


Figure: OCC

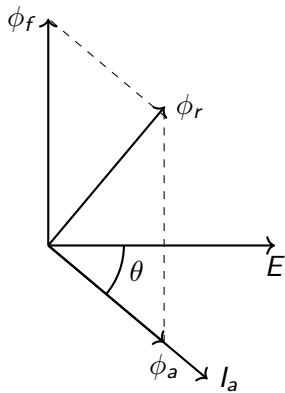
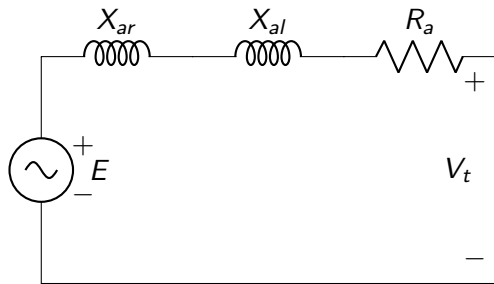


Figure: Field diagram

Equivalent Circuit

Since the operation is balanced, the per phase equivalent circuit of a synchronous machine is

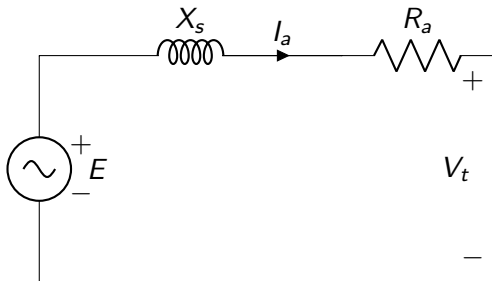


where

X_{ar} is the reactance of armature reaction.

X_{al} is the leakage reactance.

R_a is the armature resistance.



The synchronous reactance

$$X_s = X_{ar} + X_{al}$$

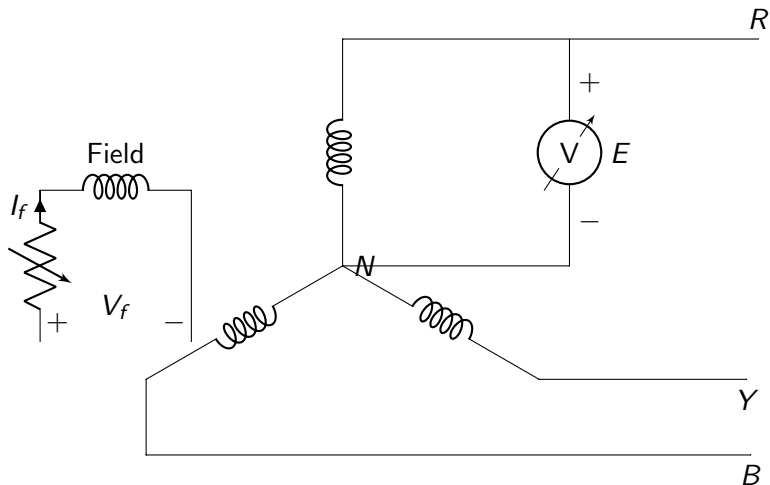
The synchronous impedance

$$Z_s = R_a + jX_s$$

$$E = V_t + I_a(R_a + jX_s)$$

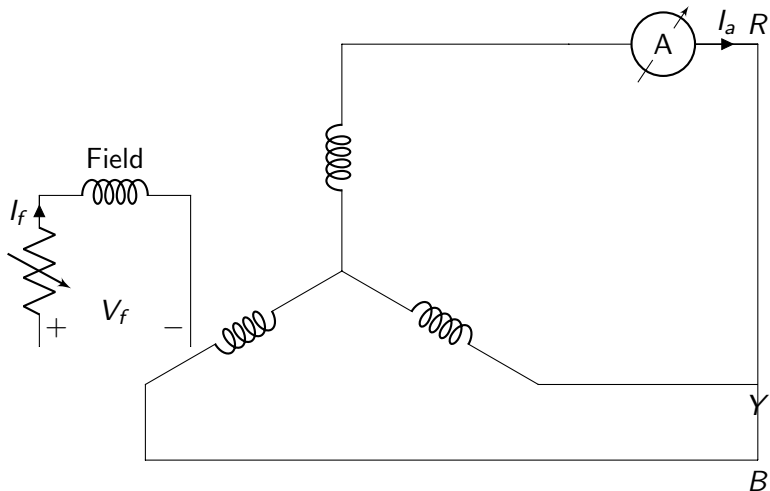
Determination of X_s

Open Circuit Test :



Vary I_f and measure E . Repeat till E reaches its rated value.

Short Circuit Test :



Vary I_f and measure I_a . Repeat till I_a reaches its rated value.

The open circuit characteristics is a non linear curve. However, the short circuit characteristics is a straight line because the flux inside the machine is low (no saturation).

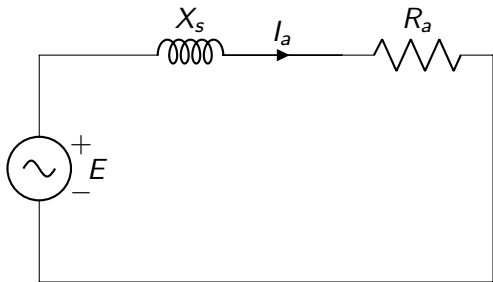


Figure: SC Test

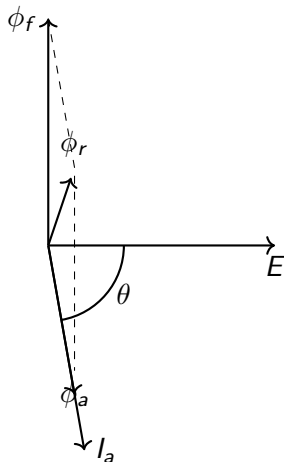
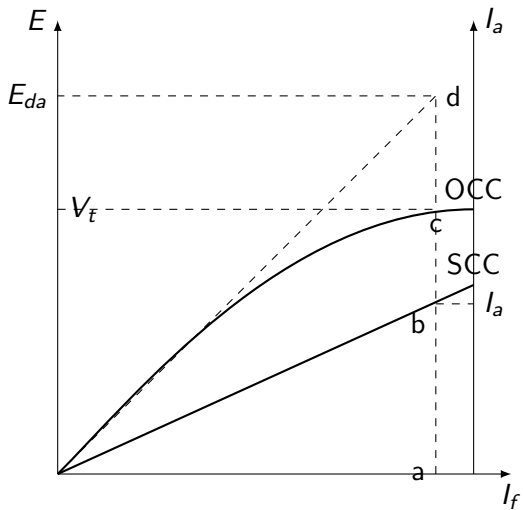


Figure: Field diagram



- ▶ Unsaturated synchronous impedance,

$$Z_{s(\text{unsat})} = \frac{E_{da}}{I_a}$$

If R_a is known, $X_{s(\text{unsat})}$ can be found.

$$X_{s(\text{unsat})} = \sqrt{(Z_{s(\text{unsat})})^2 - R_a^2}$$

- ▶ Saturated synchronous impedance,

$$Z_{s(\text{sat})} = \frac{V_t}{I_a} == R_a + jX_{s(\text{sat})}$$

If R_a is known, $X_{s(\text{sat})}$ can be found.

$$X_{s(\text{sat})} = \sqrt{(Z_{s(\text{sat})})^2 - R_a^2}$$

Saturated synchronous reactance X_s is normally used in calculations.

Alternator - Phasor Diagrams

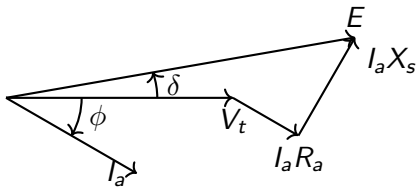


Figure: lagging power factor load

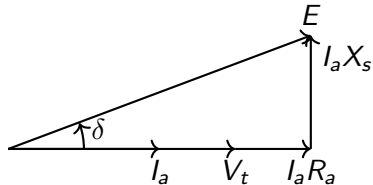


Figure: unity power factor load

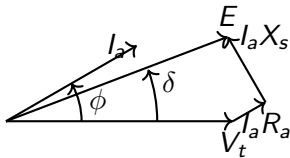


Figure: leading power factor load

In Alternators

- ▶ E leads V_t by δ . δ is positive.
- ▶ This δ is also the angle between the main field ϕ_f and the resultant field ϕ_r .
- ▶ ϕ_f leads ϕ_r by δ .

Let us neglect R_a .

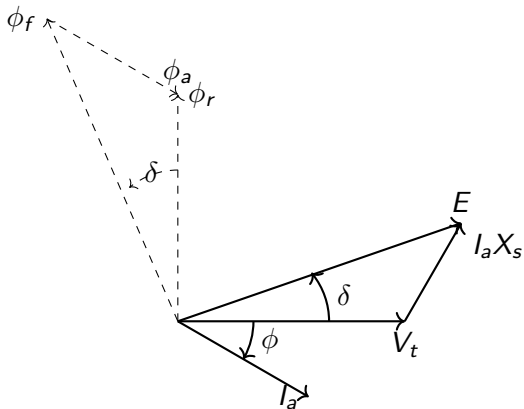
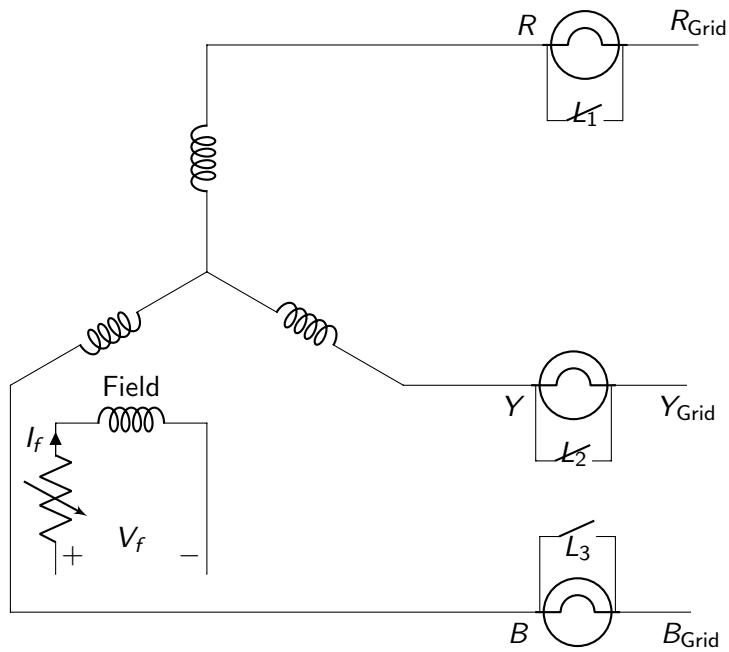


Figure: Alternator supplies a lagging power factor load - Field diagram

Synchronization of Alternators



The alternator and the grid must have the same

1. Voltage
 2. Frequency
 3. Phase Sequence
 4. Phase
- ▶ When all the above conditions are satisfied, the three lamps will be dark. It is time to close the switch.
 - ▶ Once it is synchronized, the terminal voltage and frequency of the alternator can not be changed.
 - ▶ By changing the prime mover speed, Real Power (P) can be controlled.
 - ▶ By changing the excitation, Reactive Power (Q) and hence power factor can be controlled.

Power Characteristic

It always works with an infinite bus.

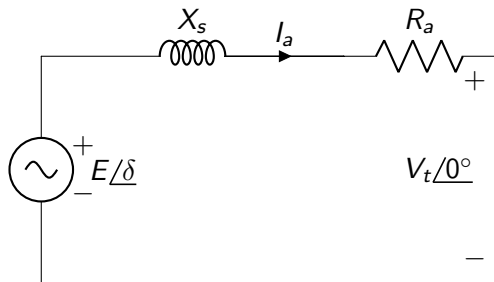


Figure: Per phase equivalent circuit

To find the power delivered by the alternator,

$$S = V_t I_a^*$$

$$S = V_t/0^\circ \left(\frac{(E/\delta - V_t/0^\circ)}{|Z_s|/\theta} \right)^*$$

$$S = \frac{EV_t/\theta - \delta}{|Z_s|} - \frac{V_t^2/\theta}{|Z_s|}$$

By taking Real and Imaginary parts,

$$P = \frac{EV_t \cos(\theta - \delta)}{|Z_s|} - \frac{V_t^2 \cos(\theta)}{|Z_s|}$$

$$Q = \frac{EV_t \sin(\theta - \delta)}{|Z_s|} - \frac{V_t^2 \sin(\theta)}{|Z_s|}$$

If we neglect R_a , $|Z_s| = |X_s|$ and $\theta = 90^\circ$.

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

$$Q = \frac{EV_t \cos \delta}{X_s} - \frac{V_t^2}{X_s}$$

Three phase real and Reactive power

$$P = 3 \frac{EV_t \sin \delta}{X_s} = P_{\max} \sin \delta$$

$$Q = 3 \left(\frac{EV_t \cos \delta}{X_s} - \frac{V_t^2}{X_s} \right)$$

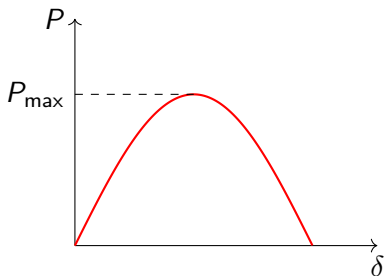


Figure: Power angle curve

V - Curves:

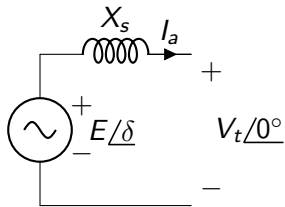


Figure: Per phase equivalent circuit

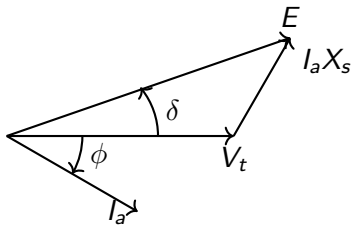


Figure: Supplying a lagging power factor load

Let us keep the real power delivered constant and change the excitation.

$$P = \frac{EV_t \sin \delta}{X_s} = V_t I_a \cos \phi$$

where ϕ is the angle difference between V_t and I_a .
if I_f is varied, E_f will vary (linearly if magnetic linearity is assumed). Since V_t is fixed,

$$E \sin \delta = \text{const}$$

$$I_a \cos \phi = \text{const}$$

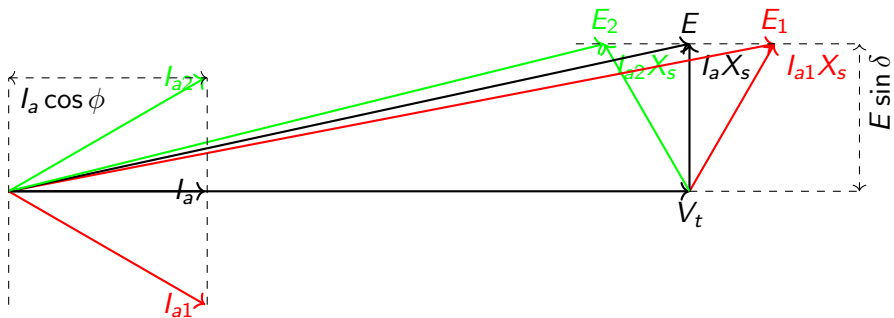


Figure: Different excitation for a constant P

$$E_1 \sin \delta_1 = E \sin \delta = E_2 \sin \delta_2$$

$$I_{a1} \cos \phi_1 = I_a \cos \phi = I_{a2} \cos \phi_2$$

1. Over Excitation :

$$E \cos \delta > V_t$$

Alternator supplies lagging current and supplies reactive power.

2. Normal Excitation :

$$E \cos \delta = V_t$$

Alternator supplies unity power factor current and supplies zero reactive power.

3. Under Excitation :

$$E \cos \delta < V_t$$

Alternator supplies leading current and draws reactive power.

If we plot I_a Vs I_f ,

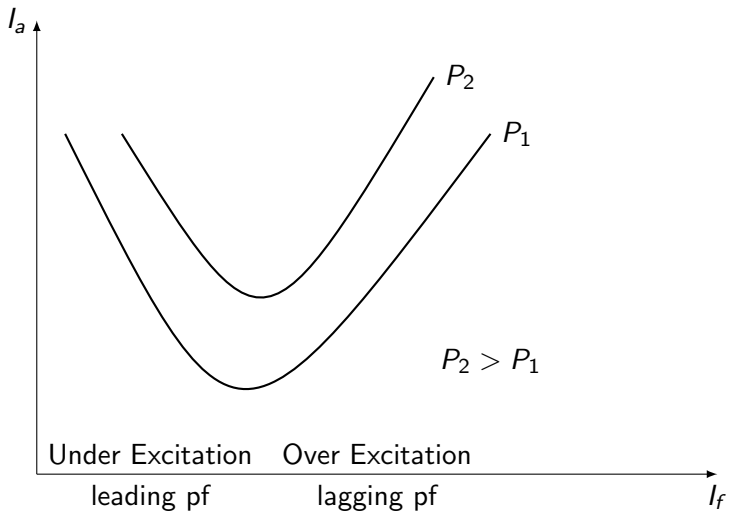


Figure: V-Curves of an Alternator

Example 1 : (Example 8.13 : Kothari)

A 3ϕ , 10 kVA, 400 V, 4-pole, 50 Hz star connected synchronous machine has synchronous reactance of 16Ω and negligible resistance. The machine is operating as generator on 400 V bus-bars (assumed infinite).

1. Determine the excitation emf (phase) and torque angle when the machine is delivering rated kVA at 0.8 pf lagging.
2. While supplying the same real power as in part (1), the machine excitation is raised by 20 %. Find the stator current, power factor, torque angle and reactive power delivered.
3. With the field current held constant as in part (1), the power (real) load is increased till the steady state power limit is reached. Calculate the maximum power and kVAR delivered and also the stator current and power factor. Draw the phasor diagram under these conditions.

1.

$$P = 10 \times 0.8 = 8\text{kW (three phase)}$$

$$I_a = \frac{8000}{\sqrt{3} \times 400 \times 0.8} = 14.43 \text{ A}$$

$$E/\delta = \frac{400}{\sqrt{3}}/0^\circ + 14.43/-36.87^\circ \times 16/90^\circ$$

$$E = 413.3 \text{ V (phase)}$$

$$\delta = 26.5^\circ$$

2.

$$E_1 = 1.2 \times E = 496 \text{ V}$$

$$E \sin \delta = E_1 \sin \delta_1$$

$$\delta_1 = 21.9^\circ$$

The stator current

$$I_{a1} = \frac{E_1/\delta_1 - V_t/0^\circ}{jX_s}$$

$$I_{a1} = 18.4 \angle -50.9^\circ \text{ A}$$

$$pf = 0.63 \text{ lagging}$$

$$Q = \sqrt{3} V_t I_a \sin \phi = 9.89 \text{ kVAR (3-phase)}$$

Q can also be found by the following formula.

$$Q = 3 \left(\frac{E V_t \cos \delta}{X_s} - \frac{V_t^2}{X_s} \right)$$

Q is positive which means the machine is supplying it.

3.

$$E = 413.3 \text{ V}$$

When the real power reaches its maximum value, $\delta = 90^\circ$.

$$P_{\max} = \frac{E V_t}{X_s} = \frac{413.3 \times 231}{16} = 5.96 \text{ kW/phase}$$

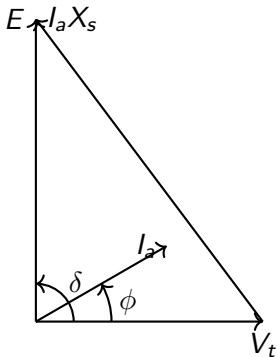
$$P_{\max} = 17.38 \text{ kW (3-phase)}$$

$$I_a = \frac{413.3\angle 90^\circ - 231\angle 0^\circ}{16\angle 90^\circ} = 29.56\angle 29.2^\circ \text{ A}$$

$$pf = 0.873 \text{ leading}$$

$$Q = \sqrt{3} \times 400 \times 29.56 \times \sin(-29.2^\circ) = -9.99 \text{ kVAR (3-phase)}$$

Since Q is negative, the machine is drawing it.



Synchronous Motor

- ▶ Stator (armature) is connected to a three phase AC supply.
- ▶ Rotor (field winding) is connected to a DC supply.

Unlike three phase induction motors and DC motors, synchronous motors are not *self-starting*.

let us consider a 4-pole synchronous machine.

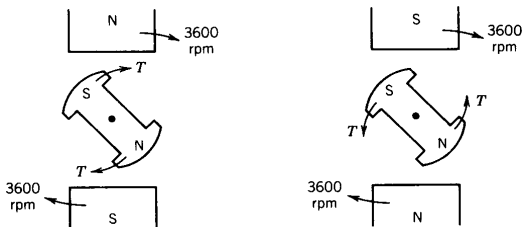
- ▶ When the three phase armature winding (stator) is supplied with a three phase balanced supply, It produces a rotating mmf in the air gap whose speed is the synchronous speed

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

For a 4-pole machine and 50 Hz supply, $N_s = 1500$ rpm.

- ▶ When the field winding (rotor) is excited by DC, it will produce a stationary field.

- ▶ When the revolving field rotates, the rotor experiences torque and is trying to rotate in the direction of revolving field.
- ▶ Due to inertia of the rotor, rotor field poles have hardly moved. By the time stator poles have moved.
- ▶ Therefore, the rotor experiences torque in the opposite direction.
- ▶ Hence there is no net torque and the motor will not develop any starting torque.



Methods of Starting

1. Use a variable frequency supply
 - ▶ The motor is started with a low frequency supply.
 - ▶ This will make stator field move slowly so that the rotor can follow.
 - ▶ Then the frequency is gradually increased.
2. Start as an induction machine
 - ▶ Synchronous machines normally have damper or amortisseur winding mounted on the rotor.
 - ▶ Do not excite the rotor.
 - ▶ If the stator is connected to the three phase ac supply, the machine will start as induction motor.
 - ▶ After reaching the steady speed ($N_r < N_s$), excite the rotor with the DC supply.
 - ▶ The rotor will get locked to the revolving field and rotate at N_s .
 - ▶ At N_s , damper winding will get no induced emf (no relative motion).

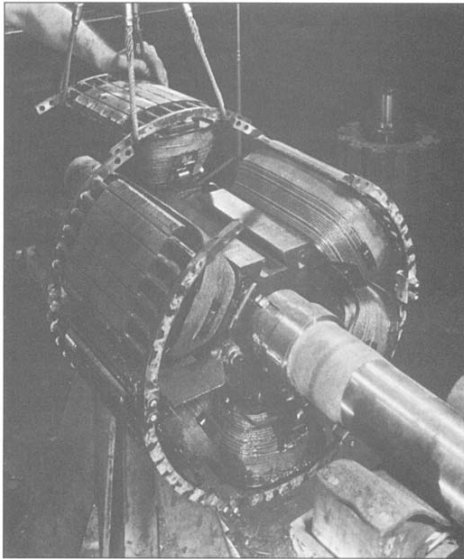
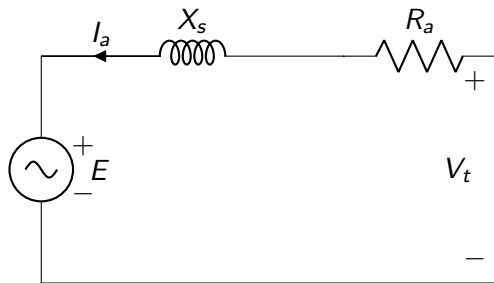


Figure: Synchronous Machine Rotor

Synchronous Motor - Equivalent Circuit



$$E = V_t - I_a(R_a + jX_s)$$

Synchronous Motor - Phasor Diagrams

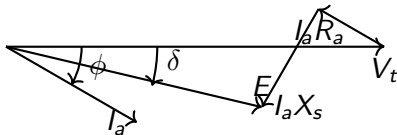


Figure: lagging current

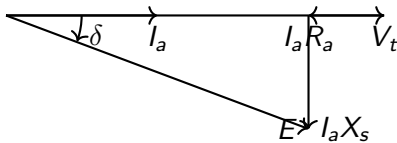


Figure: unity power factor current

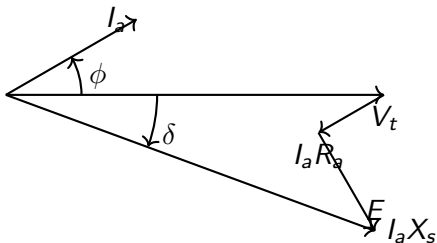


Figure: leading current

In Syn. Motors

- ▶ E lags V_t by δ . δ is negative.
- ▶ This δ is also the angle between the main field ϕ_f and the resultant field ϕ_r .
- ▶ ϕ_f lags ϕ_r by δ .

Let us neglect R_a .

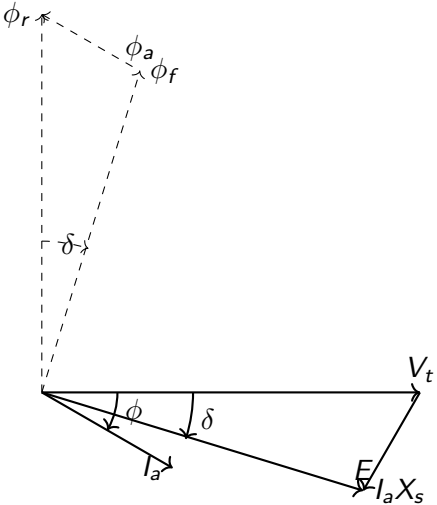


Figure: Syn. Motor draws a lagging current - Field diagram

Torque Characteristics

$$T = \frac{P_{3\phi}}{\omega_s}$$

where ω_s is the synchronous speed in rad/sec. $\omega_s = \frac{2\pi N_s}{60}$

$$T = \frac{3EV_t \sin \delta}{\omega_s X_s} = T_{\max} \sin \delta \text{ Nm}$$

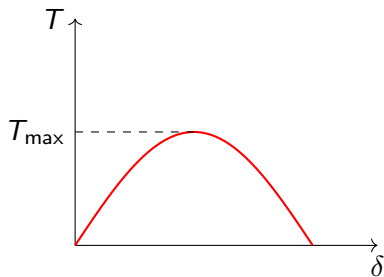


Figure: Torque angle curve

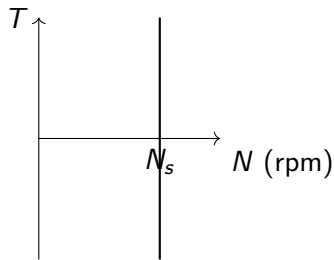


Figure: Torque speed curve

Power Factor Control

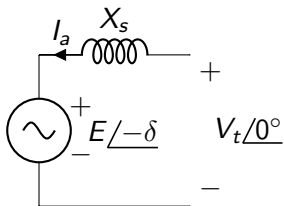


Figure: Per phase equivalent circuit

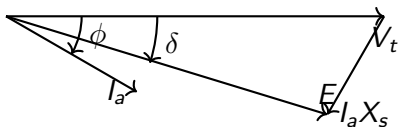


Figure: Drawing a lagging current

Let us keep the real power supplied to the motor constant and change the excitation.

$$P = \frac{EV_t \sin \delta}{X_s} = V_t I_a \cos \phi$$

if I_f is varied, E_f will vary (linearly if magnetic linearity is assumed). Since V_t is fixed,

$$E \sin \delta = \text{const}$$

$$I_a \cos \phi = \text{const}$$

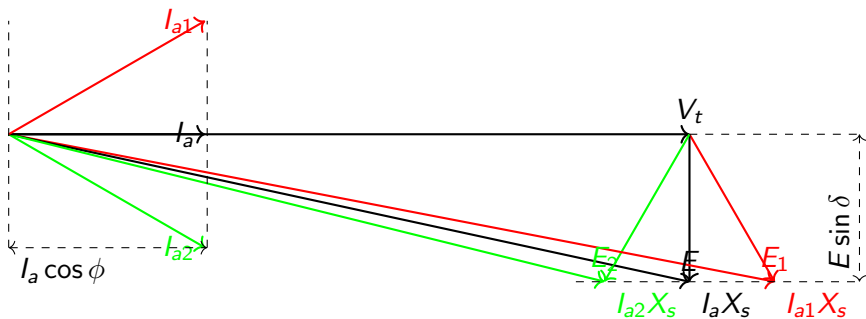


Figure: Different excitation

$$E_1 \sin \delta_1 = E \sin \delta = E_2 \sin \delta_2$$

$$I_{a1} \cos \phi_1 = I_a \cos \phi = I_{a2} \cos \phi_2$$

1. Over Excitation :

$$E \cos \delta > V_t$$

Syn. motor draws leading current and supplies reactive power.

2. Normal Excitation :

$$E \cos \delta = V_t$$

Syn. motor draws unity power factor current and draws zero reactive power.

3. Under Excitation :

$$E \cos \delta < V_t$$

Syn. motor draws lagging current and draws reactive power.

If we plot I_a Vs I_f ,

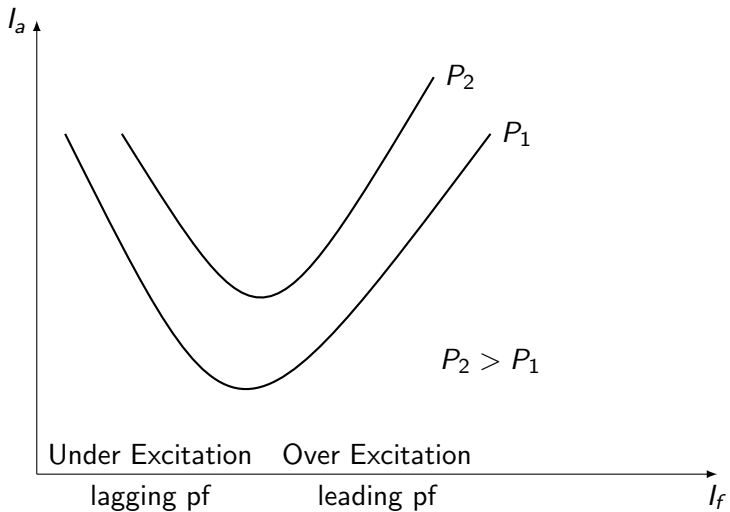
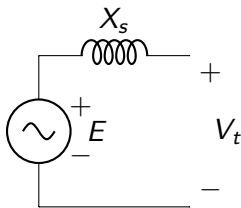


Figure: V-Curves of a Syn. Motor

Synchronous Condenser



Let us vary the excitation. Since V_t is fixed,

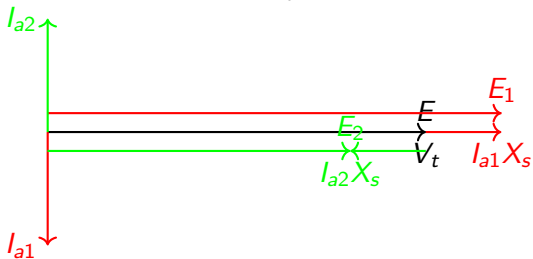


Figure: Phasor diagram - Generator Convention

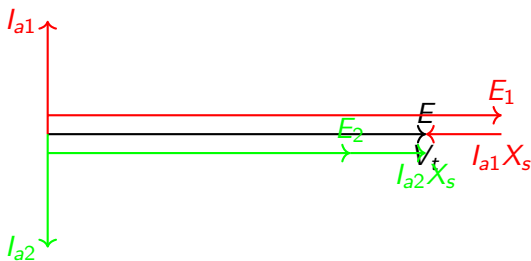


Figure: Phasor diagram - Motor Convention

- ▶ An overexcited unloaded synchronous machine supplies a pure lagging current (draws a pure leading current).
- ▶ An under excited unloaded synchronous machine supplies a pure leading current (draws a pure lagging current).

When the synchronous machine is not transferring any real power,

- ▶ its power factor is zero.
- ▶ the stator current either leads or lags the voltage by 90° .
- ▶ the magnitude of the stator current can be changed by changing the excitation.
- ▶ it behaves like a variable inductor or capacitor.

An unloaded synchronous machine is called *synchronous condenser* and is used to improve the power factor of the system.

Example 2 :

A 3 ϕ , 10 kVA, 400 V, 4-pole, 50 Hz star connected synchronous machine has synchronous reactance of 16 Ω and negligible resistance. The machine is operating as a motor on 400 V bus-bars (assumed infinite). The field excitation is adjusted so that the power factor is unity when the machine draws 6 kW.

1. Determine the excitation emf and torque angle. Draw the phasor diagram.
2. If the field excitation is held constant and the shaft load is suddenly increased, determine the maximum torque that the motor can deliver.

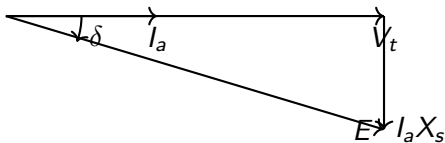
1.

$$P_{3\phi} = 6 \text{ kW}; \quad pf = 1$$

$$I_a = \frac{6 \times 10^3}{\sqrt{3} \times 400 \times 1} = 8.66 \text{ A}$$

$$E = V_t - jI_a X_s = 231\angle 0^\circ - 8.66\angle 0^\circ \times 16\angle 90^\circ$$

$$E = 269.37 \angle -30.96^\circ \text{ V (phase)}$$



2. Maximum torque will be developed at $\delta = 90^\circ$.

$$P_{\max (3\phi)} = \frac{3 \times 231 \times 269.37}{16} = 11.67 \text{ kW}$$

$$T_{\max} = \frac{11.67 \times 10^3}{2 \times \pi \times 1500/60} = 74.28 \text{ Nm}$$