Three-Phase Synchronous Machines

The synchronous machine can be used to operate as:

1. **Synchronous motors**
2. **Synchronous generators (Alternator)**

- ❖ **Synchronous generator is also referred to as alternator since it generates alternating voltage.**
- ❖ **Synchronous machine is designed to be operating at synchronous speed, n_S.**

Two main parts: → **Stator**, → **Rotor**

Construction details of a field and armature:

Types of synchronous machines classified as according to the arrangement of the field and armature windings.

1. Rotating-Armature type:

The *armature winding* is on the *rotor* and the *field system* is on the *stator*. The generated current is brought out to the load via three (or four) slip-rings. Insulation problems, and the difficulty involved in transmitting large currents via the brushes, limit the maximum power output and the generated electromagnetic field (e.m.f) this type is only used in small units, and its main application is as the main exciter in large alternators with brushless excitation system.

(Limited applications).

2. **Rotating-field type**

The *armature winding* is on the *stator* and the *field system* is on the *rotor*. Field current is supplied from the exciter via two slip-rings, while the armature current is directly supplied to the load. This type is employed universally since very high power can be delivered. (Used in commercial application).

- ❖ **The part of the machine in which *voltage is induced* is called *armature*.**

Advantages of rotating field and stationary armature system

1. **Ease of construction for large three-phase SYG. Since the armature winding is more complex than the field winding.**
2. **Number of slip-rings required only two slip-rings.**
3. **It is easier to insulate the armature coils from the core if the windings are placed on the stator instead of on the rotor.**
4. **The weight of the field system placed on the rotor is comparatively much lower than the armature windings placed on stator.**
5. **Improved ventilation arrangement air-cooling or/and hydrogen cooling for large gen. can easily be made on a stationary armature**

Construction of synchronous generators:

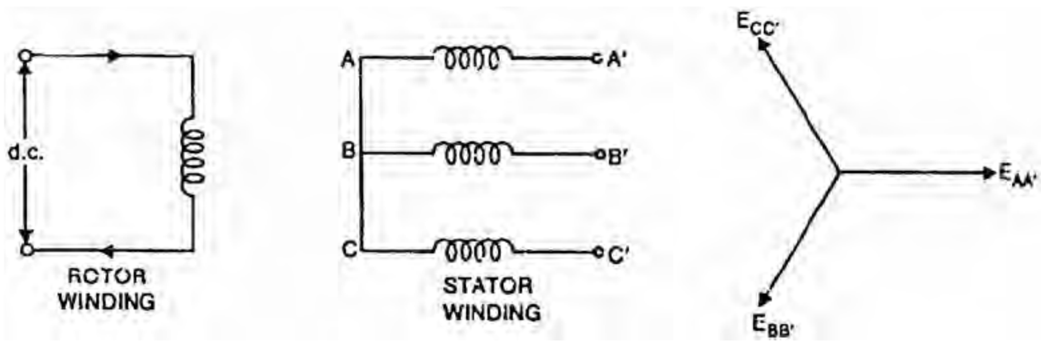
The armature winding, usually on the stator and the field windings usually on the rotor is d.c excited.

1- Stator (armature): Three-phase windings connected on star or delta.

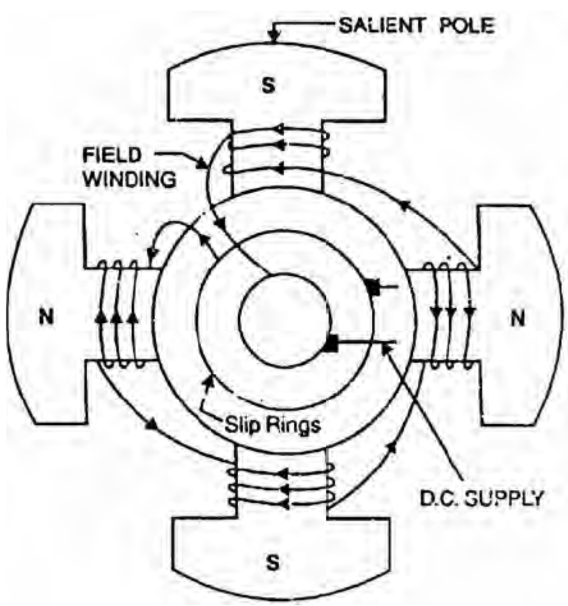
2- Rotor (field)

The types of synchronous machines classified as according to the shape of the field.

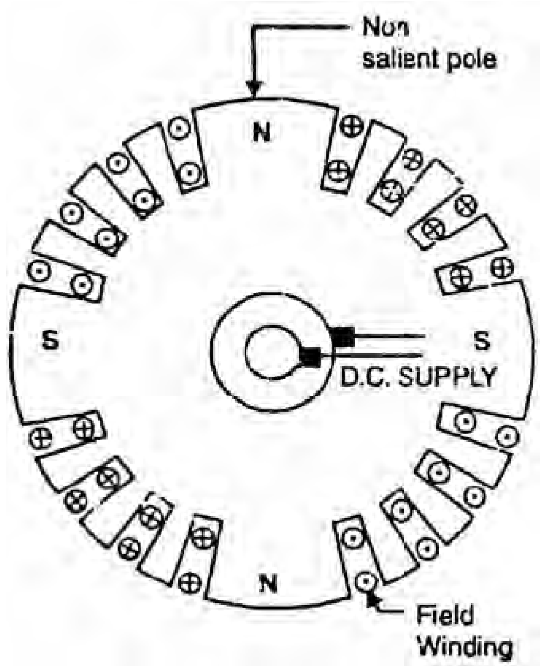
a) Cylindrical rotor, round rotor, non-salient-pole rotor.
b) **Salient-pole rotor**



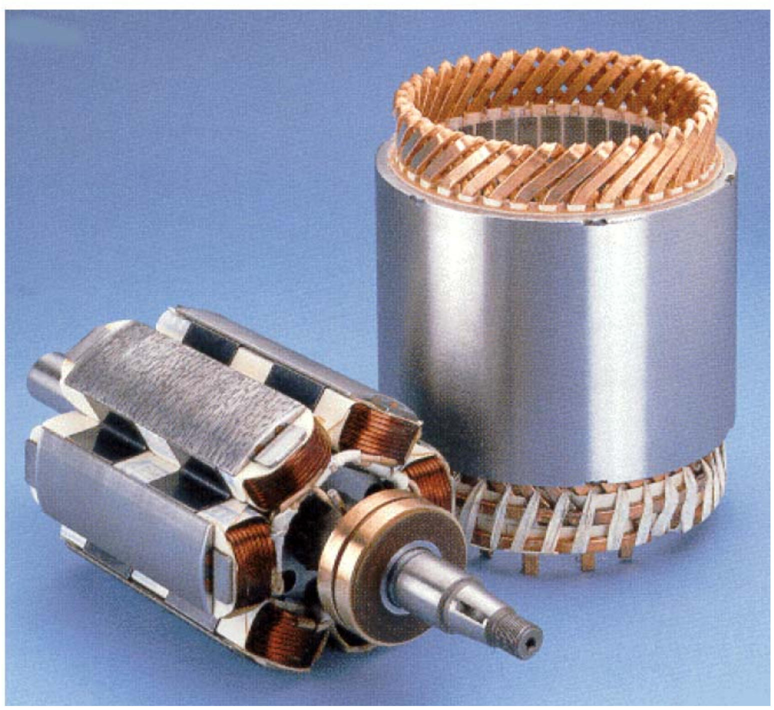
<u>Types of rotor constructions</u>

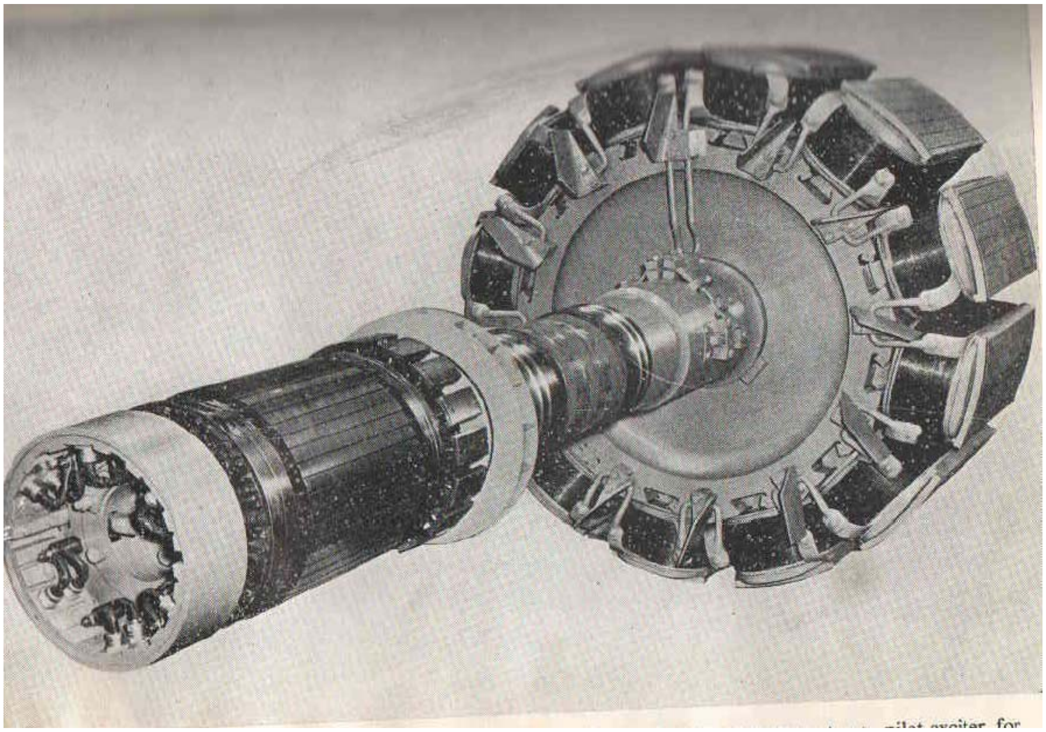


Salient-poles rotor machine



Round rotor machine

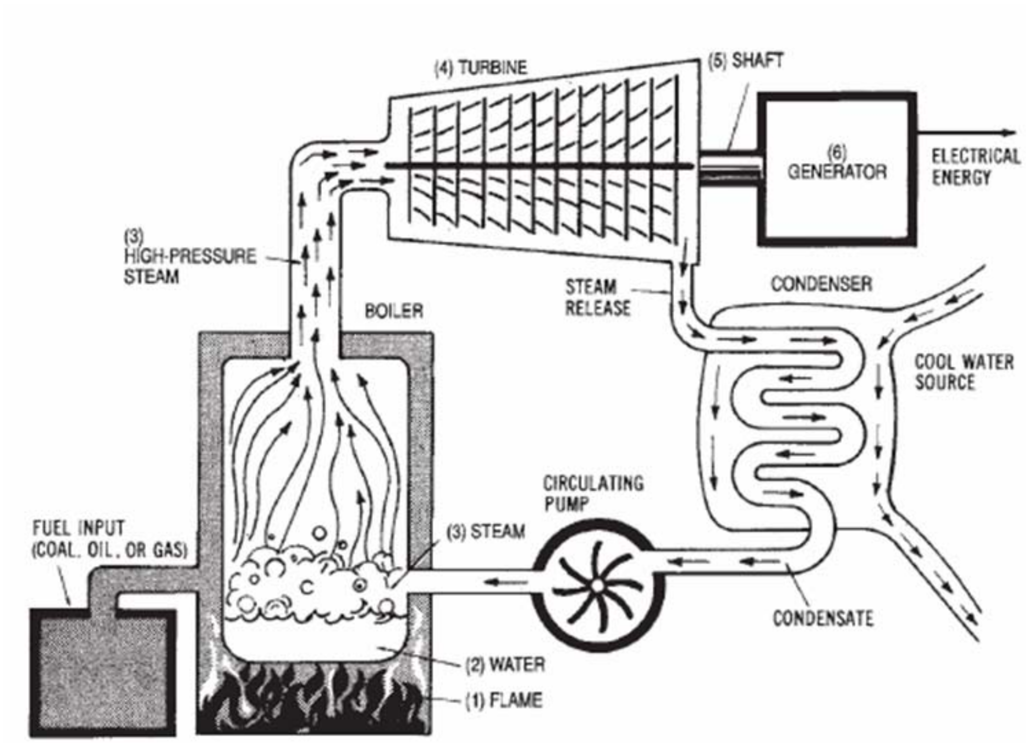


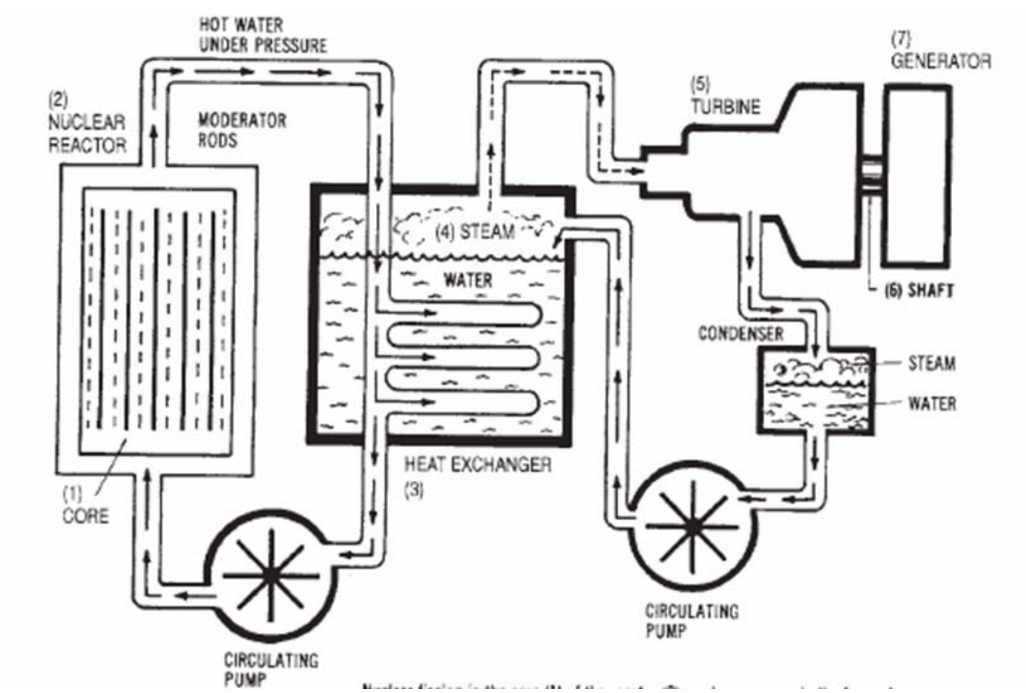


Construction of synchronous generator depends upon the type of prime mover used to rotate the rotor.

<u>Three types of prime mover are generally used:</u>

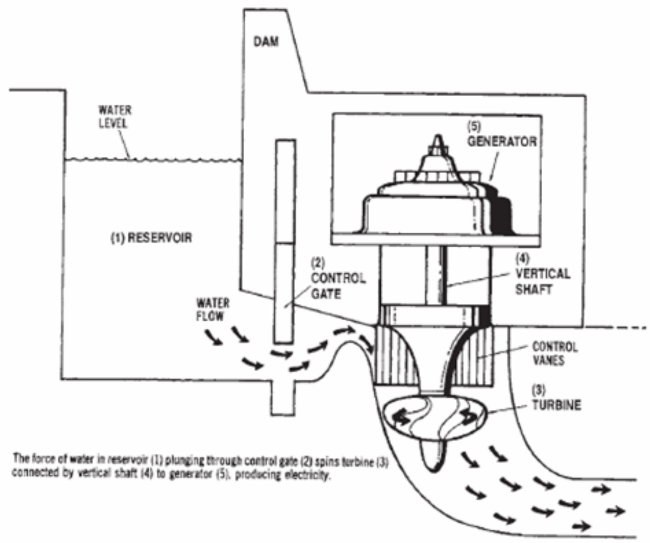
1- **<u>Thermal or nuclear power station (steam turbine).</u>**
   - ❖ **Steam turbines are designed to rotate at high speed (3000 r.p.m.) as at high speed. The efficiency of the steam turbine is high.**
   - ❖ **The rotor of SYG is non salient-pole (cylindrical rotor).**
   - ❖ **Steam turbine generator set is mounted horizontally.**


(4) TURBINE
(5) SHAFT
(6) GENERATOR
ELECTRICAL ENERGY
(3) HIGH-PRESSURE STEAM
BOILER
STEAM RELEASE
CONDENSER
COOL WATER SOURCE
CIRCULATING PUMP
FUEL INPUT (COAL, OIL, OR GAS)
(3) STEAM
CONDENSATE
(2) WATER
(1) FLAME


HOT WATER UNDER PRESSURE
(7) GENERATOR
(2) NUCLEAR REACTOR
MODERATOR RODS
(5) TURBINE
(4) STEAM
WATER
(6) SHAFT
CONDENSER
STEAM
WATER
HEAT EXCHANGER (3)
(1) CORE
CIRCULATING PUMP
CIRCULATING PUMP

2-Hydroelectric power stations:

The water turbine and the alternator are coupled together and mounted vertically. The speed of such prime mover vary from 50 to 500 r.p.m, the rotor (field) have a large number of poles and large diameters.



The force of water in reservoir (1) plunging through control gate (2) spins turbine (3) connected by vertical shaft (4) to generator (5), producing electricity.

3-Diesel engines:

- **Diesel engines are used as prime movers for low rating synchronous generators.**
- **Diesel engines are at low speeds as compared to steam turbines.**
- **The generators have more than two poles and always mounted horizontally.**

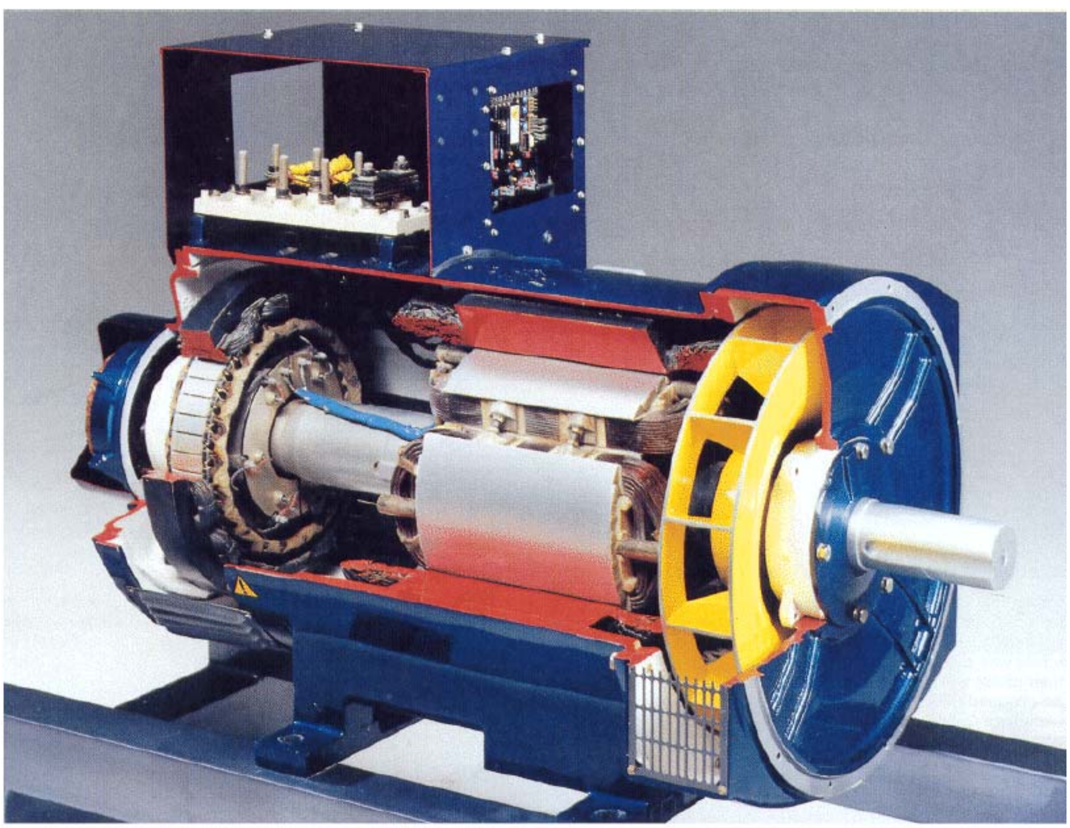
Excitation for rotating field system:

a) **In older machines, the excitation current was typically supplied through slip-rings from a D.C machine, referred to as the exciter, which was often mounted on the same shaft.**

b) **In more modern system, the excitation is supplied from A.C exciter. The output of exciter is rectified through a rectifier and then fed to the field windings.**

c) **On larger generators, brushless exciters are used to supply the D.C field current to the machine.**

- ❖ **Many SYG which include brushless exciters also have slip-rings and brushes, so that an auxiliary source of D.C field current is available in emergencies.**



According to the shape of the field, the synchronous machines may be classified as:

1. **Non-salient pole** (operate at high speeds usually two poles).

Why non-salient pole machine usually has small diameter-to-length ratio? In order to avoid excessive a windage loss and excessive mechanical stress on the rotor due to the large centrifugal forces and also avoid noise.

2. Salient pole (operate at low speeds).

Why salient pole machine usually has a large diameter-to-length ratio? Since a frequency of 50 Hz is required, we must use a large number of poles on rotor of slow-speed alternators.

Magnitude of induced e.m.f in each phase:

The magnitude of the voltage induced in each phase depends upon the rotor flux, the number and position of conductors in the phase and the speed of rotation the rotor.

$$E_g = K.\phi.n$$

Where:

K: Is a constant representing the construction of the machine.

n: Mechanical speed (r.p.m).

φ: Flux it depends on the current flowing in the rotor field circuit.

Frequency:

The frequency of induced e.m.f in the armature conductors depends upon speed and the number of poles.

$$f = \frac{n_S.P_P}{60}$$

Where:

f: Frequency of e.m.f in Hz.

n_s: Rotor speed in (r.p.m), synchronous speed.

P_P: Number of rotor pair pole.

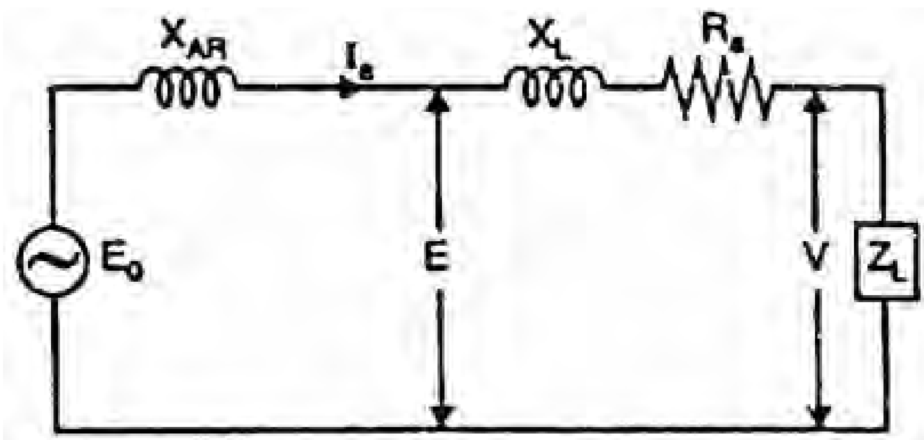
Equivalent circuit model:

We will explore the effects of the first three factors and derive a machine model from them, the effects of a salient-pole shape on the operation of synchronous machine will be ignored, in other words, all the machines assumed to have non salient-pole rotors.

E_O: Is the internal generated voltage produced in one phase.

E: It is the induced e.m.f after allowing for armature reaction.

V: Terminal voltage.



$$E_O = E + I_a (jX_{AR})$$

$$E = V_{ph} + I_a (R_a + jX_L)$$

$$E_O = V_{ph} + I_a R_a + jI_a (X_L + X_{AR})$$

Synchronous Reactance (X_S):

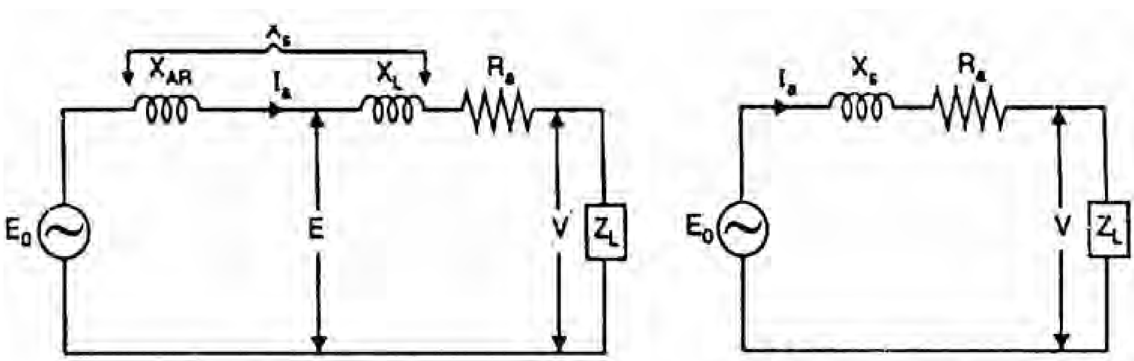
The sum of armature leakage reactance (X_L) and reactance of armature reaction (X_{AR}) is called synchronous reactance (X_S). Note that all quantities are per phase:

$$X_S = X_L + X_{AR}$$

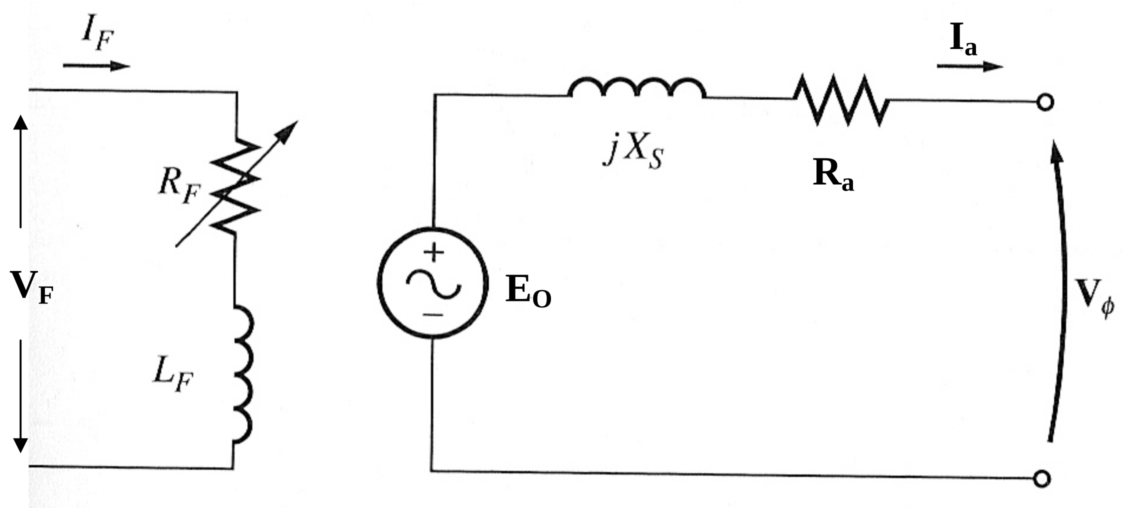
Synchronous impedance

$$Z_S = R_a + jX_S$$

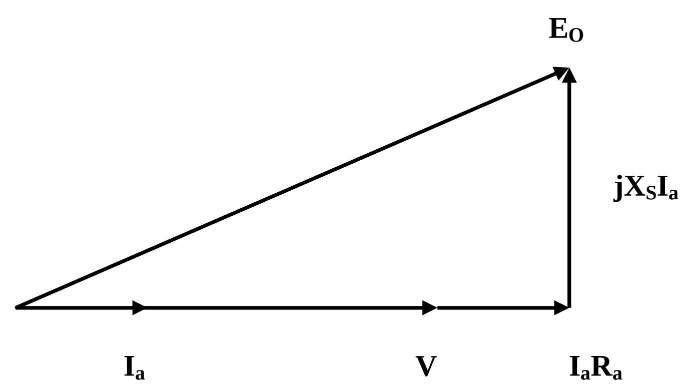
$$E_O = V_{ph} + I_a Z_S$$



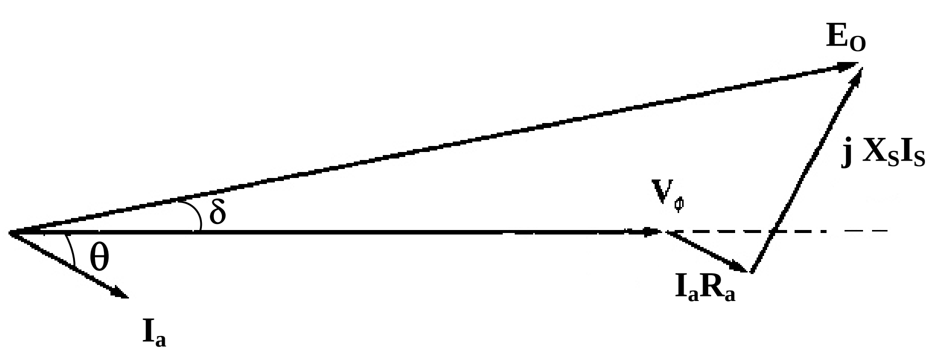
Phasor Diagram of a Synchronous Generator



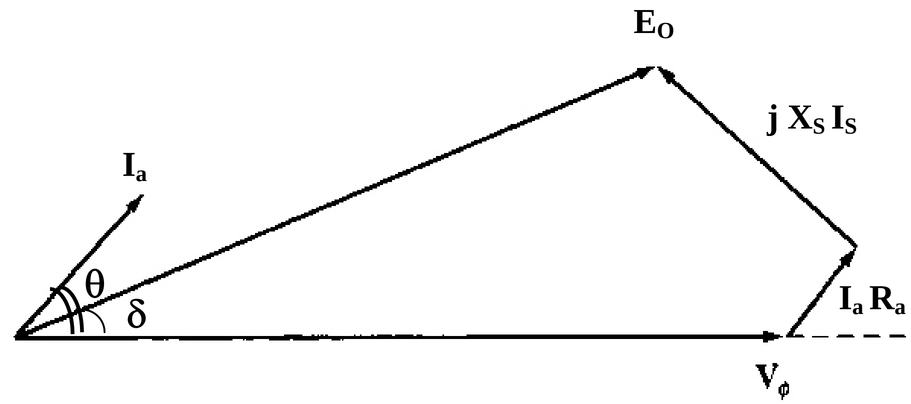
When the synchronous generator non-salient pole is supplying a load; at unity power factor (purely resistive load)



Load at lagging P.F



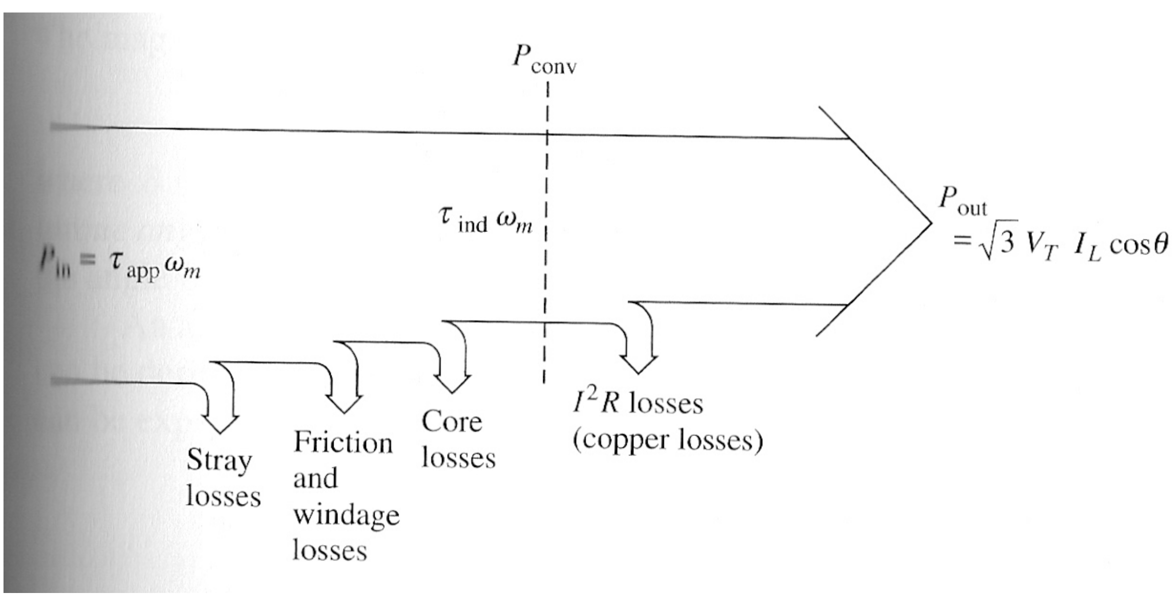
Load at leading P.F



Power and Torque in Synchronous Generators

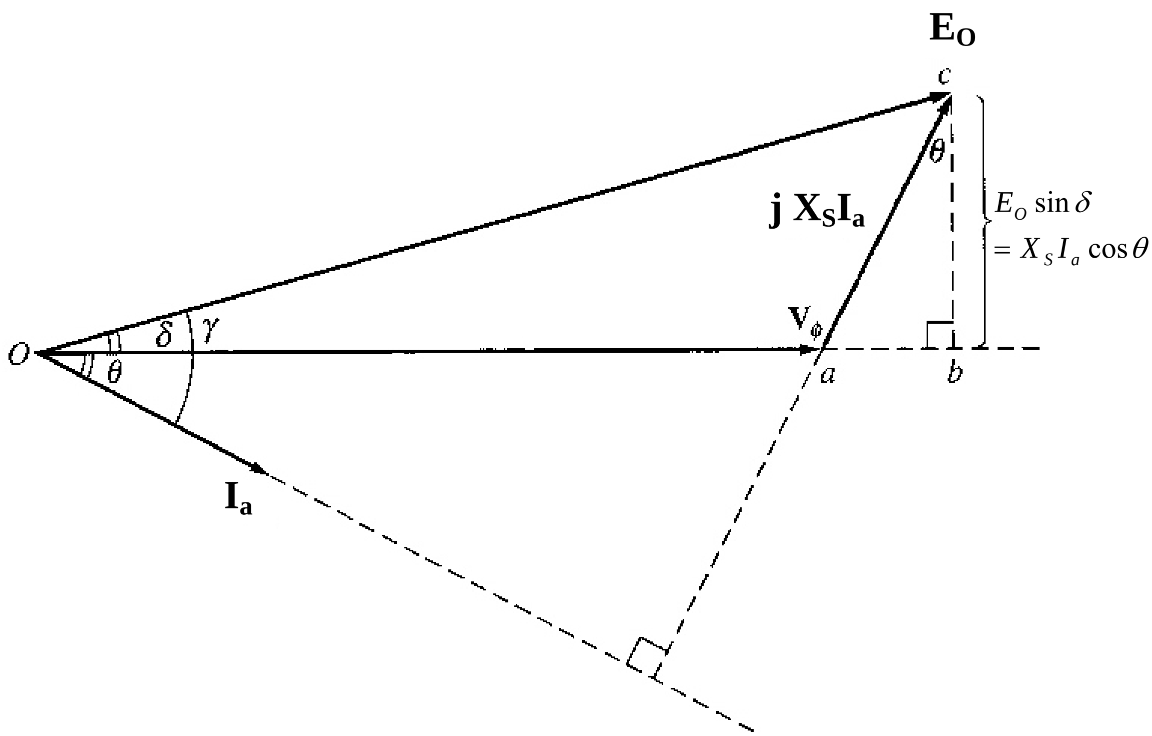
A generator converts mechanical energy into electrical energy; hence the input power will be a mechanical prime mover, e.g. diesel engine, steam turbine, water turbine or anything similar. Regardless of the type of prime mover, the rotor velocity must remain constant to maintain a stable system frequency. .

The power-flow diagram for a synchronous generator is shown



Since $X_S \rangle\rangle R_a$

The armature resistance R_a is ignored,
Simplifying the phasor diagram, an assumption may be made whereby the armature resistance R_A is considered to be negligible and assuming that load connected to it is lagging in nature. This gives a phasor diagram as shown:



$$X_S I_a \cos\theta = E_O \sin\delta$$

$$I_a \cos\theta = \frac{E_O \sin\delta}{X_S}$$

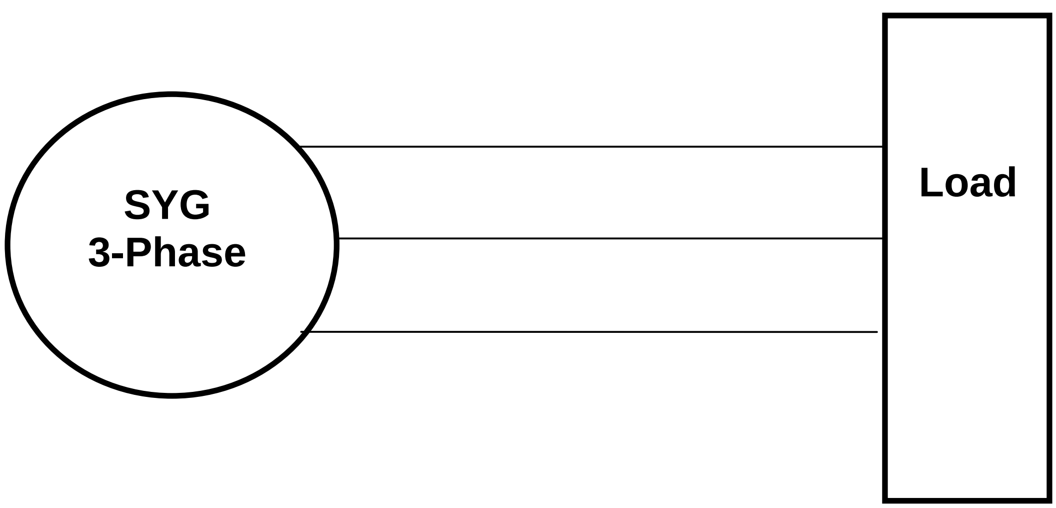
$$P = \frac{3V_{ph} E_O \sin\delta}{X_S}$$

Notice also that maximum power that the generator can be supply occurs when $\delta = 90^\circ$, at $\delta = 90^\circ, \sin\delta = 1$

$$P_{Max.} = \frac{3V_{ph} E_O}{X_S}$$

The maximum power indicated by this equation is called the **static stability limit** of the generator.

The Effect of Load Changes on a Synchronous Generator Operating Alone



The behavior of a synchronous generator under load varies greatly depending on the power factor of load. Assume a generator is connected to a load.

What happens when we increase the load on the generator operating alone?

Assumptions

1- The field current is constant, therefore the flux is constant.

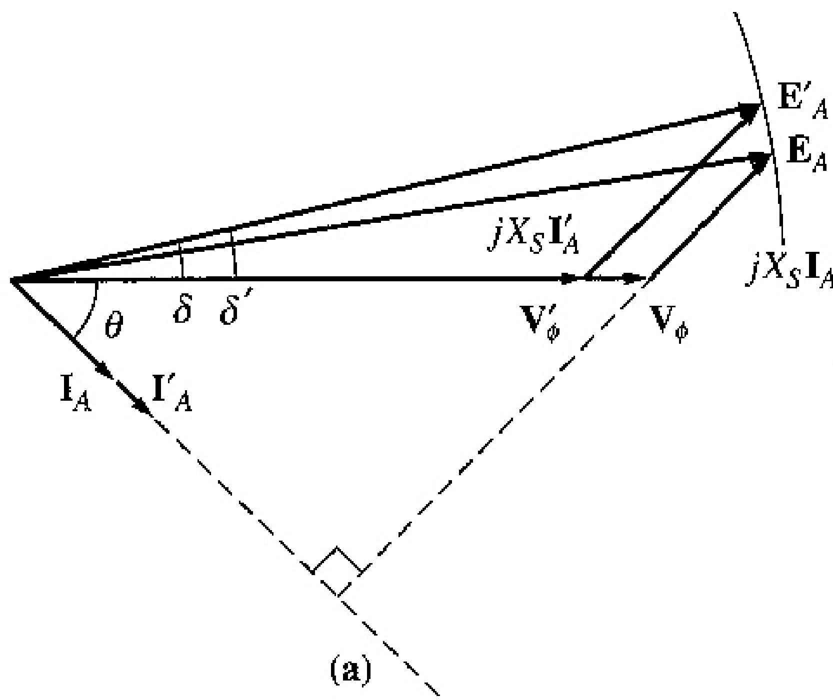
2- The prime mover keeps a constant speed the magnitude of the internal generated voltage Eo constant $E_O = K.\phi.n$

3- The load at the same power factor

At lagging power factor

Increase the load at the same power factor, then armature current increases. Therefore, the armature reaction voltage is larger than before.

$$E_O \angle \delta = V_{ph.} \angle 0 + jX_S I_a \angle \theta$$

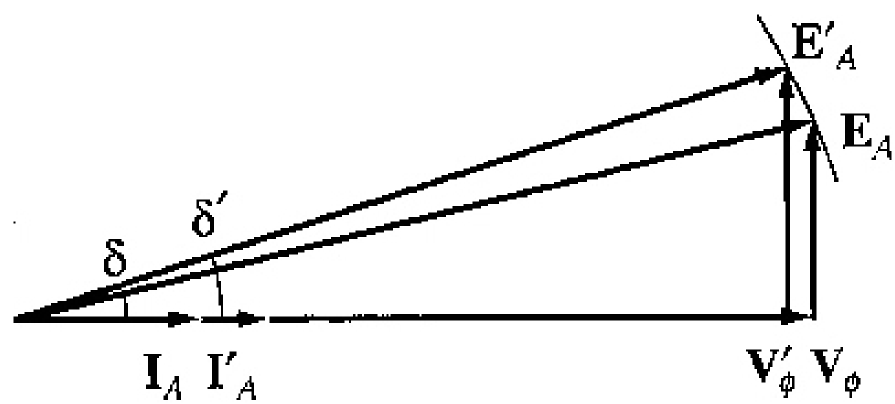


(a)

- Note that E_o has to remain constant (refer to the assumption stated earlier)
- Hence the only element which would change to compensate would be V□. This change may be seen in the phasor diagram.

At unity-power factor

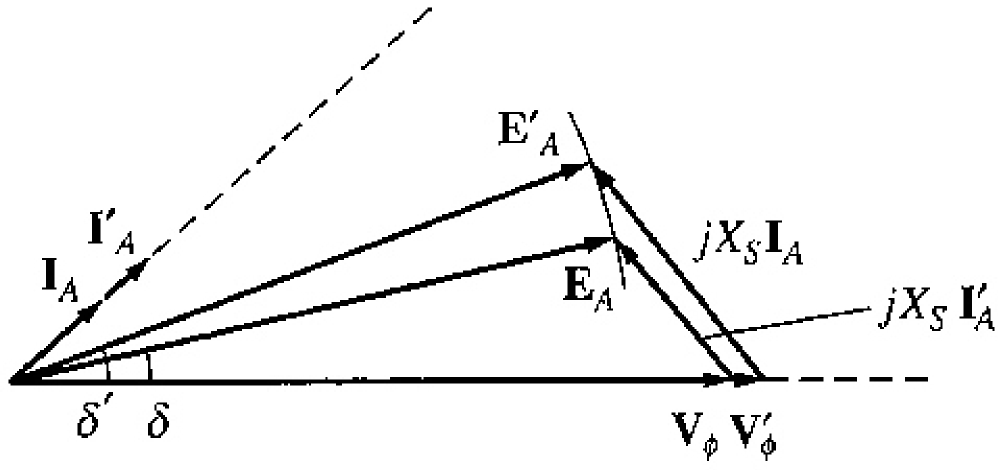
The load increases due to the voltage decreases



(b)

At leading power factor

In this case an increase in the load in the generator produced an increase in the terminal voltage.



(c)

Voltage Regulation

The voltage regulation of an alternator is defined as the change in terminal voltage from no-load to full-load (the speed and field excitation being constant) divided by full-load voltage

$$VR\% = \frac{E_O - V_{F.L}}{V_{F.L}} \times 100$$

An alternative way to explain this is via the **voltage regulation formulae**.

- For lagging loads, VR would be positive.
- For leading loads, VR would be negative.

For unity loads, VR would positive

Conditions for Paralleling Alternator with Infinite Bus-bars

The proper method of connecting an alternator to the infinite bus-bars is called **synchronizing.** A stationary alternator must not be connected to live bus-bars. It is because the induced e.m.f. is zero at standstill and. In order to connect an alternator safely to the infinite bus-bars, the following conditions are met:

1- The r.m.s line voltages of the incoming alternator and the infinite bus-bar must be equal.

2- Frequency of the generated voltage of the incoming alternator must be slightly higher than the frequency of the running system.

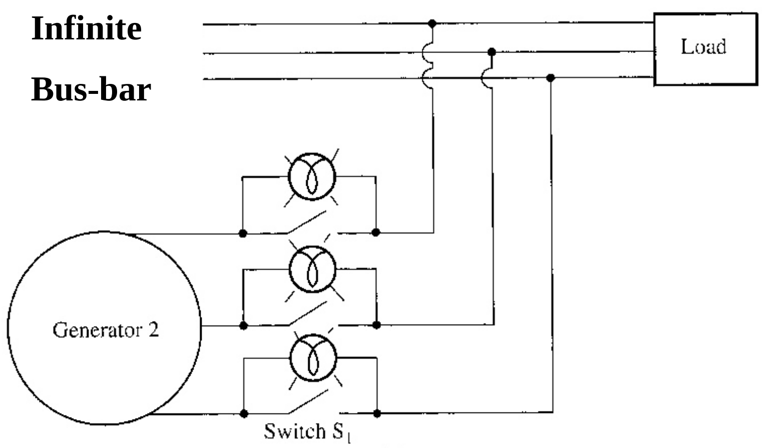
3- The incoming alternator and the infinite bus-bar must have the same phase sequence.

- ***Generated voltage*** of the incoming alternator can be adjusted by adjusting the field excitation by {automatic ***voltage regulation (AVR)*** or manually by a resistance
- ***Frequency*** of the incoming alternator can be controlled and made equal to bus-bar frequency by controlling the speed of the prime mover driving the alternator (***governor mechanism***)

Phase sequence of the alternator and the bus-bar can be checked by a phase sequence indicator (lamps) or special instruments called ***synchroscopes***

Three lamp method

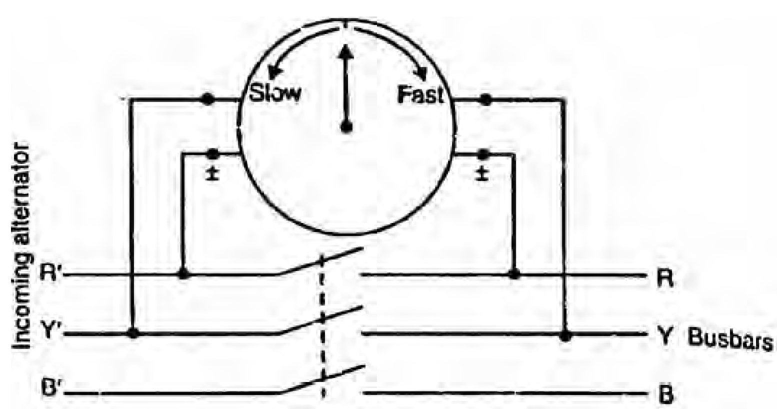
- ☒ If all the lamps glow together and become dark together then the phase sequence of the incoming alternator is the same as that of the bus-bar.
- ☒ If the lamps brighten in succession, then the systems have the opposite phase sequence, and one of the sequences must be reversed



(b)

Synchroscope:

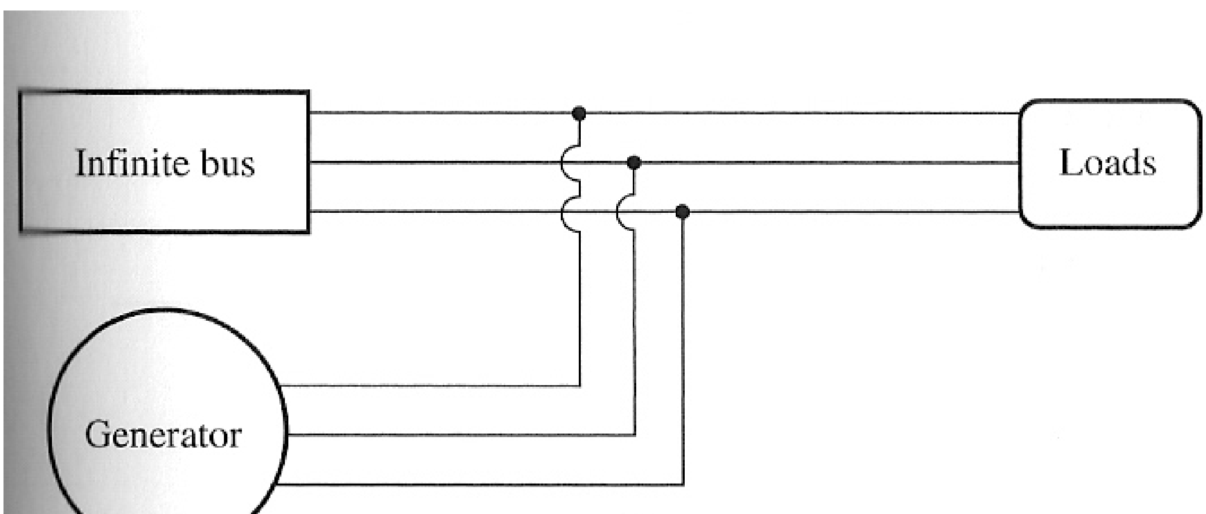
A synchroscope is an instrument that indicates by means of a revolving pointer the phase difference and frequency difference between the voltages of the incoming alternator and the bus-bars.



- In large generators belonging to power system, this whole process of paralleling a new generator to the line is automated, and a computer does this job.

Operation of generators in parallel with large power systems:

- An infinite bus is a power system so large that its voltage and frequency do not vary regardless of how much real and reactive power is drawn from or supplied to it.
- When a generator is connected in parallel with a large system, the generator will be essentially "**floating**" on the line, supplying a small amount of real power and little or no reactive power.



(a)

The behavior of alternators connected to an infinite bus-bar:

Case1:

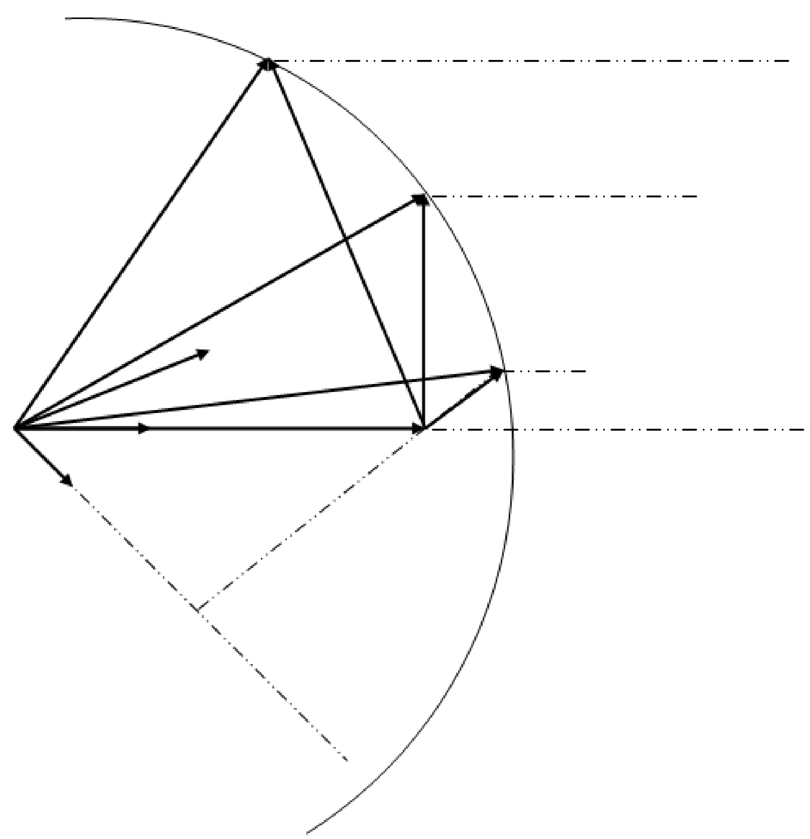
What happens when it governor mechanism set point (prime-mover) are increases, but that the field excitation is kept constant?

Any change made in the operating conditions of one alternator will not change the terminal voltage or frequency of system.

V_T , E_O (constant) since E_O=Kφ n

$$\uparrow P_{in} = T_{app}\,\omega_S$$

Conclusion: increasing the mechanical input power to the prime mover will not change the speed ultimately but will increase the power angle (δ). As a result, the change of driving torque controls the active output power increased

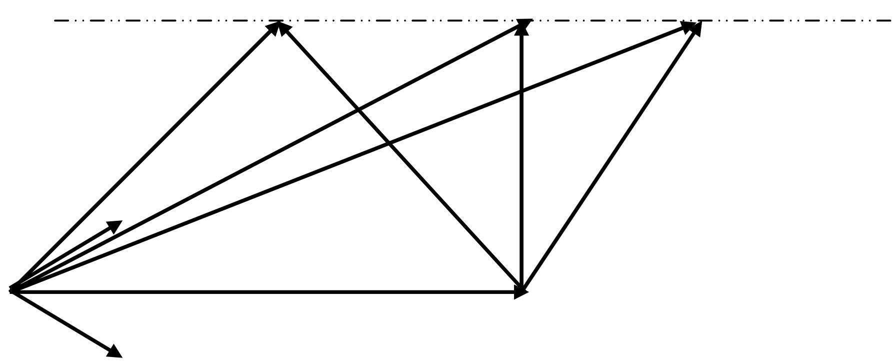


After the real power of the generator has been adjusted to the desired value, the phasor diagram of generator look like at this time the generator is actually operating a slightly leading power factor, supplying negative reactive power. How cans the generator be adjusted so that it will supply some reactive power to the system?

<u>Case 2:</u>

How can the generator be adjusted so that will supply some reactive power to system?

Can be done by adjusting the field current of the alternators, when the field current is increased, the flux ϕ increases, and therefore $E_O=K\phi n$, and V=constant.



Increasing the field current due to increases the reactive power output of the generator

Summary:

When a generator is operating by itself supplying the system loads (alone):

1. The real and reactive power supplied by the generator will be the amount demanded by the attached load.

2. The governor set points of the generator will control the operating frequency of the power system.

3. The field current set points control the terminal voltage of the power system.

When a generator is operating in parallel with an infinite bus-bar:

1. The frequency and terminal voltage of the generator are controlled by the system to which it is connected.

2. The governor set points of the generator control the real power supplied by the generator to system.

3. The field current in the generator controls the reactive power supplied by the generator to the system.

Advantages of Parallel Operation of Alternators

The following are the advantages of operating alternators in parallel:

1. **Continuity of service**. The continuity of service is one of the important requirements of any electrical apparatus. If one alternator fails, the continuity of supply can be maintained.

through the other healthy units. This will ensure uninterrupted supply to the consumers.

2. Increased Efficiency: The load on the power system varies during the whole day; being minimum during die late night hours. Since alternators operate most efficiently when delivering full-load, units can be added or put off depending upon the load requirement. This permits the efficient operation of the power system.

3. Maintenance and repair can be done without power disruption. It is often desirable to carry out routine maintenance and repair of one or more units. For this purpose, the desired Unit/units can be shut down and the continuity of supply is maintained through the other units

4. Load growth. The load demand is increasing due to the increasing use of electrical energy. The load growth can be met by adding more units without disturbing the original installation.