SYNCHRONOUS MACHINES - INTRODUCTION

- The synchronous m/c produces the ac power that we use in home, office, factory, etc. These m/cs are the largest energy converters in the world – they convert mech. energy into electrical energy, in powers ranging up to 1500 MW.

- 3-ϕ synchronous generators are preferred for generation of bulk electric power, since they can operate at much higher voltage levels than those of d.c. generators.

- They do not have commutators to change the alternating current produced in the armature into direct current.

- Synchronous m/cs can operate as generators or motors : large motors are used for pumps in generating stations; small motors are used in electric clocks, timers, etc. $\Rightarrow$ used mainly where constant speed is desired.

- Called synchronous m/cs because they operate at constant speeds and constant frequencies under steady-state conditions.

$\Rightarrow$ Constant speed termed synchronous speed (n_s)

$$n_s = \frac{120f}{p}$$

where : f = system frequency
p = no. of poles on the ROTOR

e.g. 60-Hz, 2-pole m/c has n_s = 3600 rpm
50-Hz, 2-pole m/c has n_s = 3000 rpm

Construction

A synchronous m/c has two basic parts :

1. Stator

- Also called armature
- Fixed part
- Carries three distributed windings separated in space by 120^o electrical
- 3-phase EMFs produced in the stator windings
- Rotor flux sweeps the stator coils at a uniform speed and induces a.c. voltages in them
- 3-ϕ stator winding voltages are balanced & separated by 120^o

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2. Rotor

- Rotating part
- Driven at a fixed speed inside a stator
- Carries a field winding excited by a dc source
- Produces sinusoidal flux distribution in the air gap
- Also called field/excitation circuit
- The rotor is driven by a turbine or engine sharing a common shaft
- Turbine/engine may be driven by
  - Steam from coal, nuclear,...
  - Oil, gas,...
  - Waterfall,...

Two Types of Rotors

1. Cylindrical pole rotor (non-salient)
2. Salient-pole rotor

Salient means “protruding”/”sticking out”.

$\Rightarrow$ Salient pole is a magnetic pole that sticks out from the surface of the rotor.
$\Rightarrow$ Non-salient pole is a magnetic pole constructed flush with the rotor surface.

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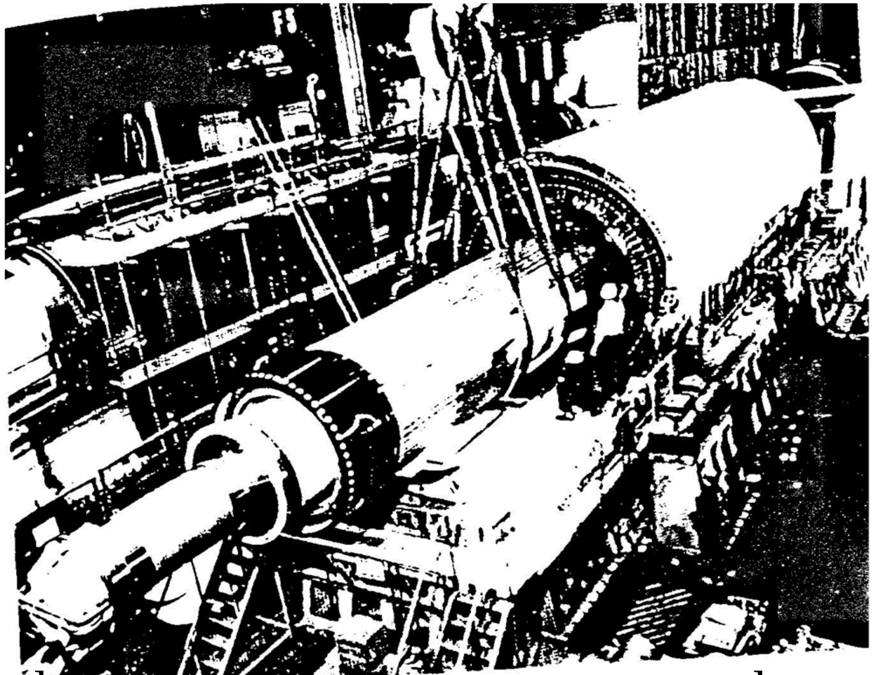
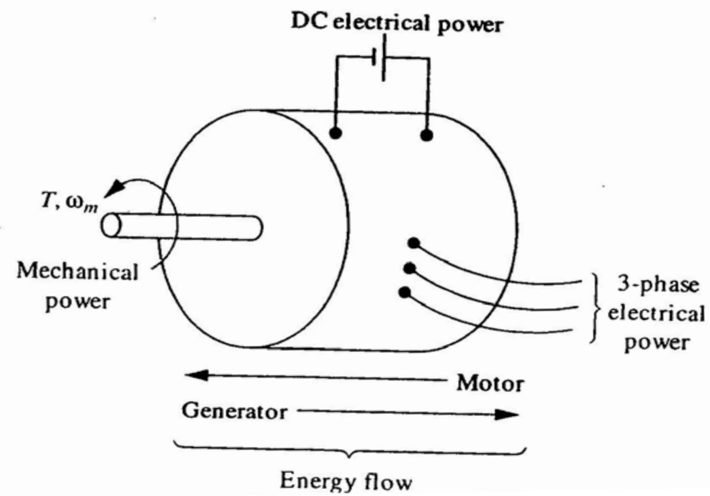
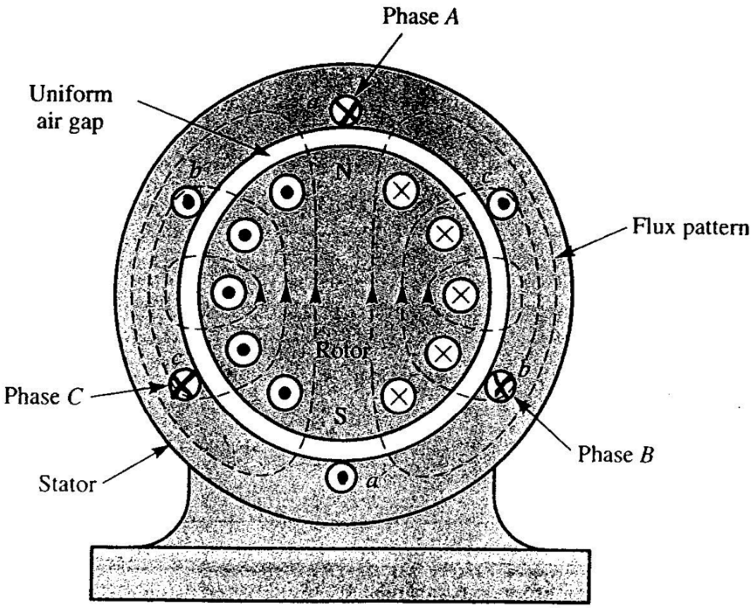
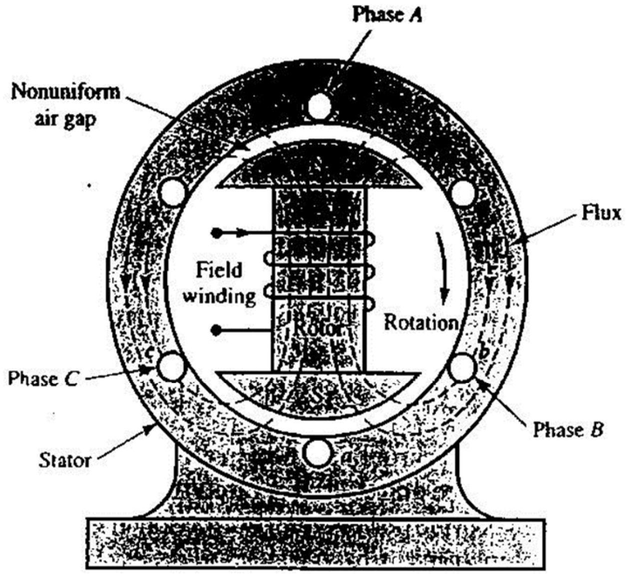


Cylindrical-rotor (synchronous generator under construction)



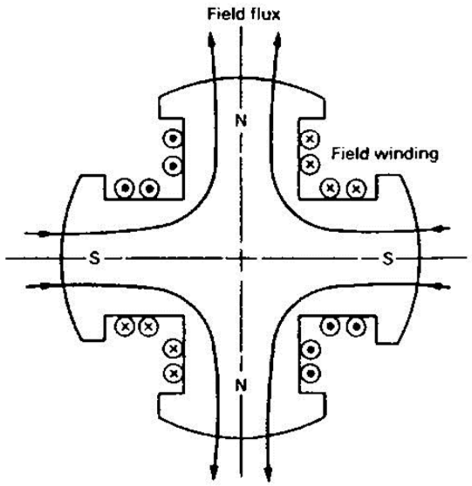
Schematic of synch. m/c operation



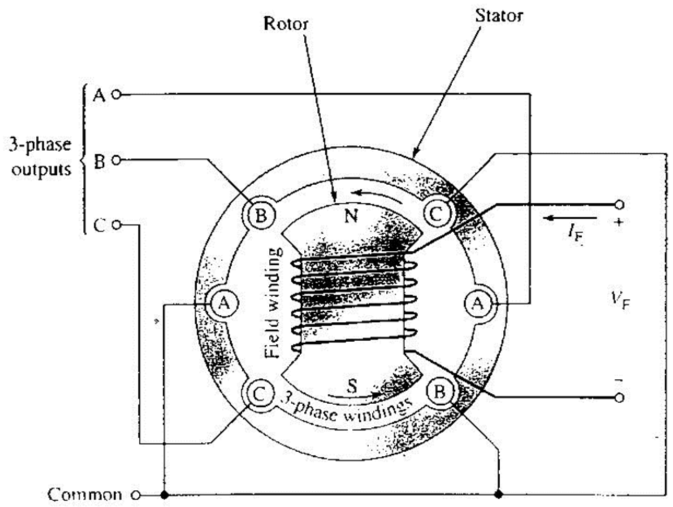


Cylindrical rotor synch. m/c

Salient pole synch. m/c (2-pole)



Field winding on a 4-pole salient rotor



Basic 2-pole 3-phase salient-pole generator with star-connected stator output

⇒ Salient-pole rotor is used in low- & medium-speed generators, e.g. hydroelectric generators.

e.g. 60-Hz, 24-pole synch. gen. is driven at $n_s = \dfrac{120f}{p} = 300$ rpm.

- Gen. must have a large diameter to accommodate so many poles.

⇒ Need for cylindrical rotors arises when the centrifugal forces would be too strong for salient poles. This is the case with large, high-speed synch. m/cs driven by steam/gas turbines running at high speeds (1800 or 3600 rpm).

- Generally 2-pole; max. 4-pole

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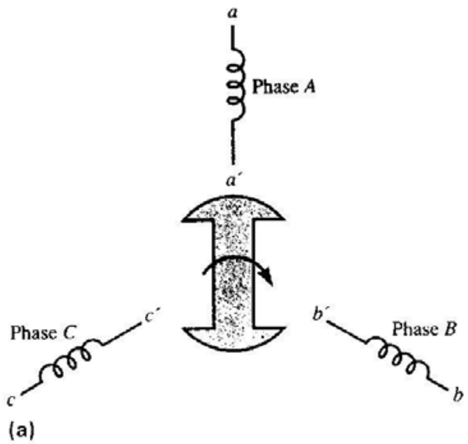
- Cylindrical construction has the advantage that flux distribution around the air-gap is approximately sinusoidal (better than that of salient pole type)
- Synch. m/cs of this type called turboalternators.

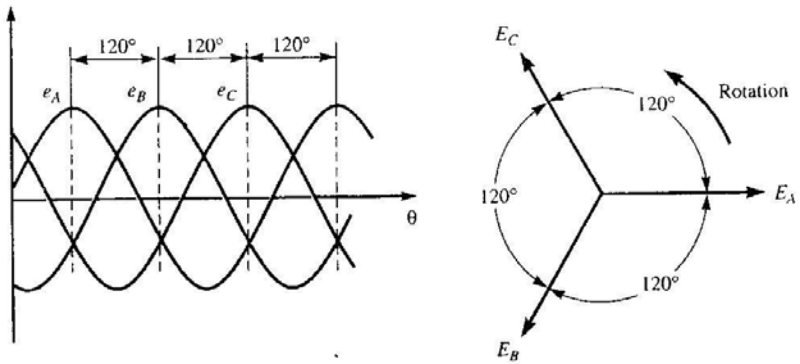
⇒ The high mmf produced in the field winding (when excited by d.c.) combines with the mmf produced by currents in the armature windings.
The resultant flux across the air-gap betn. the stator & rotor generates voltages in the coils of the armature windings, and provides the electromagnetic torque.

⇒ Induced EMFs

- The operation of synch. gen. is based on Faraday's Law of electromagnetic induction.
- Rotor rotates at constant speed; the stationary stator winding sees the field flux as rotating sinusoidal flux.
- The flux cutting the stator coils varies sinusoidally ⇒ induced EMF in stator coil will be sinusoidal.
- Three stator coils separated in space by 120^{o} electrical ⇒ induced EMF in coils will be separated by 120^{o} in time phase, producing 3-ϕ balanced system.

- Induced EMF in stator coil lags flux linkage (& MMF) by 90^o.





Synchronous Reactance (X_S) & Equivalent Circuit (Cynlindrical Rotor Generator)

When a synch. gen. supplies a 3-ϕ load, 3-ϕ currents will flow in the armature winding. The terminal voltage of an AC generator depends on the load, and is

- Higher than the generated voltage when the load PF is leading

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- Lower than the generated voltage for unity PF & lagging PF loads

$\Rightarrow$ Armature resistance voltage drop

Let E = per phase generated voltage
I_a = per phase current in the stator
R_a = per phase resistance of stator (armature) winding
$\therefore$ I_aR_a = voltage drop across armature winding (in phase with load current I_a)

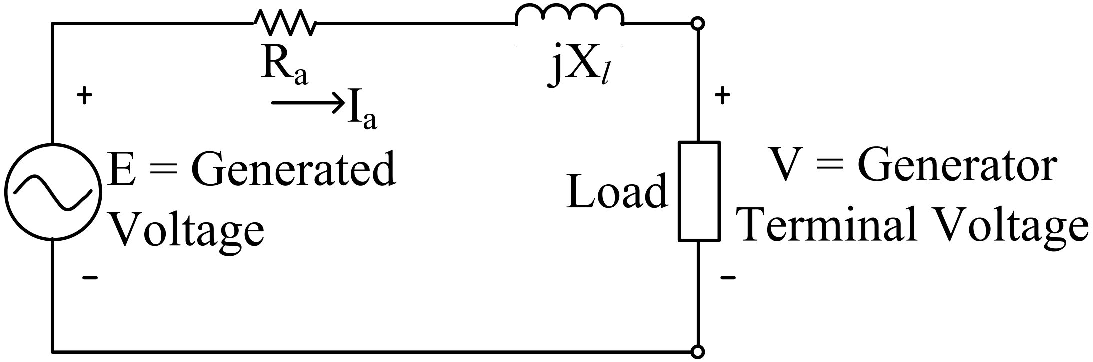
$\Rightarrow$ Armature leakage-reactance voltage drop

- I_a produces a flux in the armature winding. Part of this flux called leakage flux links the armature winding only, and gives rise to a leakage reactance X_l.

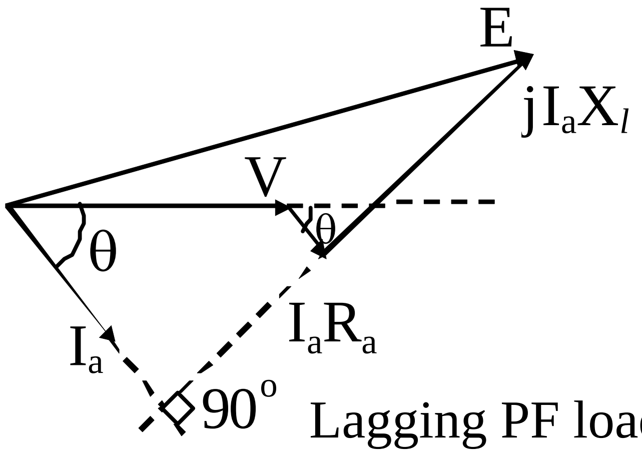
$\therefore$ Volt. drop in leakage reactance = I_aX_l. (This leads I_a by 90^o).

Phasor diagram showing these quantities for leading, lagging & UPF loads are shown next.

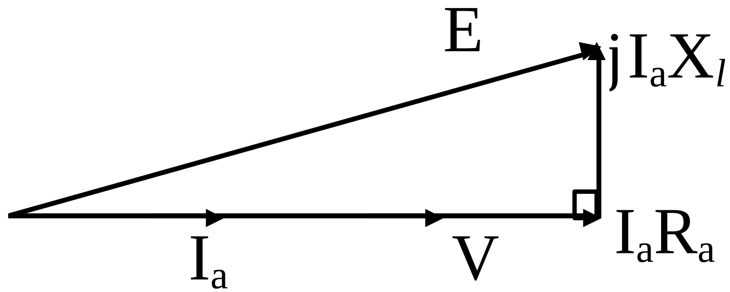
θ = PF angle
V = Reference phasor



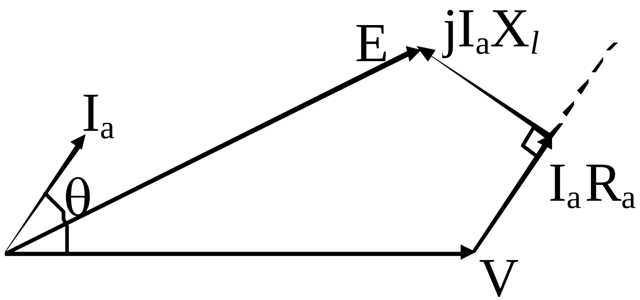
Per-phase equiv. CKT. of synch. gen. w/o armature reaction.



Lagging PF load



Unity PF load



Leading PF load

⇒ Armature Reaction Effect (Please refer to Appendix B for details)

- When gen. supplies load, arm. current I_a will flow, creating its own magnetic field & flux in the arm. winding
- Flux created by I_a interacts with the “original” flux created by field excitation I_f
- Resultant air-gap flux due to this interaction is responsible for power generation
- Resultant flux will affect terminal voltage V of gen.
- This overall effect called armature reaction

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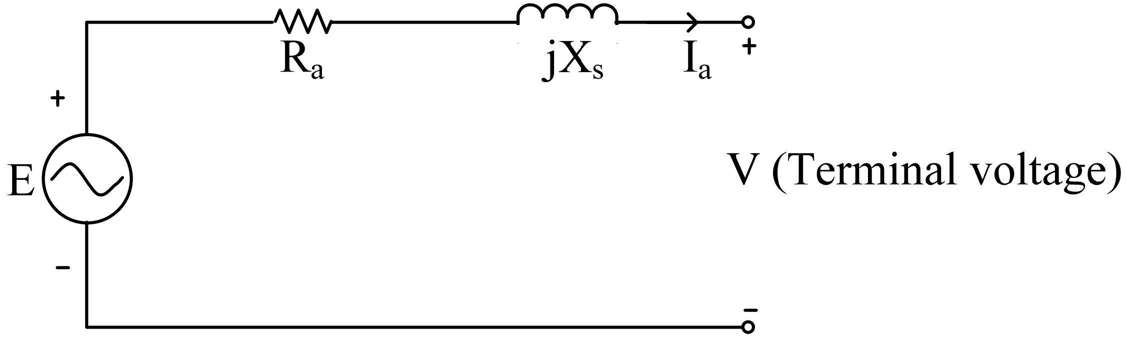
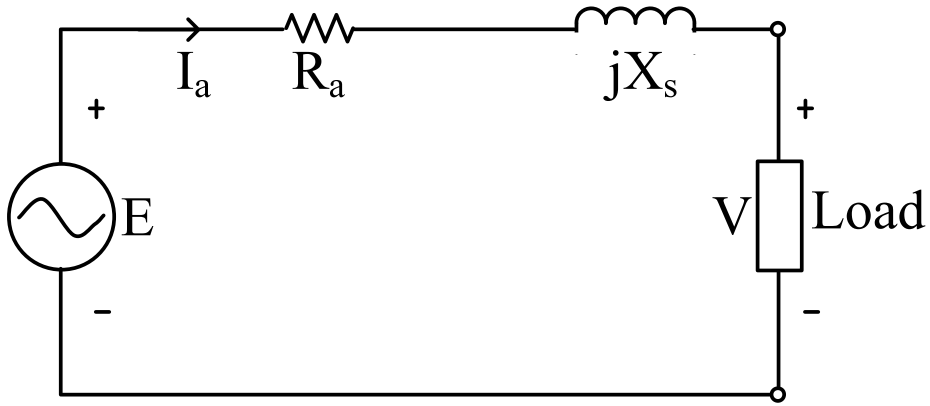


where X_s = Synchronous reactance

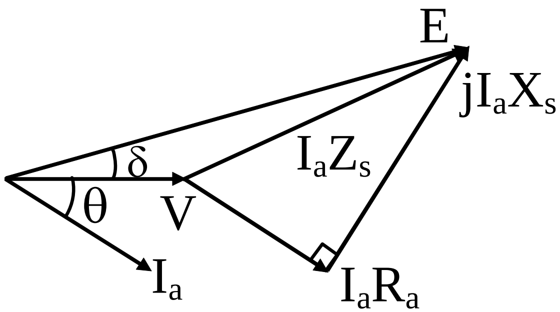
R_a = Arm. resistance

$\therefore$ $Z_s = R_a + jX_s$ = Synchronous impedance

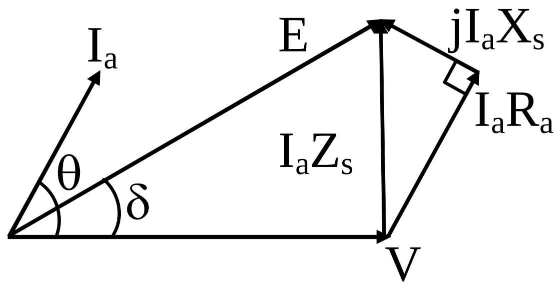
- More often than not, $R_a \ll X_s$, hence $Z_s = jX_s$.



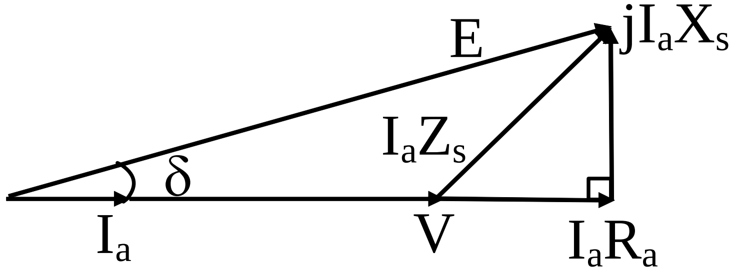
Equiv. CKT. of a synch. gen. (including armature reaction)



(Lagging load)



(Leading load)



(UPF load)

<u>Notes</u> :

$E = V + I_a Z_s$

- $E \propto I_{field}$ & $E = V$ if armature is open-circuited.
- δ is the <u>power</u> or <u>torque angle</u> of the machine. It varies with load and is a measure of the air-gap power in the machine.
- E is called induced EMF (generated or internal EMF) behind the synchronous reactance/impedance.

Voltage Regulation of a Synchronous Machine

- Defined as the ratio of change in terminal voltage from no-load value (V_{NL}) to full-load value (V_{FL}) as a percentage of V_{FL}.

$$\text{Volt. regulation (VR\%)} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

$$= \frac{E - V}{V} \times 100\%$$

$\rightarrow$ Note that it may actually be negative (indicating that terminal voltage is greater than the internal voltage)

Example 6 :

A 200-kVA, 660-V, 60-Hz, 3-phase synch. gen. is Y-connected with $R_a = 0.12\ \Omega$/ph & $X_s = 1.08\ \Omega$/ph.

(a) Determine the volt. regulation for a 0.8 pf (lag) load of 200-kVA at 660-V.
(b) Find the power angle at this load condition.

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Solution :

(a) Let $V_b = 0.66$ kV & $S_b = 0.2$ MVA

$$\Rightarrow Z_b = \frac{V_b^{\ 2}}{S_b} = 2.178\ \Omega$$

$$\Rightarrow R_{a\ pu} = \frac{R_a(\Omega)}{Z_b(\Omega)} = \frac{0.12}{2.178} = 0.0551$$

$$\& \ X_{s\ pu} = \frac{1.08}{2.178} = 0.496$$

$$\begin{aligned} \therefore Z_{s\ pu} &= R_{a\ pu} + jX_{s\ pu} \\ &= 0.0551 + j0.496 \\ &= 0.499\angle 83.66° \end{aligned}$$

$S = VI_a^*$

$\Rightarrow \quad I_a = 1\angle\text{-}36.87°$ pu

$E_{pu} = V_{pu} + I_aZ_s$

$\Rightarrow \quad E_{pu} = 1\angle 0° + (1\angle\text{-}36.87°)(0.499\angle 83.66°) = 1.39\angle 15.16^o$

$\Rightarrow \quad |E| = |E_{pu}| \times V_b = 1.39 \times 0.66 = 0.9174$ kV (L-L value)

$\delta = 15.16^{\,o}$

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$$\therefore \text{Voltage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \frac{E - V}{V} \times 100\%$$

$$= \frac{1.39 - 1.0}{1.0} \times 100\% = 39\%$$

(b) Power angle $\delta = 15.16^o$ (E leads V by δ)

<u>Exercise 9</u>

A 9-kVA, 208-V, 3-ϕ, Y-connected synch. gen. has a winding resistance of 0.1 Ω/phase and a synch. reactance of 5.6 Ω/phase. Determine its voltage regulation when the power factor of the load is

(a) 80% lagging <u>(94.8%)</u>
(b) Unity <u>(55.02%)</u>
(c) 80% leading <u>(-0.36%)</u>

Power developed in cylindrical rotor machine

Recall that

$$P_{pu} = \frac{VE}{X_s} \sin \delta \text{ (Neglecting } R_a\text{)}$$

$$P_{max\ pu} = \frac{VE}{X_s} \text{ (} P_{max} \text{ occurs at } \delta = 90^o\text{)}$$

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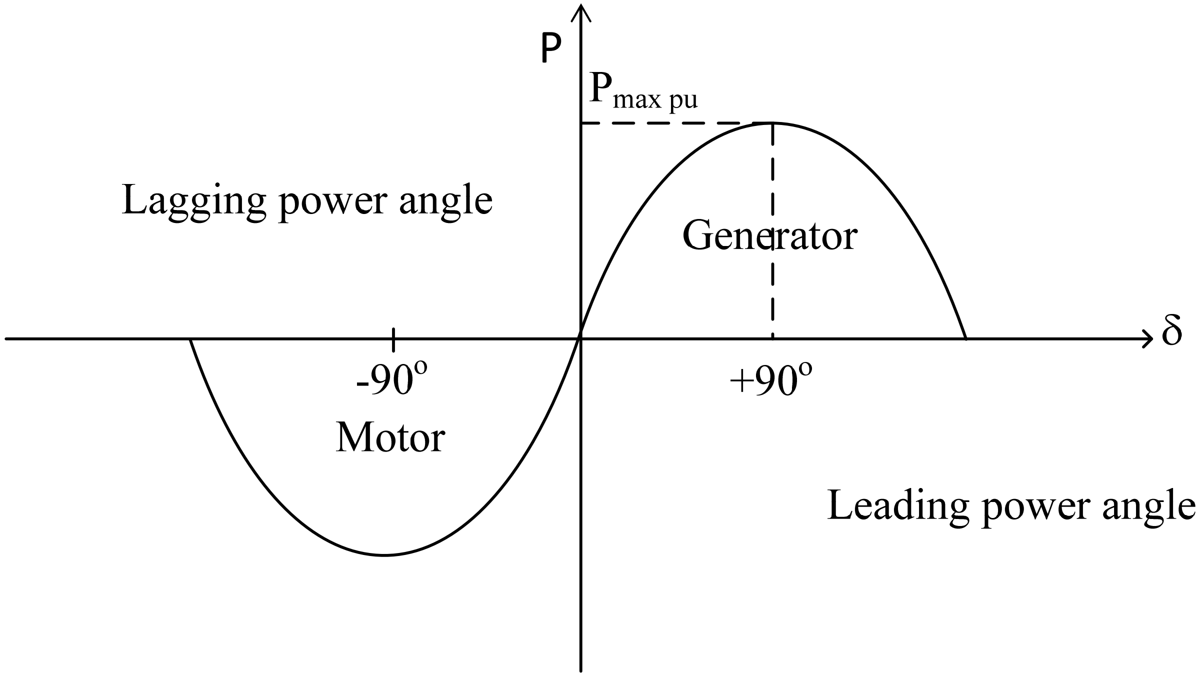
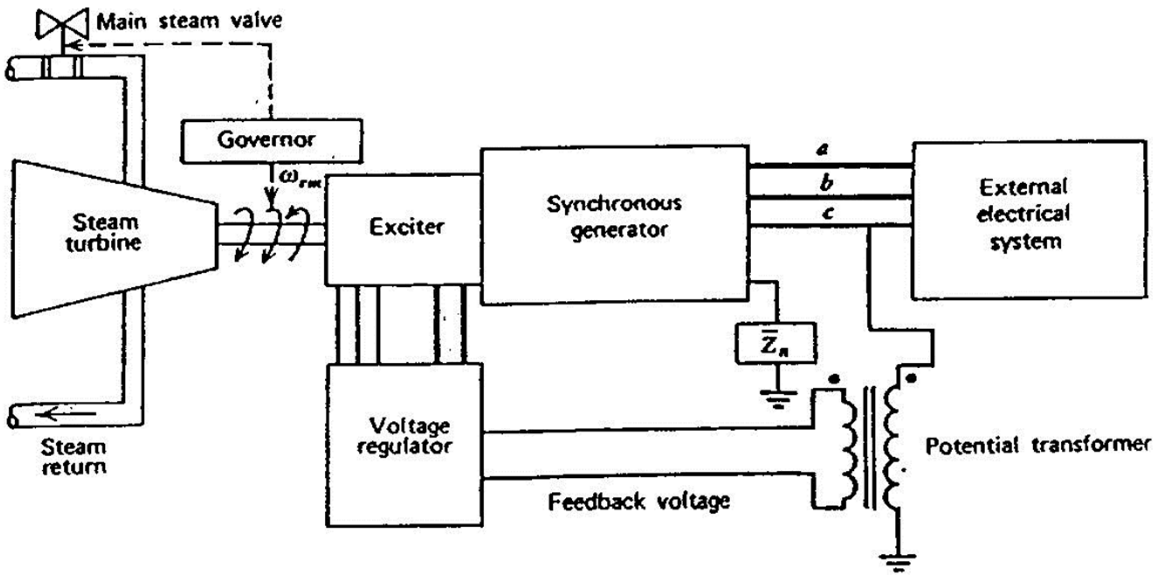


Power & frequency control

Synchronous gen. have two main controls :

1) Governor control
2) Excitation control

A schematic showing the two controls connected to the gen. :



Turbine-Generator-Exciter System : Governor and Exciter Controls

Excitation Control is used to adjust the induced EMF & consequently the terminal voltage V & reactive power Q. Usually, excitation is controlled automatically. The voltage regulator provides the excitation control to achieve a constant V. The regulator utilizes the voltage deviation at the gen. terminals to achieve the desired control of the excitation i.e. rotor dc field current. Later we'll see how $\underline{V}$ is kept constant.

Generator operation : analysis

Two possibilities exist :

a) Generator is operating alone

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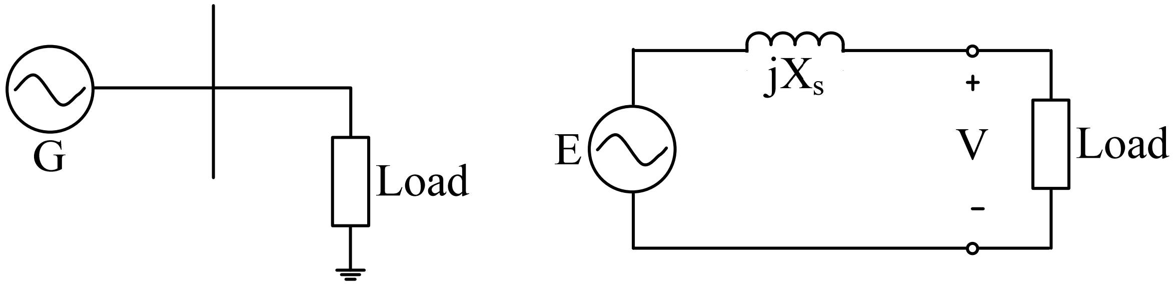

(Neglecting R_a)

- Power supplied depends on load connected, voltage & frequency.
- DC field current determines the induced voltage & terminal voltage (may not be constant).
- Governor position will determine the freq. of supply (may not be constant).

b) Generator operating in parallel with <u>infinite bus</u>

<u>Infinite bus</u> : If the system (to which the generator is connected) is so large that it can absorb all the power the gen. generates, or supply all the power the m/c would require as a motor, <u>without any change in system frequency or voltage at the m/c terminals</u>, we say that the m/c is connected to an infinite bus!

$\Rightarrow$ Voltage at the generator bus will not be altered by changes in the generator's operating condition.

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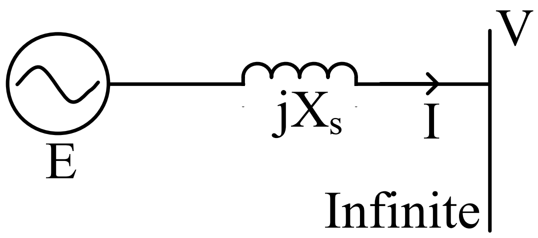


- Terminal voltage & freq. are fixed by the system.
- Governor setting will determine the real power supplied to the system.

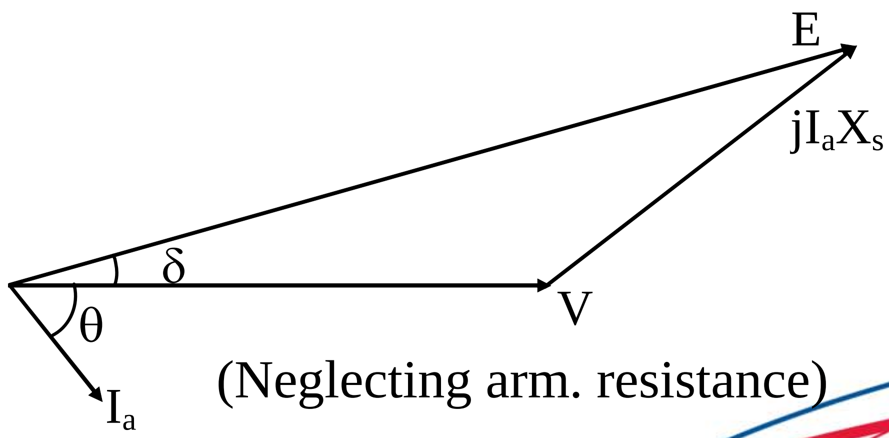
⇒ If we increase the mech. drive to the generator, we contribute more real power to the grid.

- DC field excitation (I_f) determines the reactive power supplied to the system.

⇒ If we increase I_f, we change the reactive power contributed to the system.

<u>Recall</u> :

$V = V\angle 0°$
$E = E\angle\delta$



(Neglecting arm. resistance)

<u>Note</u> : V, E & X_s are all in pu.

$$P_{pu} = \frac{VE}{X_s}\sin\delta$$

$$Q_{pu} = \frac{VE}{X_s}\cos\delta - \frac{V^2}{X_s}$$

$$P_{max\ pu} = \frac{VE}{X_s} \text{ at } \delta = 90^o$$

$$\& \; Q_{max\ pu} = \frac{VE}{X_s} - \frac{V^2}{X_s} \text{ at } \delta = 0^o = \frac{V}{X_s}[E - V]$$

What happens to gen. operation when the d.c. excitation is changed?

$\Rightarrow$ When I_f is changed :

- This is termed <u>excitation control</u>.
- Let us consider changes in the phasor diagram as the dc field current is varied (thus varying the <u>magnitude</u> of the internal voltage or induced EMF E).
- Assume that mech. drive torque & speed are kept constant $\therefore$ real power of gen. remains constant.
- Terminal voltage V is constant [since gen. is connected to an infinite bus]

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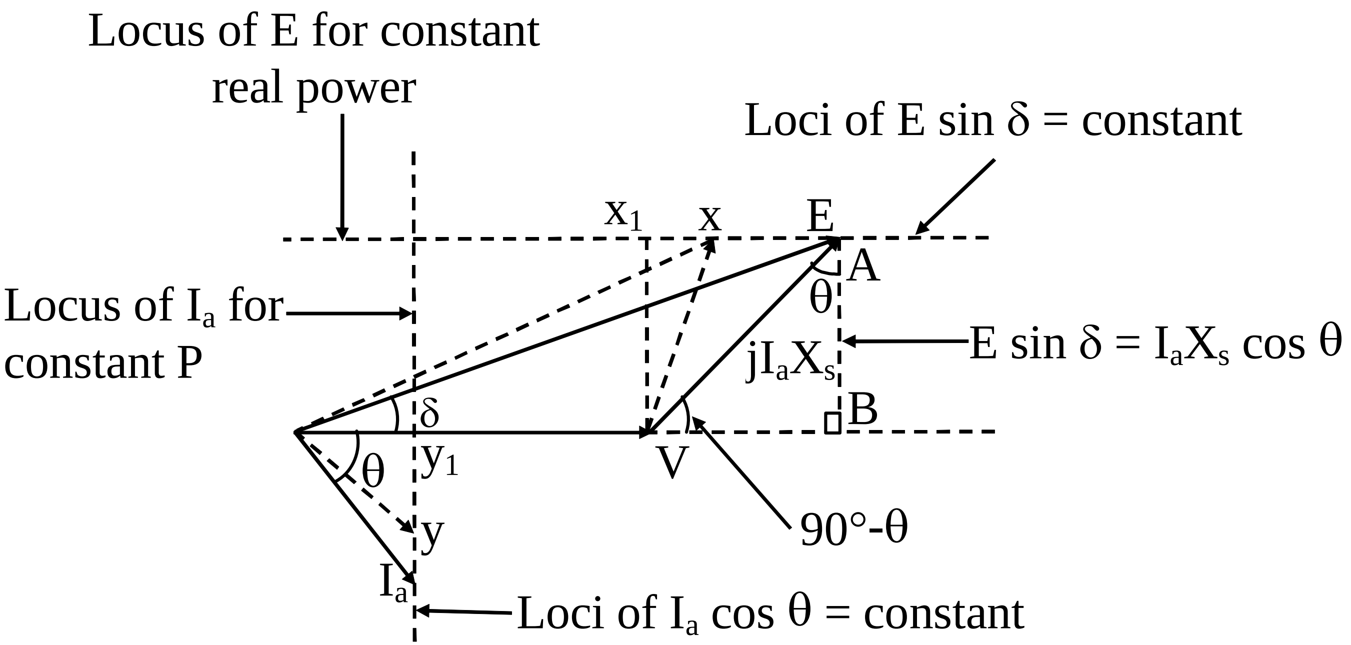
Note : P, V, I_a, X_s are in per unit.

$\therefore$ $P = VI_a \cos\theta$

$\Rightarrow$ $I_a \cos\theta$ must be constant (since P & V are constant)

$\Rightarrow$ As I_f changes, magnitude & phase of I_a vary, but $I_a \cos\theta$ = constant.

- Also, $P = \dfrac{VE}{X_s}\sin\delta \Rightarrow E\sin\delta = \dfrac{PX_s}{V} = \text{constant}$



$$\sin(90^\circ - \theta) = \frac{AB}{I_a X_s} \quad \Rightarrow \quad AB = I_a X_s \cos\theta$$

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→ Consider, for example, the effect of decreasing the dc field current ⇒ E magnitude decreases ⇒ E moves to point x (say) ⇒ I_a moves to point y

→ If E magnitude is reduced further, it will reach point x_1

⇒ I_a will now be in phase with V, i.e. I_a will move to point y_1. (The points x_1 & y_1 correspond to unity PF load, don't they?)

⇒ As I_f is reduced, I_a becomes more in phase with V. PF moves towards unity, and $|I_a|$ reduces.

→ If we reduce E magnitude further, I_a will swing ahead of V & therefore we will have a leading PF condition!

⇒ $\angle I_a$ is controlled by $|E|$ (which in turn is controlled by $|I_f|$).

⇒ In-phase component of I_a, i.e. $I_a \cos\theta$ is constant, but the out-of-phase component, i.e. $I_a \sin\theta$ varies in magnitude & sign. Hence, the reactive power exchanged betn. gen. & infinite bus (system) is controlled by the dc field excitation!

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Conclusion :

1) I_a leads V for small I_f (& E) with constant real power output.

   ⇒ underexcited generator

2) I_a lags V for large I_f (& E)

   ⇒ overexcited generator

3) $|I_a|$ is minimum for unity PF (at x_1, y_1)

   ⇒ normally excited generator

4) Real power output P is controlled by the throttle on the mech. drive to gen.

5) Sign & magnitude of reactive power Q are controlled by dc field excitation.

   - overexcited gen. supplies positive Q
   - underexcited gen. supplies negative Q (⇒ absorbs +Q)
   - normally excited gen. does not supply or absorb reactive power

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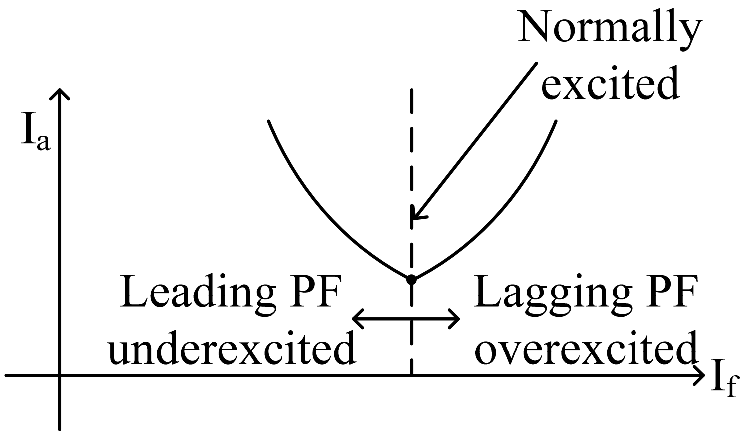
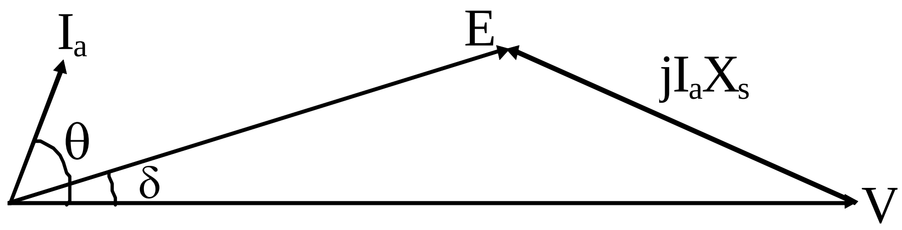
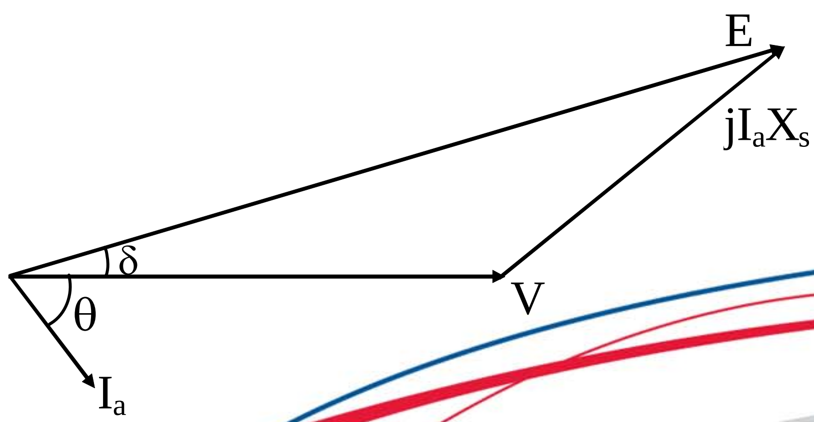


V-curve of synch. gen.

6) Normal excitation : $E \cos \delta = V$

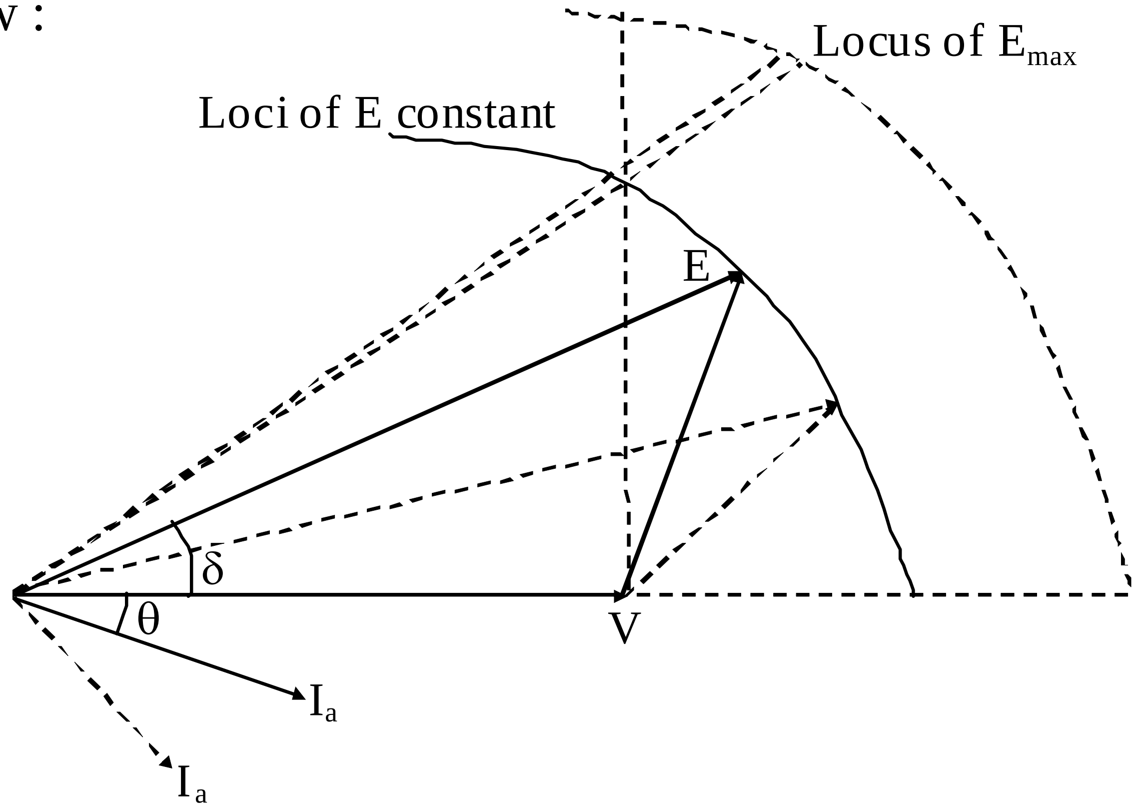
7) Underexcited : $E \cos \delta < V$ and Overexcited : $E \cos \delta > V$





Operation at constant excitation

- If I_f (& E) can be maintained constant, then the phasor diagram will change as shown below :



Notes :

1) Since V must be constant, real power output must change as $P = \frac{VE}{X} \sin\delta$ (all in per unit)

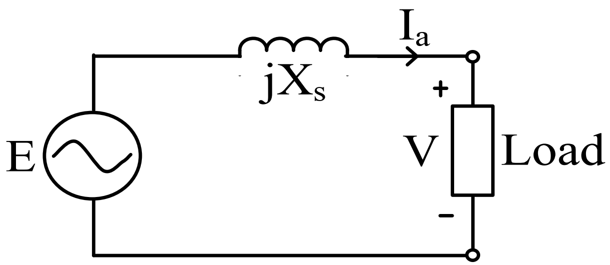
$\Rightarrow$ δ must change accordingly.

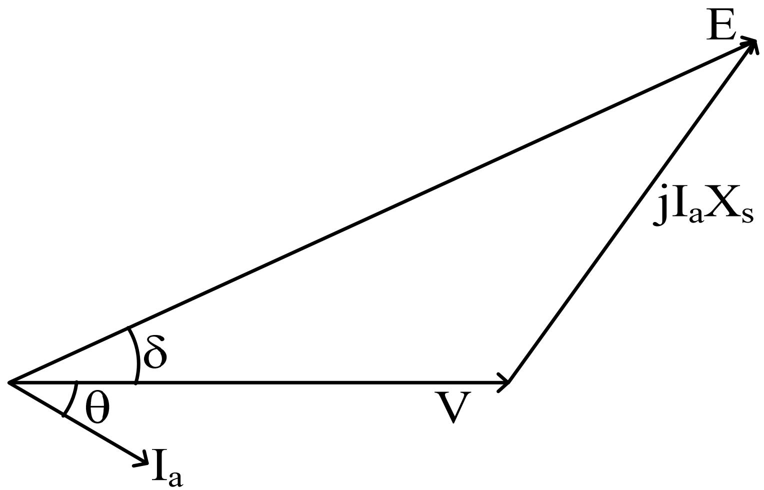
2) Max. value of E that can be attained depends on the max. current rating of the rotor winding. E_{max} is shown in diagram as well.

Example 7 :

A 880 MVA, 18 kV synch. gen. with $X_s = 0.2577\ \Omega$ supplies 880 MVA at 0.8 pf lag at rated constant voltage. (a) Find P, Q, δ & E for this operating condition. (b) At the given level of excitation, what is the maximum P & Q this m/c can deliver? (c) What will be the terminal voltage if the load is disconnected, keeping the excitation constant?

Solution :





Let S_b = 880 MVA & V_b = 18 kV

$$\Rightarrow Z_b = \frac{V_b^{\ 2}}{S_b} = \frac{18^2}{880} = 0.36818\ \Omega$$

$$\therefore X_{s\ pu} = \frac{X_{s\ ACTUAL}(\Omega)}{Z_b} = 0.7\ \text{pu}$$

<u>At Rated Values</u> $V = 1\angle 0^o$ pu

S = 880 MVA, 0.8 pf lag = $880\angle 36.87^{\,o}$ MVA = $1\angle 36.87^{\,o}$ pu

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$$\Rightarrow S_{pu} = V_{pu} I^*_{a\ pu} \Rightarrow I^*_{a\ pu} = \frac{1\angle 36.87^\circ}{1\angle 0^o}$$

$$\Rightarrow I_{a\ pu} = 1\angle\text{-}36.87^o$$

$$\Rightarrow E_{pu} = V_{pu} + j(I_{a\ pu})(X_{s\ pu}) = 1\angle 0^\circ + (1\angle\text{-}36.87^\circ)(0.7\angle 90^o)$$

$$= (1+j0)+(0.42+j0.56) = 1.42+j0.56 = 1.526\angle 21.523^o$$

(a) $\Rightarrow P_{pu} = |V_{pu}|\,|I_{pu}| \cos\theta = (1)\,(1)\cos 36.87^\circ = 0.8$ pu

$\Rightarrow P = 0.8 \times 880 = \underline{704\text{ MW}}$

$Q_{pu} = V_{pu} I_{pu} \sin\theta = 0.6$ pu

$\Rightarrow Q = 0.6 \times 880 = \underline{528\text{ MVAr}}$ lag

$|E| = |E_{pu}| \times V_b = 1.526 \times 18 = \underline{27.47\text{ kV}}$ and $\delta = \underline{21.52^o}$

(b) $$P_{max\ pu} = \frac{|V_{pu}||E_{pu}|}{|X_{pu}|} = \frac{(1)(1.526)}{0.7} = 2.18$$

$\Rightarrow P_{max} = 2.18 \times 880 = \underline{1918\text{ MW}}$

$$Q_{max\ pu} = \frac{|V_{pu}|}{|X_{pu}|}\left(|E_{pu}| - |V_{pu}|\right) = \frac{1}{0.7}(1.526-1) = 0.7514$$

$\Rightarrow Q_{max} = 0.7514 \times 880 = \underline{661.26\text{ MVAr}}$

(c) If load is disconnected (with E fixed)

Then $I_a = 0 \Rightarrow I_a X_s = 0$

$\therefore \ |V| = |E| = \underline{27.47 \text{ kV}}$

Example 8 : Revisit Example

(a) E is increased by 20%, keeping P constant. Find the new Q & δ.

(b) Power input to the m/c is increased by 20%, keeping the excitation constant. Find the new Q & δ.

Solution :

(a) $E_1 = 1.526$ pu $\qquad \delta_1 = 21.523^o$

$E_2 = 1.2 \times E_1 = 1.8312$ pu $\qquad \delta_2 = ?$

Recall if P = constant, then E sin δ = constant.

$$\Rightarrow E_1 \sin \delta_1 = E_2 \sin \delta_2$$

$$\Rightarrow \sin \delta_2 = \frac{E_1}{E_2} \sin \delta_1 = \frac{\sin \delta_1}{1.2} = \frac{0.367}{1.2} = 0.3057$$

$$\Rightarrow \delta_2 = 17.8^o$$

$\Rightarrow$ Power angle δ <u>decreased</u> from 21.523^o to $\underline{17.8}^o$.

$$Q_{2\,pu} = \frac{E_2 V}{X}\cos\ \delta_2 - \frac{V^2}{X} = \frac{(1.8312)(1)}{0.7}\cos\ (17.8°) - \frac{1^2}{0.7} = 2.4907 - 1.4286 = 1.0622 \text{ pu}$$

$\Rightarrow$ $Q_2 = 1.0622 \times 880 = \underline{934.71 \text{ MVAr}}$

$\Rightarrow$ Reactive power Q <u>increased</u> from 528 MVAr to 934.7 MVAr.

(b) $E_1 = E_2 = 1.526$ pu, $\delta_1 = 21.523^o$

$P_1 = 0.8$ pu, $X_s = 0.7$ pu

$\Rightarrow$ $P_2 = 1.2\ P_1 = 0.96$ pu

<u>Recall</u> :

$$P_{2\,pu} = \frac{E_2 V}{X}\sin\delta_2$$

$$\Rightarrow \sin\delta_2 = \frac{(P_{2\,pu})(X_{pu})}{(E_{2pu})(V_{pu})} = \frac{0.96 \times 0.7}{1.526 \times 1}$$

$$= 0.4404$$

$$\Rightarrow \delta_2 = 26.12^o$$

$\therefore$ Power angle δ <u>increased</u> from 21.5^o to 26.12^o.

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$$Q_{2\,pu} = \frac{E_2 V}{X_s}\cos\delta_2 - \frac{V^2}{X_s}$$

$$= \frac{(1.526)(1)}{0.7}\cos(26.12°) - \frac{1^2}{0.7}$$

$$= 1.9572 - 1.4286$$

$$= 0.5286 \text{ pu}$$

$\therefore$ Reactive power Q <u>decreased</u> from 0.6 pu to <u>0.5286 pu</u>

<u>Conclusions</u> :

- Increase in excitation has a <u>major</u> impact on Q and a small impact on δ.
- Increase in input power has a <u>major</u> impact on δ and a small impact on Q.

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Exercise 10

A three-phase round-rotor synchronous generator, rated 16 kV and 200 MVA, has a synchronous reactance of 1.65 pu. It is connected to a 15-kV infinite bus. The internal emf and power angle of the machine are found to be 24 kV (line-to-line) and 27.4^o respectively.

(a) Determine the line current and the three-phase real and reactive power being delivered to the infinite bus system.

(b) If the mechanical power input and the field current of the generator are now adjusted so that the line current of the machine is reduced by 25% and the power factor is the same as in part (a) above, find the new internal emf and the new power angle of the generator.

(c) While delivering the reduced line current of part (b) above, the mechanical power input and the excitation are further adjusted so that the machine operates at unity power factor at its terminals. Calculate the new values of the internal emf and the power angle.

(d) Assume that this synchronous generator is operating at an internal emf of 23.41 kV and supplying power to the infinite bus.

- (i) The prime mover power is adjusted without changing the excitation so that the machine delivers zero reactive power to the system. Determine the power angle of the generator and the real power delivered to the system.
- (ii) What is the maximum reactive power that the machine can deliver at the excitation level of part (d)(i) above?

(a) 3.477 kA, 78.44 MW, 44.8 MVAr

(b) 21.4 kV, 22.77^o

(c) 17.776 kV, 32.45^o

(d)(i) 50.157^o, 127.66 MW (ii) 59.74 MVAr

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Exercise 10.1

A 30-MVA, 13.2-kV, 0.9 pf lag, 4-pole, Y-connected synchronous generator has a synchronous reactance of 0.8 pu. The generator supplies power to a 50-Hz, 13.2-kV infinite bus. Calculate :

(a) the speed of the generator
(b) synchronous reactance of the generator in ohms
(c) armature current and the induced emf of the machine at rated conditions, and the maximum power possible at this level of excitation
(d) armature current and the induced emf of the machine at full load at 0.9 pf lead, and the maximum power possible at this level of excitation
(e) Sketch the phasor diagrams for (c) and (d).

(a) 1500 rpm
(b) 4.65 Ω
(c) 1312.16 A, 20.18 kV, 57.33 MW
(d) 1312.16 A, 12.82 kV, 36.4 MW

Exercise 10.2

A three-phase synchronous generator has a no-load line-to-line output voltage of 2400 V at a field current of 12 A dc. The generator is connected to a 2300-V infinite bus, and its mechanical drive is adjusted such that the generator output is 48 kW + j12 kVAr, with the same field current of 12 A dc. Assume that the magnetic circuit is unsaturated. Neglecting the armature resistance, calculate the per phase synchronous reactance of the generator.

15.16 Ω

Exercise 11

A 100-MVA, 22-kV generator with synchronous reactance of 1.7 pu supplies power to an infinite bus at rated voltage.

(a) Find the induced emf and the power angle when the generator is supplying 50 MW at 0.85 pf lag.

(b) If the steam input is kept constant and the excitation is increased by 15%, determine the induced emf, the power angle, the reactive power, and the power factor of the generator.

(c) If the steam input is now adjusted, while the excitation is kept constant at its value in (b), to operate the generator at the pf of 0.85 lag again, determine the power angle, the real power and the reactive power supplied by the generator.

(d) Calculate the maximum real power that the generator can supply at the excitation level in (c).

(a) 38.4 kV, 29.1^o

(b) 44.2 kV, 25.02^o, 48.3 MVAr, 0.72 lag

(c) 33.2^o, 64.7 MW, 40.1 MVAr

(d) 118 MW

Review Exercise 12

(a) A 3-ϕ, 1.5-MVA, 22-kV, 50-Hz, Y-connected, 6-pole synchronous generator supplies 1 MW to a 22-kV infinite bus at 0.7 pf lag. Calculate (Given that $X_s = 309.8\ \Omega$)

(i) armature current

(ii) δ

(iii) induced emf of the machine.

Is the m/c over- or under-excited?

37.5 A, 21.17^o, 39 kV (over-excited)

(b) Re-do the calculations for a 0.7 pf lead case for the above.

37.5 A, 61.5^o, 16 kV (under-excited)

(c) If the steam input is kept constant for the m/c in (a) above, and the excitation is reduced by 10%, find the (i) induced emf (ii) δ (iii) Q & pf of the generator (iv) what is the max. power delivered under this excitation?

(i) 35.1 kV, (ii) 23.66^o, (iii) 0.72 MVAr, 0.81 lag, (iv) 2.49 MW

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Exercise 13

A 10-MVA, 11-kV, 3-phase, 4-pole, 60-Hz, Y-connected synchronous generator has a synchronous reactance of 1.5 ohms per phase, and negligible stator resistance. The generator is connected to an infinite bus at 11 kV and 60 Hz.

(a) Find the internally-generated emf and the power angle when the machine is delivering rated MVA at 0.8 pf lagging.

(b) The field excitation is increased by 20% without changing the power input from the prime mover. Find the stator current, power factor, and reactive power supplied by the machine.

(c) With the field excitation as in (b) above, the input power from the prime mover is increased slowly. What is the steady-state limit? Evaluate the stator current, power factor and reactive power at this limiting condition.

(a) 11.868 kV, 5.274^{o}
(b) 1301.29 A, 0.322 lag, 23.47 MVAr
(c) 104.42 MW, 6924.81 A, 0.791 lead, -80.66 MVAr

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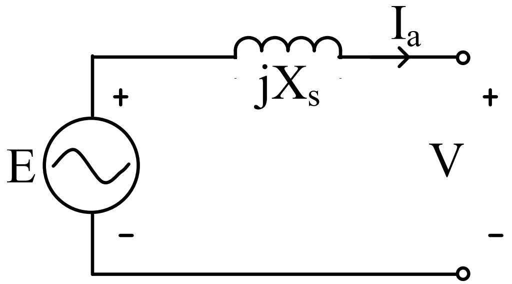
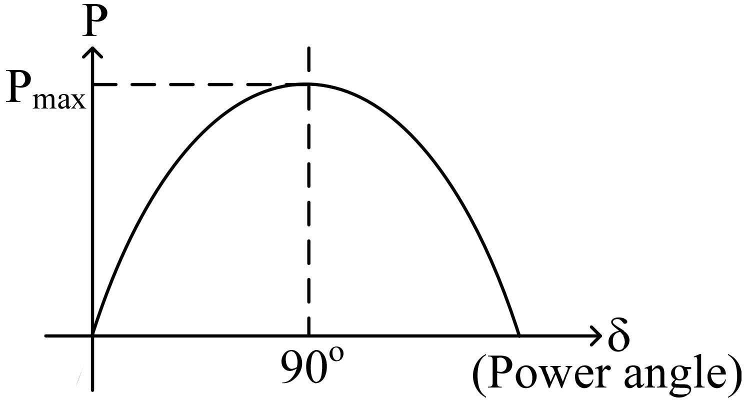
Governor Control

- The governor controls the steam input to the turbine, and thus the power input to the m/c (consequently the power output of the m/c)
- Consider a synch. m/c at constant excitation connected to an infinite bus.





Real power developed, $P_{pu} = \frac{EV}{X_s}\sin\delta$

(E, V & X_s are in pu)

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- Governor action

  - Increase steam input $\Rightarrow$ increase P $\Rightarrow$ increase in δ.
  - Decrease steam input $\Rightarrow$ decrease P $\Rightarrow$ decrease in δ.

  (No wonder δ is called power angle!!)

- For a given V & E,

  P_{max} occurs at $\sin\delta = 1 \Rightarrow \delta = 90^{o}$ &

  $P_{max\ pu} = \dfrac{EV}{X_s}$ $\Rightarrow$ <u>Steady state stability limit of the machine</u>

- Theoretically, therefore, governor can increase the steam input until the power P reaches the max. value.

- Any further increase in input power thru governor action will increase δ beyond $90^{o} \Rightarrow$ P starts to decrease!!

- This creates a serious imbalance between the input & output power

  $\Rightarrow$ Rotor becomes unstable & starts to accelerate without control.

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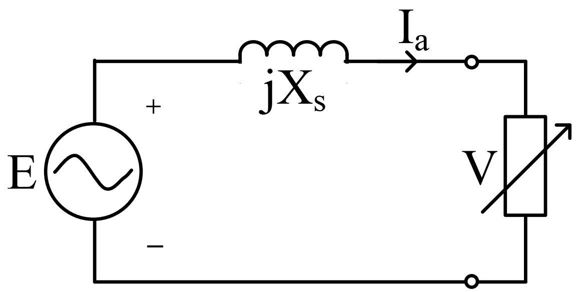
⇒ Gen. loses synchronism i.e. rotor & stator magn. fields are not in synchronism.

⇒ This has serious consequences in power systems.

- In practice, maximum rotor angle/power angle is usually slightly below 90^o.

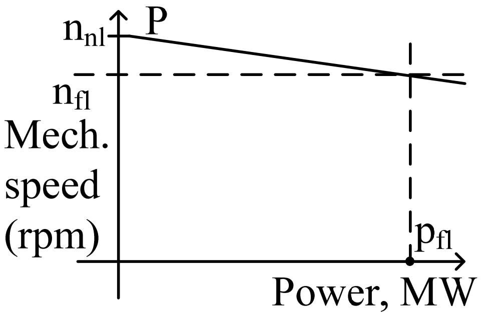
Load freq. characteristics

- Consider a synch. gen. supplying a varying load.

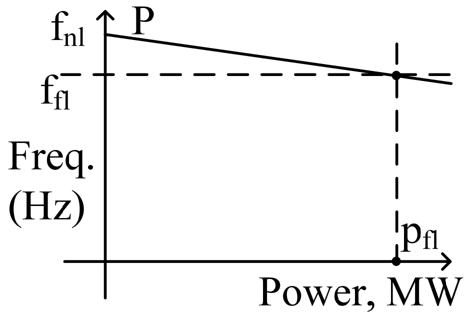


- As the power drawn from the prime mover (steam turbine, diesel engine, gas turbine, water turbine, wind turbine, etc.) increases, the speed at which the prime movers turn decreases.
- The governor senses the deviation in speed, and actuates the steam input accordingly to oppose the change in speed.
- The decrease in speed of the prime mover (and therefore the gen. shaft) is in general non-linear, but some form of governor mechanism is usually included to make the decrease in speed linear with an increase in power demand.

- A steady state feedback is used in the design of the governor so as to achieve a steady state load frequency (or speed) characteristics in such a way that the speed or frequency decreases slightly with increasing load. $\Rightarrow$ drooping characteristic



Speed vs. power curve
for a typical prime mover



Freq. vs. power curve
for the synch. gen.

Speed droop (SD) of a prime mover is defined as :

$$SD = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\%$$

(% change in speed from no load to full load)

where : n_{nl} = no-load prime-mover speed

n_{fl} = full-load prime-mover speed

But $f = \frac{n_s p}{120}$ where p = no. of rotor poles, and n_s = synch. speed

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$\Rightarrow$ f $\propto$ speed

$$\therefore \ SD = \frac{f_{nl} - f_{fl}}{f_{fl}} \times 100\%$$

where :

f_{nl} = no-load gen. freq. and f_{fl} = full-load gen. freq.

- Different machines have different droops, but for a given m/c the droop is fixed.
- Initial no-load freq. can be adjusted

  $\Rightarrow$ Diff. load-freq. characteristics are possible.

- Load-freq. charcs. play an important role in parallel operation of synch. generators, as we shall see shortly.
- Using the shown charcs., it can be proved that

$P = S_p (f_{nl} – f_{sys})$

where :

P = gen. power output, MW
f_{nl} = no-load freq. of gen, Hz
f_{sys} = operating system freq., Hz
S_p = slope of droop, MW/Hz

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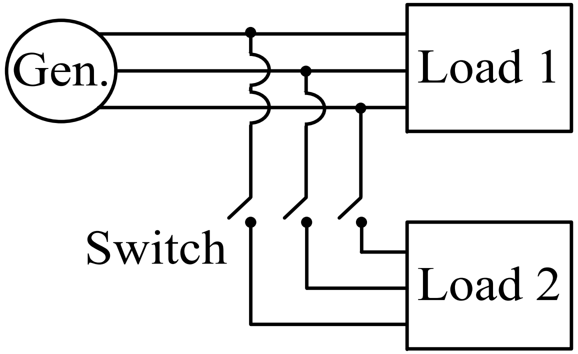
$$\left[S_p = \frac{P_{fl} - 0}{f_{nl} - f_{fl}} \right]$$

<u>Example 9</u>

Consider the generator operating alone, supplying a load (Load 1). A second load is to be connected in parallel with load 1. The gen. has a no-load freq. of 61 Hz, and a slope of 1 MW/Hz.



Load 1 = 1 MW, 0.8 pf lag

Load 2 = 0.8 MW, 0.707 pf lag

(a) Before connecting load 2, what is the system operating freq.?

(b) After connecting load 2, what is f_{sys}?

(c) After connecting load 2, what action could the system operator take to restore the system freq. to 60 Hz?

Solution :

(a) $P = S_p\,(f_{nl} - f_{sys})$

$$\Rightarrow f_{sys} = f_{nl} - \frac{p}{S_p}$$

$$= 61 - \frac{1}{1} = \underline{60\ \text{Hz}}$$

(b) $$f_{sys} = f_{nl} - \frac{p}{S_p}$$

$$= 61 - \frac{1.8}{1} = \underline{59.2\ \text{Hz}}$$

(c) Increase governor no-load set points by <u>0.8 Hz</u>, to <u>61.8 Hz</u>, in order to restore system freq. to 60 Hz.

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Parallel Operation of Generators

- In today's world, an isolated synch. gen. supplying its own load is very rare, except as emergency generators, etc.
- Usually, more than 1 gen. operate in parallel to supply total power demand of the loads, e.g. in the U.S. power grid, literally thousands of generators share the system load!
- Why are synch. gen. operated in parallel?

1) Several gen. can supply a bigger load than a single m/c by itself.
2) System is more reliable, since failure of any one gen. does not cause a total loss of power to load.
3) One or more gen. can be removed for shutdown/preventive maintenance.
4) Depending on the load, generators may be brought on-line, or taken off $\Rightarrow$ most efficient & economical system operation.
5) For future expansion, gen. may be added on easily.

However, some conditions must be satisfied before generators are connected in parallel. These are :

- RMS line voltages of gens. must be equal
- Gens. must have same phase sequence
- Phase angles of their "a" phases must be equal. (Likewise for other phases)

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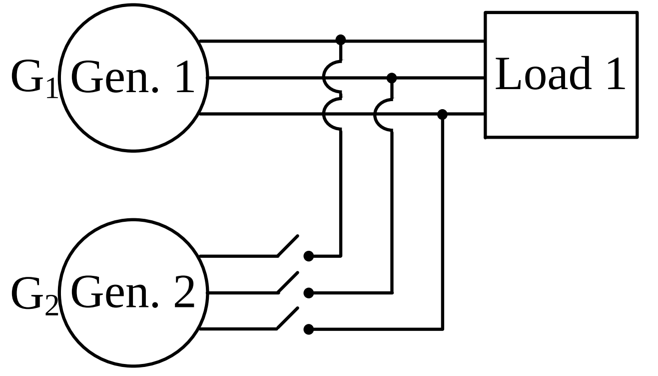
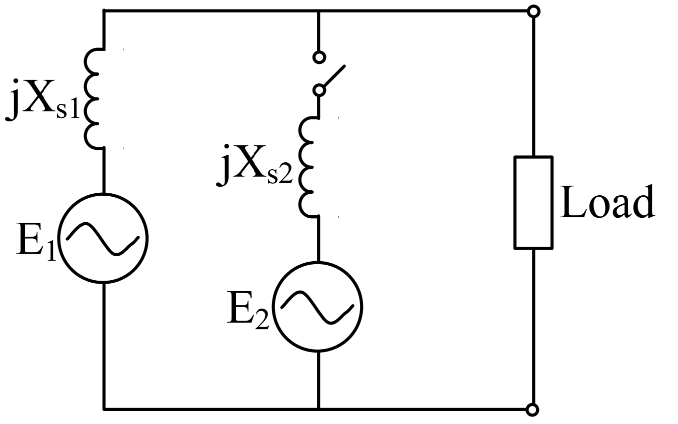
- Gens. must have same frequency
  - Usually the freq. of the new generator (oncoming gen. being “paralleled” with other gens.) must be slightly higher than the freq. of the running system.

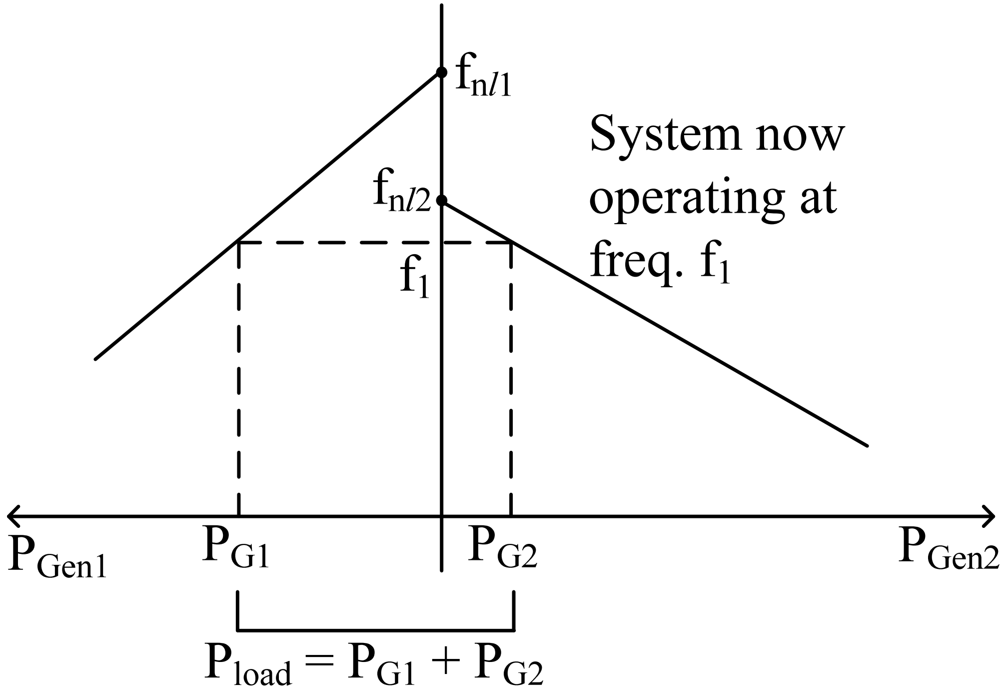
Process of paralleling a new generator with running system is called synchronization. A device called synchroscope is used for this purpose.





- Basic constraints : $P_{load} = P_{G1} + P_{G2}$
  $Q_{load} = Q_{G1} + Q_{G2}$

- System freq. not constrained to be constant, neither is the power of any given gen. constrained to be constant.
- Power-freq. diagram <u>immediately</u> after G_2 is paralleled :



- <u>What happens when governor set points of G2 are increased</u>? The power-freq. curve of G2 shifts upward, as shown below :

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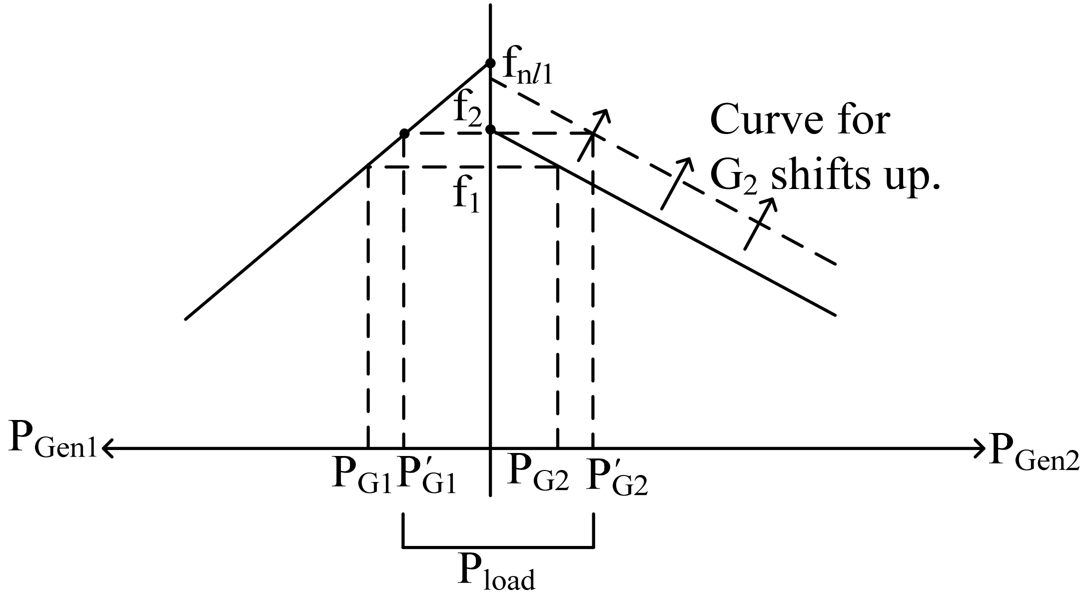

Note that P_{load} does not (cannot) change!!

- At the original operating freq. f_1, P_{load} will now be much larger than load demand, so the system cannot continue to operate at f_1 now.
- In fact, there is only one freq. at which $P_{load} = P_{G1} + P_{G2}$. This freq. f_2 is higher than original operating freq. f_1.
- At f_2, G_2 supplies more power than at f_1; G_1 supplies less power.
- Therefore, when 2 gen. are operating in parallel, an increase in governor set points on one of them
  - Increases the system freq. (from f_1 to f_2)
  - Increases power supplied by that generator, while reducing the power supplied by the other.

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- If the slopes and, no-load freq. of the generator's speed droop curves are known, then the powers supplied by each gen. & the resulting system freq. can be obtained quantitatively.
- An example will help illustrate the concept.

Example 10

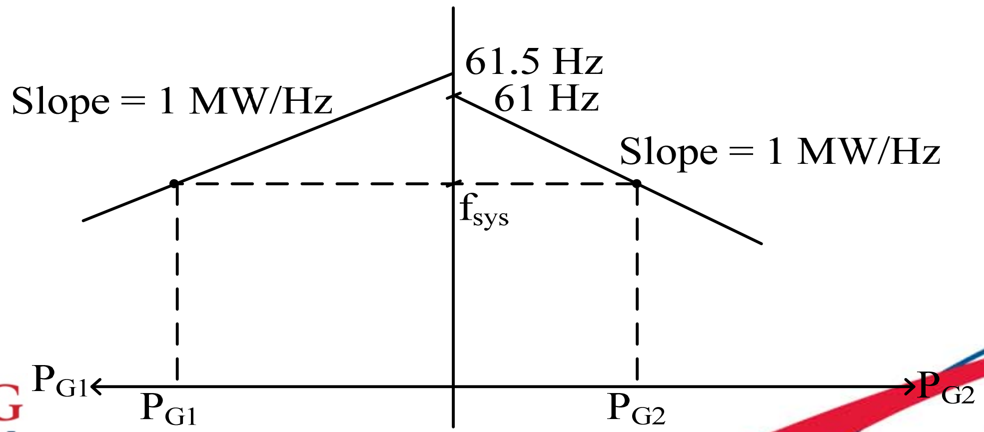
Consider two gen. in parallel.

G_1 : No-load freq = 61.5 Hz; Slope S_{p1} = 1 MW/Hz
G_2 : No-load freq = 61.0 Hz; Slope S_{p2} = 1 MW/Hz
Total system load = 2.5 MW, 0.8 pf lag.

(a) At what freq. is the system operating? How much power is supplied by each gen.?

(b) What will be the corresponding values if the governor set point on G_2 is increased by 0.5 Hz?

Solution :



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$P_{G1} = S_{p1} (f_{nl1} - f_{sys})$
$P_{G2} = S_{p2} (f_{nl2} - f_{sys})$
$P_{load} = P_{G1} + P_{G2}$

$\therefore \quad 2.5 = 1(61.5 - f_{sys}) + 1(61 - f_{sys}) = 122.5 - 2 f_{sys}$

$\Rightarrow \; f_{sys} = \underline{60 \text{ Hz}}$

$\therefore \quad P_{G1} = 1(61.5 - 60) = 1.5$ MW and $P_{G2} = 1(61 - 60) = 1.0$ MW

(b) $2.5 = 1(61.5 - f_{sys}) + 1(61.5 - f_{sys}) = 123 - 2 f_{sys}$

$$\Rightarrow f_{sys} = \frac{120.5}{2} = 60.25 \text{ Hz}$$

$\therefore \quad P_{G1} = 1(61.5 - 60.25) = 1.25$ MW and $P_{G2} = 1(61.5 - 60.25) = 1.25$ MW

(c) Suppose the system is operating as in (a), and the load is increased to 3.5 MW. Find the new system freq. & powers gen. by each m/c.

$3.5 = 1(61.5 - f_{sys}) + 1(61 - f_{sys})$
$= 122.5 - 2 f_{sys}$

$\Rightarrow \quad f_{sys} = 59.5$ Hz

$\therefore \quad P_{G1} = 1(61.5 - 59.5) = 2$ MW

$P_{G2} = 1(61 - 59.5) = 1.5$ MW

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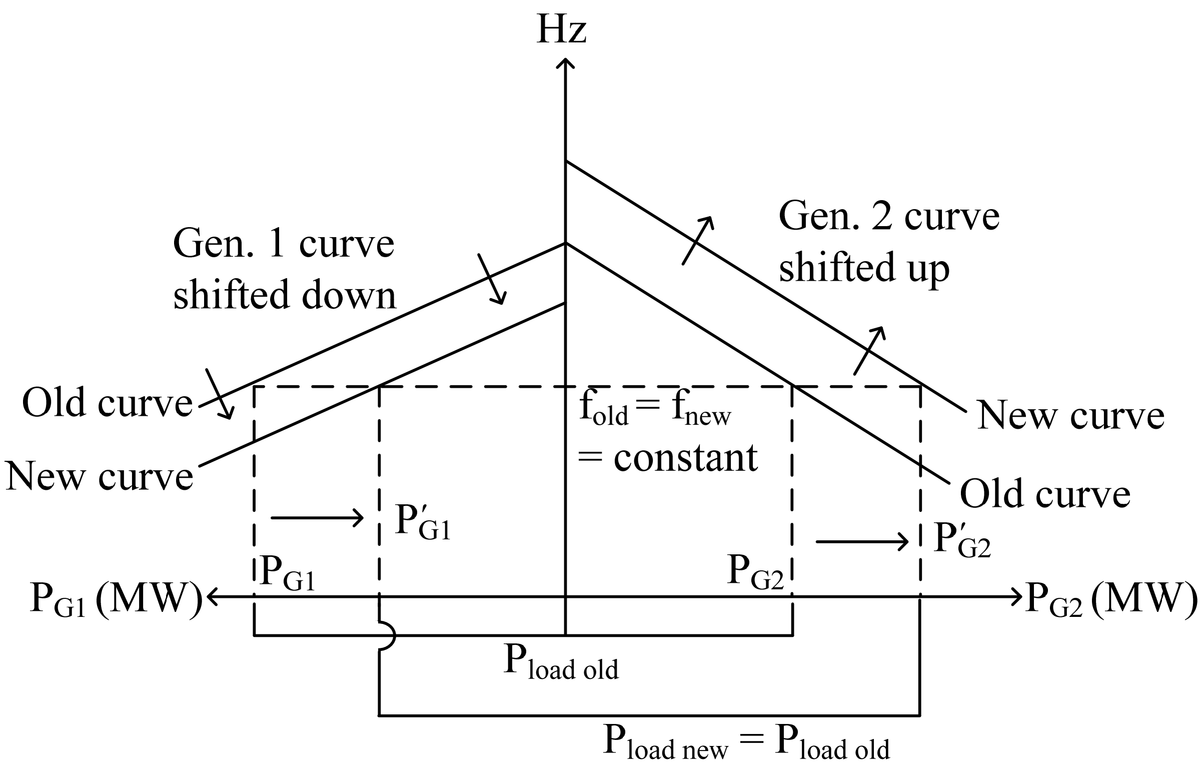
In general, power sharing shd be adjusted independently of system freq. This is done by increasing governor set points of one generator and simultaneously decreasing the governor set points of the other gen.

Similarly, to adjust system freq without changing the power sharing, simultaneously increase or decrease both governor set points.



Shifting power sharing w/o affecting system freq.

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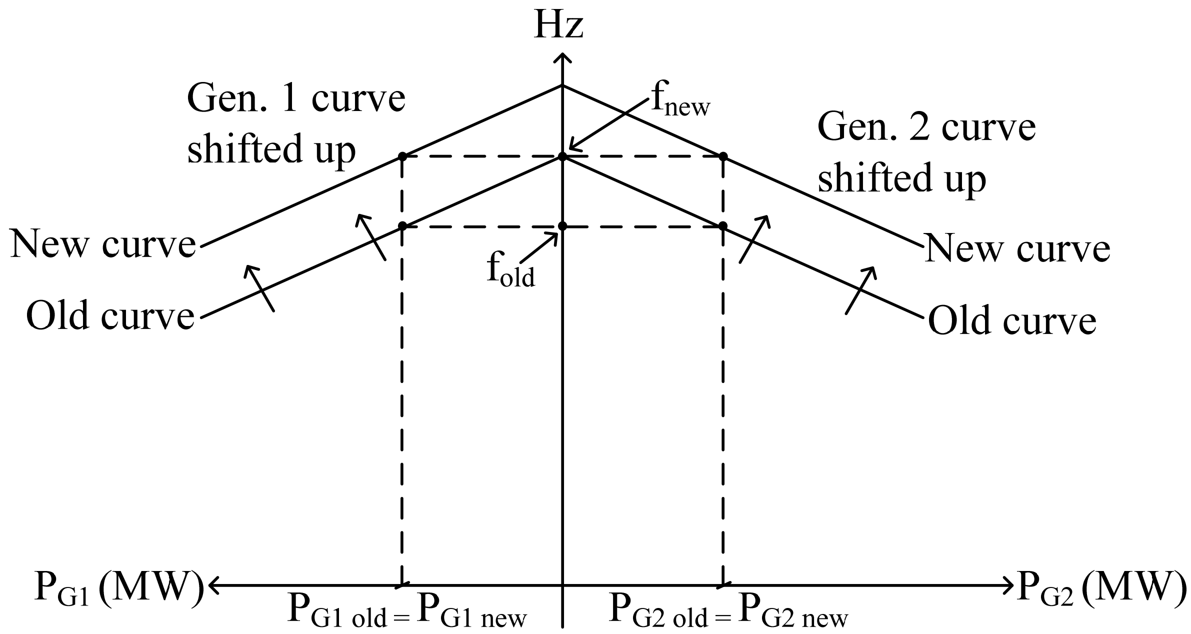

Shifting system freq. without affecting power sharing

Exercises for your doing pleasure

14. Two generators operating in parallel supply a total load of 6 MW. Gen 1 has a slope of 0.2 Hz/MW, and Gen 2 0.25 Hz/MW. The no-load frequency settings of the generators are 50.4 & 51 Hz respectively.

Find (i) the system frequency
(ii) load supplied by each generator

(i) 50 Hz, (ii) L_{G1} = 2 MW L_{G2} = 4 MW

15. Two 30-MW, 11-kV synchronous generators are operating in parallel. Each generator is set to operate at a frequency of 50 Hz while supplying its full load of 30 MW individually. Generator A has a speed droop characteristic of 20 MW/Hz, and generator B has a speed droop of 24 MW/Hz while supplying a load of 38 MW at 11 kV and 0.8 pf lagging. Calculate the system operating frequency, and the load supplied by each generator.

50.5 Hz; 20 MW (Gen A) and 18 MW (Gen B)

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Applications of Synchronous Machines

- Primary use is as an AC generator which provides more than 99% of the electrical energy used by people all over the world.
- Synchronous motors used for constant-speed, continuous-running drives such as

  → Motor-gen. sets
  → Air compressors
  → Centrifugal pumps
  → Blowers, crushers
  → In continuous-processing mills

- Synch. motors used for power factor control; as synch. condensers to regulate the voltage at the receiving end of a long transmission line; have a very high efficiency (> 90%)

- Synch. motors also used in low-speed and high horsepower drives, e.g.
  → Large low-head pumps
  → Floor-mill line shafts
  → Ship propulsion
  → Rubber mills & mixers
  → Pulp grinders

- Synch. motors are also being considered as a viable alternative for

  → Transit system &
  → Locomotive drives

Further reading for synchronous machines

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