EE240: Power Engineering LAB

Synchronous Generator/ Synchronisation

Instructor

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26/3/2021, Tuesday

SYNCHRONOUS MACHINES

- In IM $\rightarrow$ N_r is a function of load & $N_s \neq N_r$
- In synchronous machines $\rightarrow$ $N_s = N_r$ & $s = 0$ steady state N_r is independent of load
- Synchronous generator $\Rightarrow$ Alternator $\rightarrow$ used to generate electric power

$\Rightarrow$ Rating is high $\rightarrow$ in MW

$\Rightarrow$ In India largest generator is 1000 MW[†] located in Tamil Nadu Nuclear Plant.

$\Rightarrow$ Driven by turbine
- $\rightarrow$ steam turbine $\rightarrow$ high speed
- $\rightarrow$ Pelton turbine $\rightarrow$ low speed (hydro)

[†] https://cea.nic.in/wp-content/uploads/pdm/2020/09/list_power_stations_2020.pdf

Stator		Rotor
3-ϕ ac winding (similar to 3-ϕ IM)	$\rightarrow$	dc
dc	$\rightarrow$	3-ϕ ac winding

Rating - 250MVA, 'V' rating $\cong$ 16kV, Rated 'I' $\cong$ 9kA dc current $\cong$ 2600A,
dc voltage rating = 310V,
speed = 3000 rpm

If ac winding is on the rotor		dc winding is on the rotor
'V' between 2 slip rings $\cong$ 16kV		310V
'I' flowing through Slip rings	$\cong$ 9kA	2.6kA

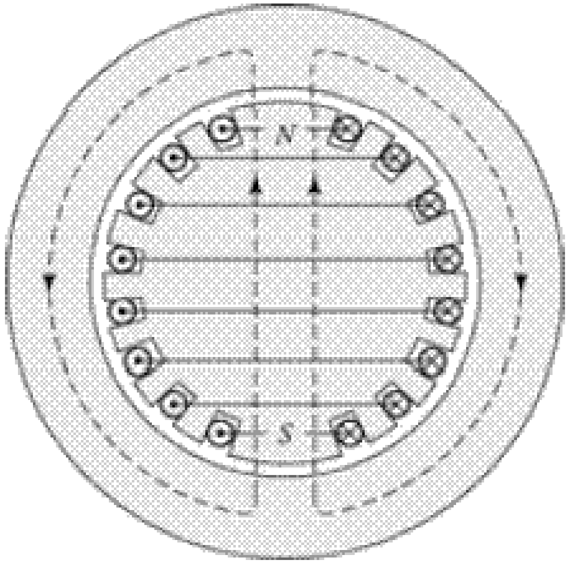
Slip rings rotate at 3000 r.p.m $\Rightarrow$ It is convenient to have dc field rotating

There are two types of rotor construction

Cylindrical rotor $\rightarrow$ rotor is circular

$\Rightarrow$ suitable for high speed operation

$\Rightarrow$ Invariably wound for 2 poles



Salient pole rotor

$\Rightarrow$ has projected poles

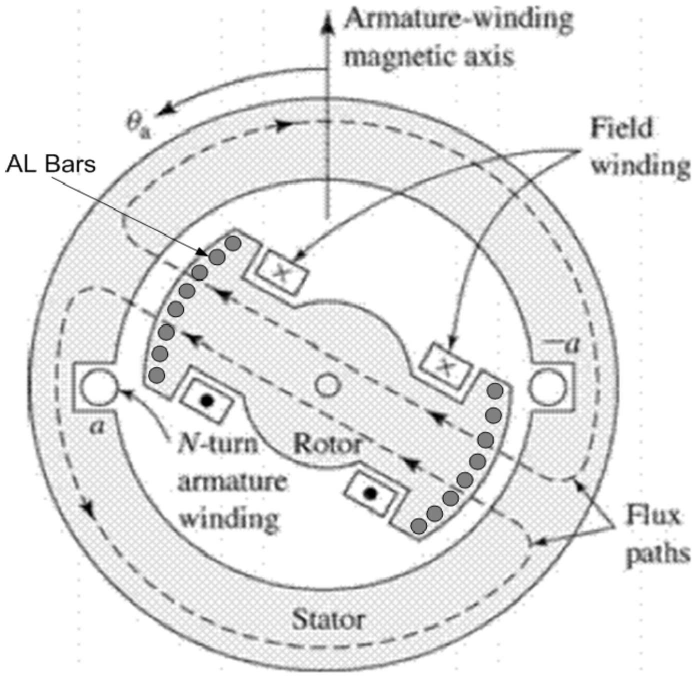
$\Rightarrow$ bars are fitted on the pole faces

(similar to cage winding)

$\Rightarrow$ suitable for low speed operation

$\Rightarrow$ no. of poles could be 24

$\Rightarrow$ In order to generate power at 50Hz, rotate the rotor at 250 rpm



Cylindrical rotor

$\Rightarrow$air gap is uniform

$\therefore \Re$ is constant ($\Re \rightarrow$ reluctance)

$\Rightarrow$ 'L' is independent of rotor position

Salient pole rotor

air gap is non-uniform & $\therefore \Re$

$\Rightarrow \Re$ is minimum along field axis (direct axis)

$\Rightarrow \Re$ is maximum along q-axis (quadrature axis)

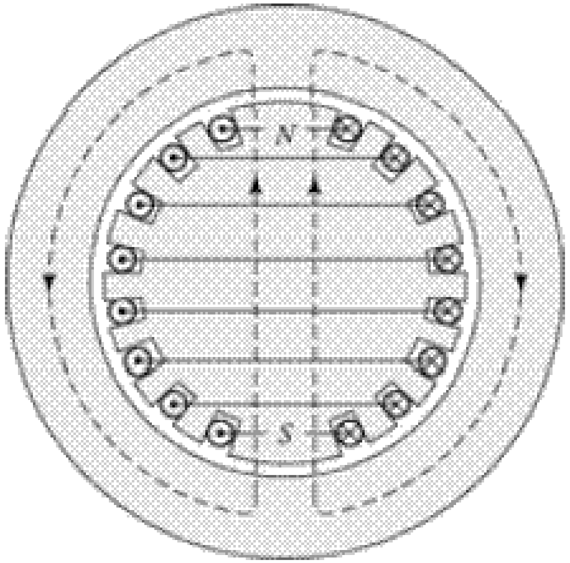
$\therefore$ 'L' depends on rotor position

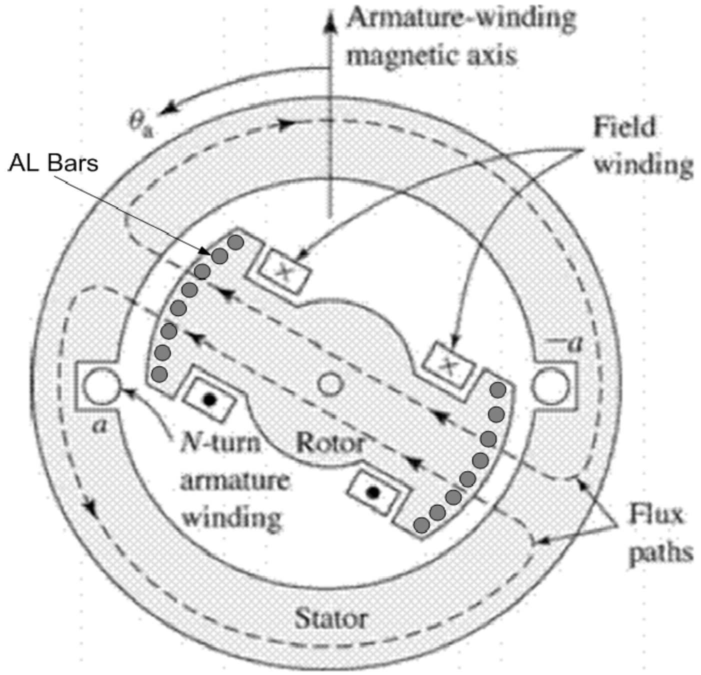
If $\Re$ is min $\rightarrow$ 'L' would be max

If $\Re$ is max $\rightarrow$ 'L' would be min

$\therefore$ 'L' varies between $L_{min}(= L_q)$ & $L_{max}(= L_d)$

$\Rightarrow$ apart from field winding there is cage winding as well





Principle of operation : stator has 3-ϕ distributed winding (similar to IM.)

Assume that generator is brand new & no. of poles = 2 ; keep the stator terminals open with I_{dc}= 0, rotate the rotor at 3000 rpm

$\because$ I_F = 0, rotor mmf & $\therefore$ field flux = 0

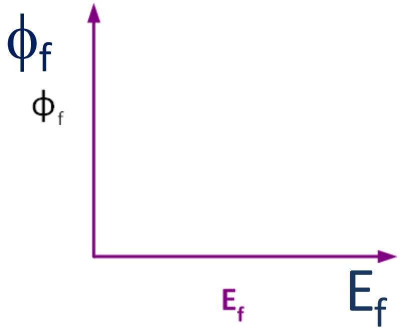
$\therefore$ 'V' induced in the stator on O.C

$(E_0) = 0$

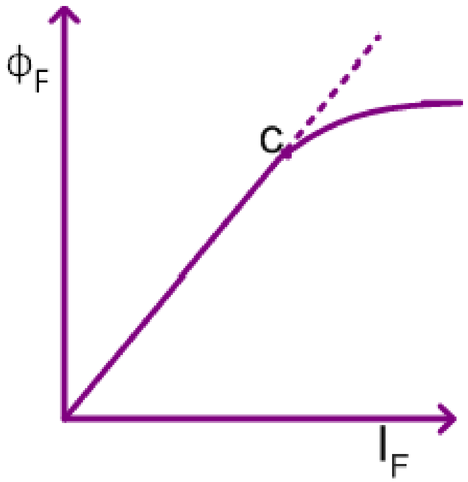
$\Rightarrow \uparrow I_F$

$\Rightarrow$ as $I_F \uparrow$, $\phi_f \uparrow$

$\Rightarrow E_0 \alpha \phi_f \omega N_{ph}$



In phasor form



$\because$ ω & N_{ph} are constant

$\therefore E_0 \alpha \phi_f$

αI_f

$\Rightarrow$ Variation of E_0 with I_f at constant ω is known as open circuit characteristic (OCC) (stator terminals are kept open)

$\Rightarrow \uparrow$ in $E_0 \propto I_f$ till point C, beyond 'C', circuit gets saturated variation is no longer linear

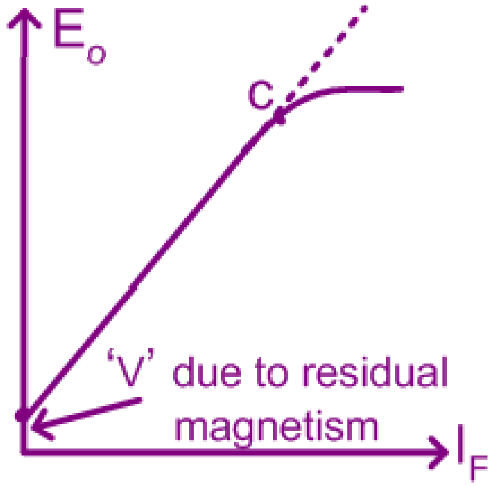
$\Rightarrow$ If I_f is made = 0, rotor will retain some magnetism (residual magnetism)

$\therefore$ If the above process is repeated when $I_f = 0$

$E_0 \neq 0$

let $R_s \rightarrow$ stator resistance/phase &

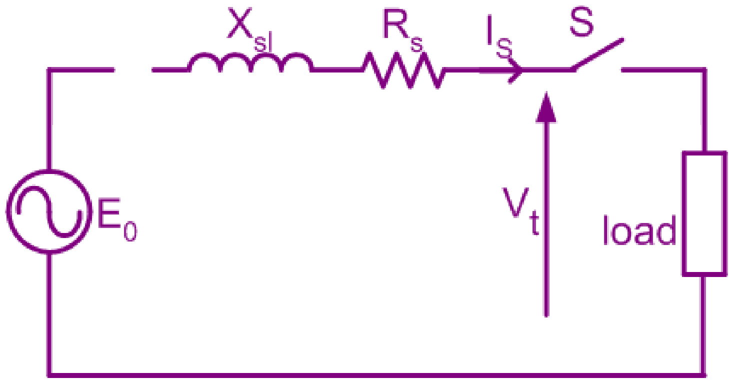
X_{sl} is the leakage reactance/phase



Load $\Rightarrow$ 'R'/Inductive/capacitive $I_S \rightarrow$ stator current /phase

$\Rightarrow$ this current flows in stator turns (distributed in space)

$\Rightarrow$ mmf distribution is sinusoidal in space



$\Rightarrow \phi_a \rightarrow$ armature flux due to I_s in N_{ph}

$\Rightarrow$ air gap flux is $\neq \phi_f$

$\Rightarrow$ vector sum of ϕ_f & $\phi_a \rightarrow \phi_r \rightarrow$ resultant flux

$\Rightarrow \phi_a$ can aid/oppose ϕ_f?(is there a third possibility ??)

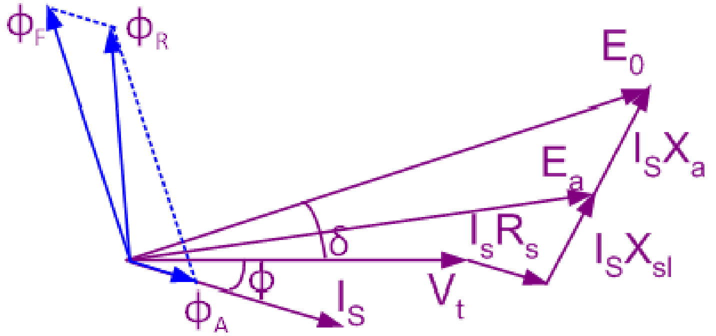
$\Rightarrow$ this effect, "effect of stator flux on rotor flux is known as armature reaction"

$\Rightarrow$ this effect depends on load P.F.

Lagging power factor:

$$\angle_{\phi_F}^{E_o} = \frac{\pi}{2}$$

$|\phi|<|\phi|$



$\Rightarrow$ lagging 'I' tries to oppose the field flux

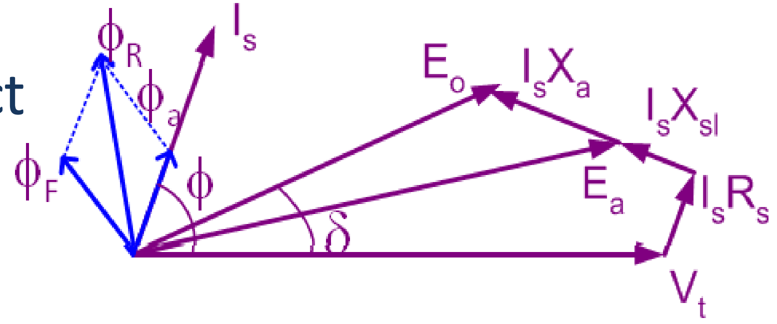
$\Rightarrow$ demagnetizing effect

Leading power factor:

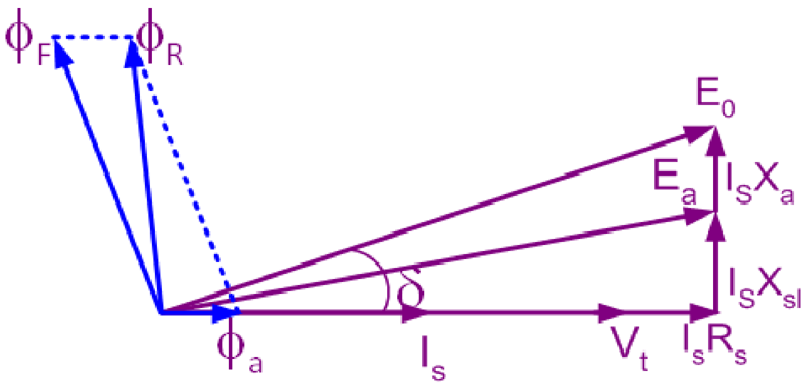
$|\phi_R|$ could be greater than $|\phi_F|$

$\Rightarrow$ leading current tries to aid the field flux

$\Rightarrow$ magnetizing effect



Unity power factor:



$\Rightarrow$ difference between $|\phi_R|$ & $|\phi_F|$ in UPF case < difference between $|\phi_R|$ & $|\phi_F|$ in lagging P.F. case

$\Rightarrow$ though in phase component of current does not directly oppose the field flux, it tries to distort the field

$\Rightarrow$ cross magnetization

How to represent armature reaction?

$\Rightarrow \phi_a \rightarrow$ links stator turns

$X_{sl} \rightarrow$ leakage reactance

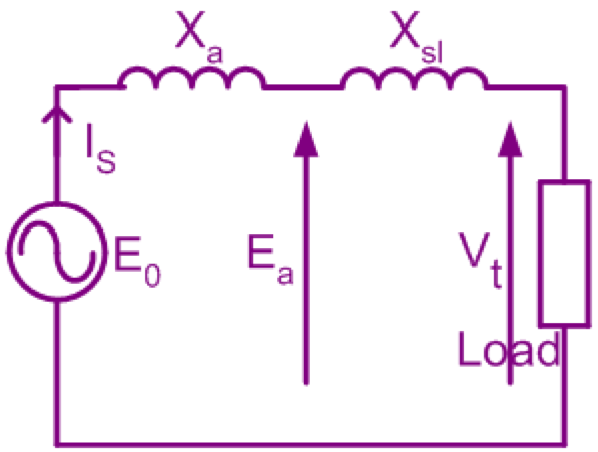
$R_s \rightarrow$ stator resistance/ph

In high power m/c $\rightarrow R_s << (X_{sl} + X_a)$

$X_s \rightarrow$ synchronous reactance

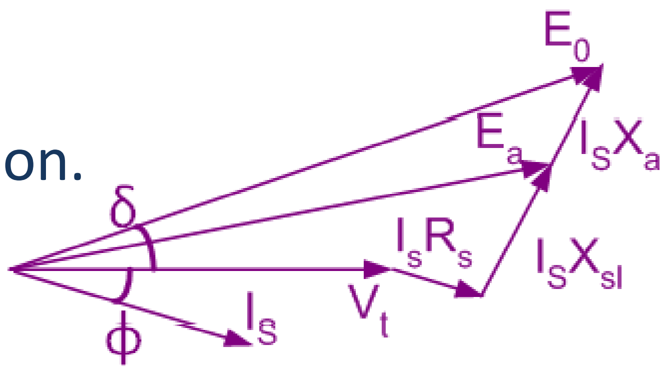
$\Rightarrow Z_S = (R_S + jX_S) \rightarrow$ synchronous impedance,

neglecting R_s, $Z_s \cong X_s$



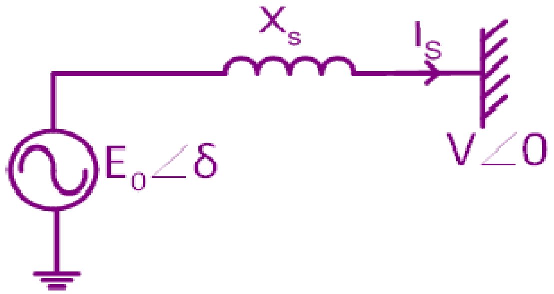
If $V_t = V\angle 0$

$\overline{E_0} = E_0 \angle \delta$ δ is +ve for generator action.



⇒ synchronous generator (rating in MVA) is always connected in parallel with other generators.

⇒ connected to grid.



Expression for power:

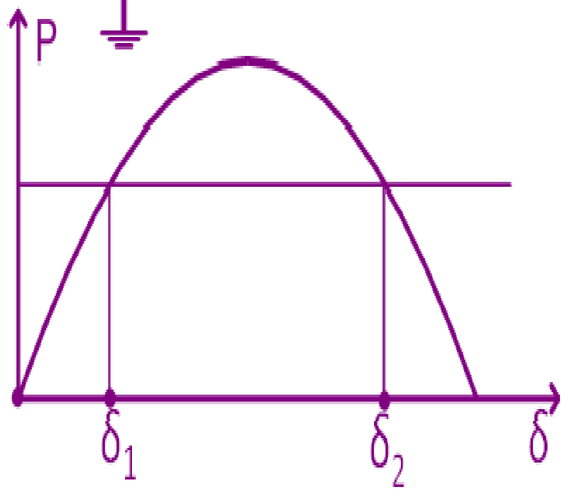
$$\overline{I_s} = \frac{E_0\angle\delta - V\angle 0}{Z_s\angle\theta} = \frac{E_0\angle(\delta-\theta)}{Z_s} - \frac{V\angle-\theta}{Z_s}$$

$$= \left[\frac{E_0}{Z_s}\cos(\delta-\theta) - \frac{V}{Z_s}\cos\theta\right] + j\left[\frac{E_0}{Z_s}\sin(\delta-\theta) - \frac{V}{Z_s}\sin\theta\right]$$

power/phase = $V I_s \cos\phi = \frac{V}{Z_s}[E_0\cos(\delta-\theta) - V\cos\theta]$

In synchronous machine $|R_S| << |X_S|$ ⇒ $|Z| \cong |X|$ & $\theta \cong \frac{\pi}{2}$

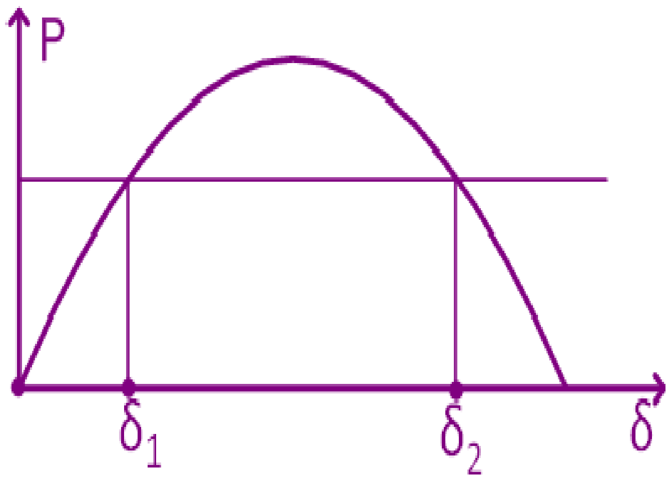
$$\text{Total power} = \frac{3E_0V}{X_s}\sin\delta$$



$\delta \rightarrow$ angle between F_s and F_R

From Newton's law, (rate of change of angular momentum is the net torque)

$$\frac{d\omega}{dt}\alpha(T_m - T_e)$$



$T_m \rightarrow$ mechanical torque Te $\rightarrow$ electrical torque

$\frac{d\delta}{dt} = \omega$ at steady state, $T_m = T_e$ & $\therefore\ \omega = \omega_{st}$ = synchronous speed

<u>Operation at δ_1</u>:

assume that for some reason, δ_1 has $\uparrow$ slightly

$\Rightarrow$ no change in mechanical input

$\Rightarrow$ $(T_m - T_e)$ (or $(P_m - P_e)$) is negative

generator would decelerate and come back to its original place

$\Rightarrow$ stable

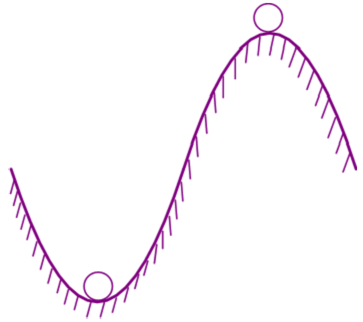
<u>Operation at δ_2</u>:

if for some reason δ_2 has $\uparrow$

$\Rightarrow$ $(T_m - T_e)$ is + ve

$\Rightarrow$ try to accelerate the rotor further

$\Rightarrow$ $\delta_2 \uparrow$ further $\therefore$ unstable



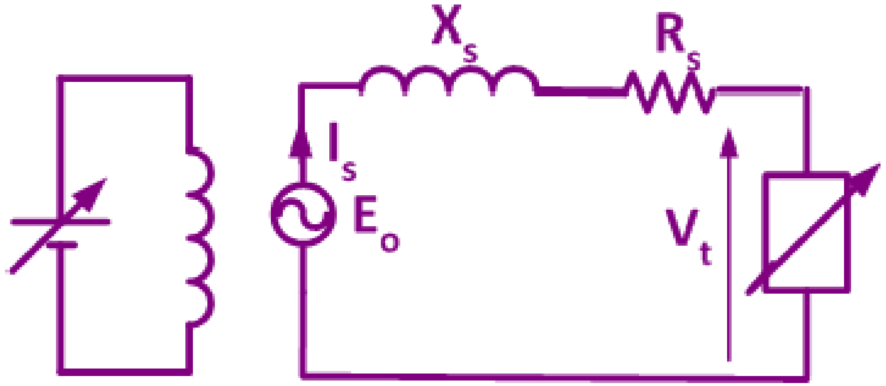
$\therefore$ stable operating range is $0 < \delta < \pi/2$

$\Rightarrow$ generally δ is around 30^0

$\Rightarrow$ If δ is high and big disturbance is given, δ may $\uparrow$ above $\pi/2$ and the system may become unstable

Generator feeding local load

Any change in I_f would result in a change in $\overline{E_0}$ & $\therefore$ $\overline{V_t}$



$\Rightarrow$ as the load changes, speed of the prime mover and

$\therefore$ 'f' of 'V' in stator would change

$\Rightarrow$ rating of synchronous machine in MVA

$\Rightarrow$ only small portable DG feed the local load

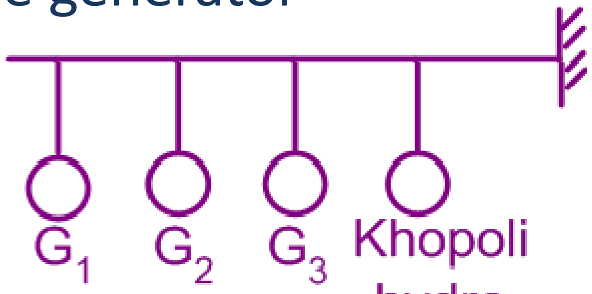
$\Rightarrow$ high power generators are connected to the grid

$\Rightarrow$Grid is a network to which a large no. of generators are connected.

In India, there is one Central Grid which is divided into 5 Regions.

$\Rightarrow$ Total installed capacity is approx. 3,75,323 MW

$\Rightarrow$ Assume that at Khopoli, engineer changes the excitation of the generator



$\Rightarrow$ Its E_o would change

$\Rightarrow$ If V_t changes, it would affect all the other generators

$\Rightarrow$ Not practical

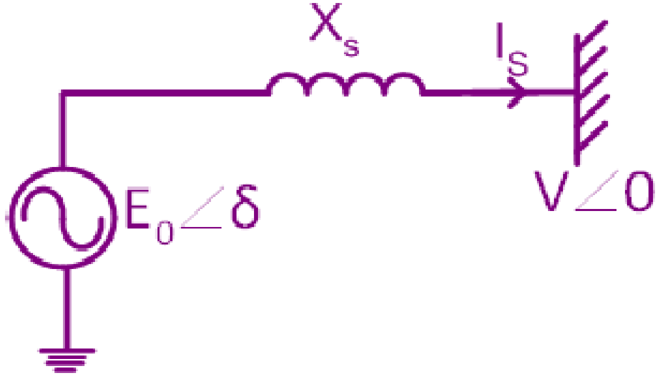
$\Rightarrow$ Grid 'V' and 'f' are kept almost constant(50.5 < f < 49)

$\Rightarrow$ Behavior of synchronous generator connected to the grid is different from that of generator feeding local load

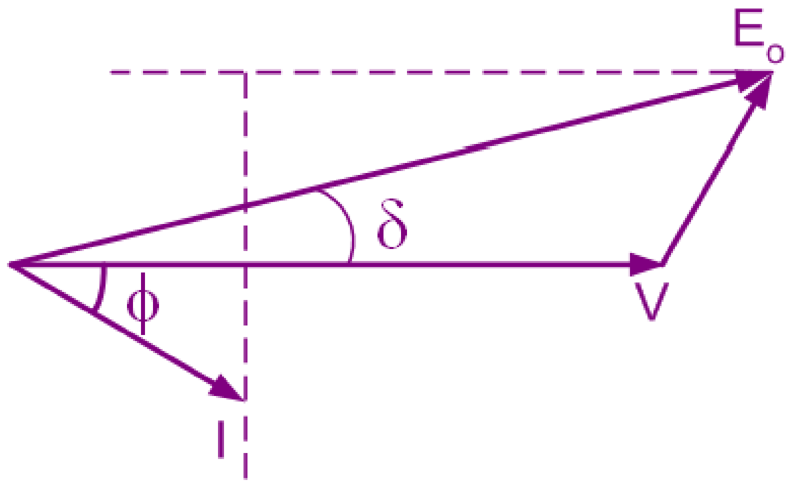
$\Rightarrow$ Grid is a network whose 'f' & 'V' are held constant & they do not change for small disturbance

$\Rightarrow$ Change of excitation of generator connected to grid will not change the terminal 'V'

$\because$ power input is held constant, output also will not change



Operation at variable excitation and constant load



At constant load, $P = \frac{E_0 V}{X_s} \sin\delta$

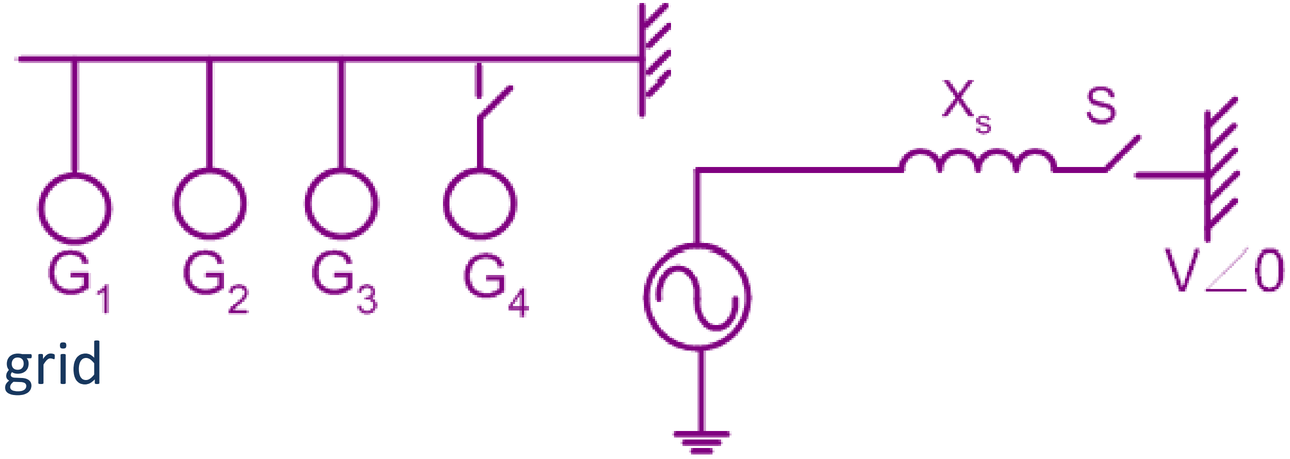
$\therefore E_0 \sin\delta = \frac{P X_s}{V}$ → constant

Also, $VI\cos\phi = P = \text{constant}$

$\therefore I\cos\phi = \text{constant}$

If excitation is varied, then E_0 and δ would change such that '$E_0 \sin\delta$' will remain constant

How to connect to the grid:



Process is known as synchronization.

Just prior to closing the switch,

⇒'f' & |V| should be ≅ same as that of grid

⇒Phase sequence should be same