2

Compensation Techniques, Voltage Profile Control & Load-Frequency Control

2.1 Compensation of Transmission Lines

Introduction

The performance of long EHV AC transmission systems can be improved by reactive compensation of series and shunt (parallel) type. Shunt reactors and series capacitors are used to reduce the shunt susceptance and the series reactance of lines and thus act as the line compensators. Compensation of lines results in improving the system stability and voltage control, in increasing the efficiency of power transmission, facilitating line energization and reducing temporary and transient over voltages.

There are mainly two techniques involved in compensation of transmission lines which are explained below one by one.

1. Series Compensation of Transmission Lines

Series compensation consists of capacitors connected in series with the line at suitable locations and thus oppose the effect of series inductive reactance of the line. It increases the power transmission capability of the line and reduces the voltage regulation as explained below.

The power transferred from sending end to the receiving end in a transmission line is

$$P_W = \frac{V_S V_R}{X_L} \sin\delta \qquad \textbf{(Without series capacitor)} \qquad ...(1)$$

When series capacitor of reactance X_C is inserted in the line, then, net reactance becomes $(X_L - X_C)$ and hence, power transmission capability of the line becomes

$$P_{se} = \frac{V_S V_R}{(X_L - X_C)} \sin\delta \qquad \textbf{(With series capacitor)} \qquad ...(2)$$

From equation (1) and (2), it is clear that denominator of equation (2) is reduced and hence for same magnitude of V_S, V_R and δ, P_{se} is much higher than P_W and the increase in power transfer capability of the line is given as

$$\frac{P_{se}}{P_W} = \left(\frac{X_L}{X_L - X_C}\right) = \frac{X_L}{X_L\left(1 - \frac{X_C}{X_L}\right)} = \frac{1}{(1 - K_{se})} \qquad ...(3)$$

where, $K_{se} = \frac{X_C}{X_L}$ is the degree of series compensation

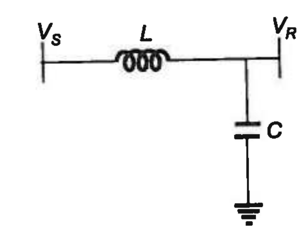
For example:
If the line is compensated to an extent of 75% i.e., $K = 0.75$, then the power transfer capability of the line becomes $\frac{1}{1-0.75} = 4$ i.e. four times of that without series compensation.

Remember

- Practically the economic degree of series compensation is found to be in the range of 40% to 70%.
- For the transfer of same amount of power and the same value of V_S and V_R, the power angle δ is lower for compensated line as compared to that in case of an uncompensated line. Due to lower value of power angle system becomes more stable.
- Series capacitors usually offer the most economic solution w.r.t both the steady state and transient stability.
- Series capacitors are mainly located along the lines which results in better voltage profile along the line, reduced short circuit current through the capacitor during a fault.
- Sometimes series compensation results in subsynchronous resonance (can develop high torsional stresses), maloperation of line protection and high recovery voltage (across the circuit breaker constants).

Effect of Compensators on SIL (Surge Impedance Loading)

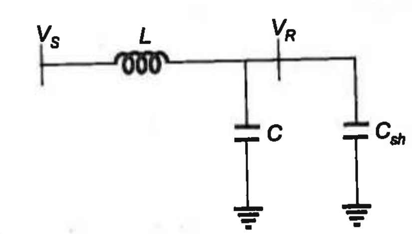
Without compensation:



$$Z_{S_1} = \sqrt{\frac{L}{C}} = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{X_L \cdot X_C}$$

$$(SIL)_1 = \frac{V_S^2}{Z_{S_1}}$$

With C_{sh} compensation:



$$C_2 = C_{eq} = C + C_{sh}$$

$$= C\left(1 + \frac{C_{sh}}{C}\right) = C(1 + K_{Csh}) \qquad \left(K_{Csh} = \frac{C_{sh}}{C}\right)$$

K_{Csh} = % or degree of C_{sh} compensation

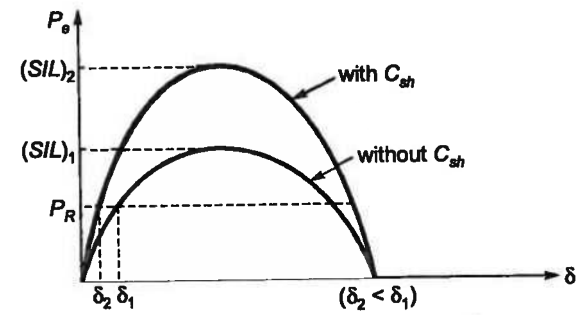
Now,
$$Z_{S_2} = \sqrt{\frac{L}{C_2}} = \sqrt{\frac{L}{C(1+K_{sh})}}$$

$$Z_{S_2} = \frac{Z_{S_1}}{\sqrt{1+K_{C_{sh}}}} \text{ and } (SIL)_2 = \frac{V_S^2}{Z_{S_2}} = \frac{V_S^2}{Z_{S_1}/\sqrt{1+K_{C_{sh}}}}$$

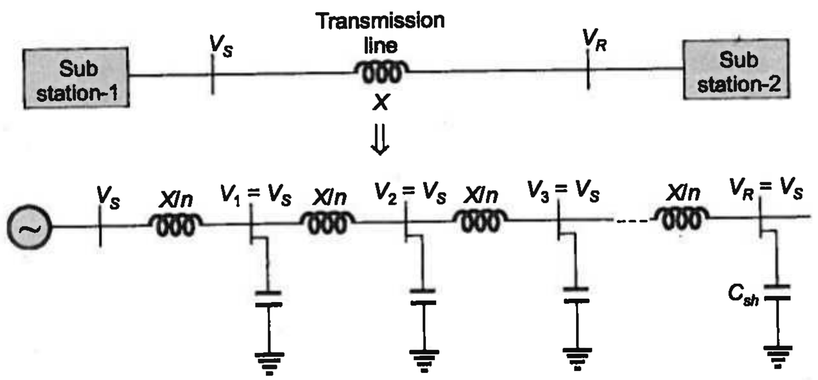
$$(SIL)_2 = (SIL)_1\sqrt{1+K_1} \qquad (K_{C_{sh}} = K_1)$$

Conclusion:

- Z_{S_1} is greater than Z_{S_2} (i.e. $Z_{S_1} > Z_{S_2}$)
- $(SIL)_2$ is greater than $(SIL)_2$ [i.e. $(SIL)_2 > (SIL)_1$]
- Improve stability of system i.e. reduces 'δ'.



Compensation for '*n*' Sections of Line

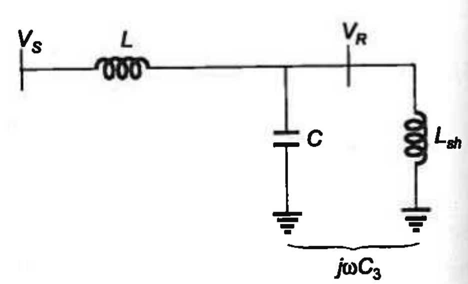


$$\boxed{P_R = \frac{V_S.V_R}{X/n}\cdot \sin\left(\frac{\delta}{n}\right)}$$

At steady state or maximum power limit

$$P_{R\max} = \left|\frac{V_s V_R}{X/n}\right|$$

Shunt Reactor Compensation (L_{sh})



$$j\omega C_3 = j\omega C + \frac{1}{j\omega L_{sh}} = j\omega C\left[1 - \frac{1}{\omega^2 C L_{sh}}\right]$$

$$= j\omega C(1 - K_2) \qquad \left(\therefore\ K_2 = \frac{1}{\omega^2 C L_{sh}}\right)$$

K_2 = % or degree of compensation

$$K_2 \text{ or } K_{sh} = \frac{1}{\omega^2 C L_{sh}}$$

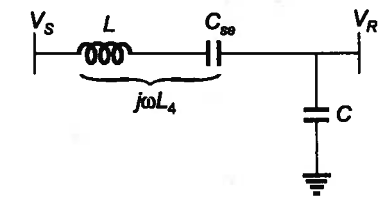
$$Z_{S_3} = \sqrt{\frac{j\omega L}{j\omega C_3}} = \sqrt{\frac{j\omega L}{j\omega C(1-K_2)}}$$

$$Z_{S_3} = \frac{Z_{S_1}}{\sqrt{1-K_2}} \text{ and } (SIL)_3 = (SIL)_1 \cdot \sqrt{1-K_2}$$

Conclusion:

- $Z_{S_3} > Z_{S_1}$
- $(SIL)_3 < (SIL)_1$
- Stability of system will be reduced i.e. δ increases

Series Capacitor (C_{se}) Compensation



$$j\omega L_4 = j\omega L + \frac{1}{j\omega C_{se}} = j\omega L\left[1 - \frac{1}{\omega^2 L C_{se}}\right]$$

$$j\omega L_4 = j\omega L\,[1 - K_{se}] \qquad (K_{se} = K_3)$$

K_{se} = % or degree of compensation

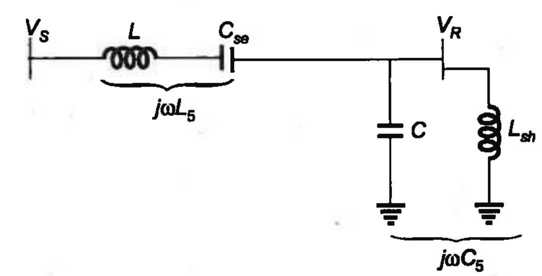
$$Z_{S_4} = \sqrt{\frac{j\omega L_4}{j\omega C}} = \sqrt{\frac{L}{C}(1-K_{se})} = Z_{S_1}\sqrt{1-K_{se}}$$

$$Z_{S_4} = Z_{S_1}\sqrt{1-K_3} \text{ and } (SIL)_4 = (SIL)_1/\sqrt{(1-K_3)}$$

Conclusion:

- $Z_{S_4} < Z_{S_1}$
- $(SIL)_4 > (SIL)_1$
- Stability of system is improved i.e. δ decreases

Both C_{se}, L_{sh} Compensation



$$j\omega L_5 = j\omega L + \frac{1}{j\omega C_{se}} = j\omega L\left[1 - \frac{1}{\omega^2 L C_{se}}\right] = j\omega L[1 - K_{C_{se}}]$$

$$j\omega L_5 = j\omega L(1 - K_{C_{se}}) \qquad \left(\text{Where, } K_{C_{se}} = \frac{1}{\omega^2 L C_{se}}\right)$$

and

$$j\omega C_4 = j\omega C + \frac{1}{j\omega L_{sh}} = j\omega C\left[1 - \frac{1}{\omega^2 C L_{sh}}\right]$$

$$j\omega C_4 = j\omega C[1 - K_{sh}] \qquad \left(\text{Where, } K_{sh} = \frac{1}{\omega^2 L C_{se}}\right)$$

$$Z_{S_5} = Z_{S_1} = \sqrt{\frac{1-K_{se}}{1-K_{sh}}}$$

$$(SIL)_5 = (SIL)_1\sqrt{\frac{1-K_{sh}}{1-K_{se}}}$$

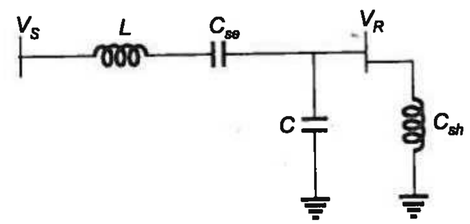
Conclusion:

Z_{S_5} and $(SIL)_5$ depends on value of C_{se} and L_{sh}.

Both C_{se}, C_{sh} Compensation

$$Z_{S_6} = Z_{S_1}\sqrt{\frac{1-K_{se}}{1+K_{sh}}}$$

$$(SIL)_6 = (SIL)_1\sqrt{\frac{1+K_{sh}}{1-K_{se}}}$$



Conclusion:

- $Z_{S_6} < Z_{S_1}$
- $(SIL)_6 > (SIL)_1$ and improve stability i.e. reduces 'δ'.

2. Shunt Compensation of Transmission Lines

In EHV transmission system, shunt compensation with capacitance VARs is used to inject reactive power and control the receiving end voltage whereas shunt reactor compensation is used to neutralize the Ferranti effect. Static compensation employing capacitors and reactors or using synchronous phase modifiers are used. Static compensation is generally preferred due to it's inherent advantage of high speed of response, absence of fault infeed to the system, lower maintenance, low cost and greater reliability. Series and shunt compensation scheme is shown in Figure 2.1.

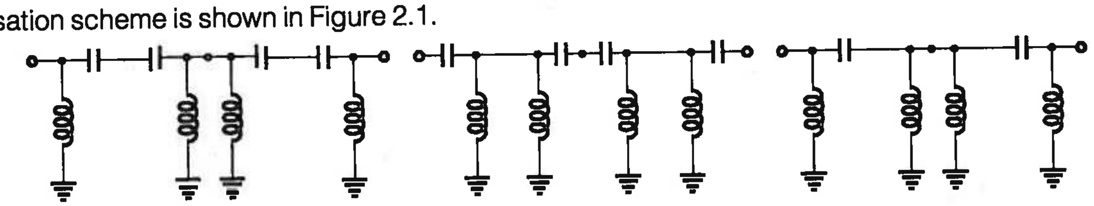


Figure-2.1 : *Series and shunt compensation scheme*

Remember

- Shunt reactors are used in EHV transmission line to control steady-state over voltages when energizing the long EHV lines or when operating under light load conditions.
- If the shunt reactors are not employed, the reactive power generated by the capacitance can cause high voltages at the receiving and of the line due to Ferranti effect explained in chapter 1.
- Shunt reactors prevents insulation stresses at the receiving end of the transmission line occurring due to Ferranti effect.
- Practically, some of the shunt reactors are kept permanently connected so as to avoid voltage increase due to sudden fall in load from heavy load conditions.

Example - 2.1 For any fixed degree of inductive shunt compensation, additional series capacitive compensation

(a) increases the effective length of line
(b) increases virtual surge impedance of line
(c) decreases virtual surge impedance loading of the line
(d) none of the above

Solution: (d)

With addition series capacitive compensation, effective reactance of the line reduces. So, effective length of the line will reduce as length of line α reactance.

Also, surge impedance, $Z_s = \sqrt{\frac{L}{C}}$

Since X is reduced so, L is also reduced and hence Z_s reduces.
As Z_s reduces therefore, surge impedance loading of line increases since $SIL \propto 1/Z_s$.
Hence, none of the given options are true.

Example - 2.2 **Shunt compensation in an EHV line is used to**

(a) improve stability
(b) reduce fault level
(c) improve the voltage profile
(d) substitute for synchronous phase modifier

Solution: (c)

Shunt compensation in an EHV line is mainly used to overcome Ferranti effect i.e. for improving the voltage profile of the line.

2.2 Methods of Voltage Control

In power system all the equipments are rated for certain voltage with a permissible voltage variation. Voltage at various buses must, therefore, be controlled within a specified regulation figure.

Consider the two-bus system shown in Figure 2.2.

The real and reactive powers delivered by the line for fixed sending end voltage $|V_S|$ and a specified receiving end voltage $|V_R^s|$ can be written as

$$P_R = \frac{|V_s||V_R^s|}{X}\sin\delta \qquad ...(4)$$

and

$$Q_R^s = \frac{|V_R^s|}{X}(|V_s| - |V_R^s|) \qquad ...(5)$$

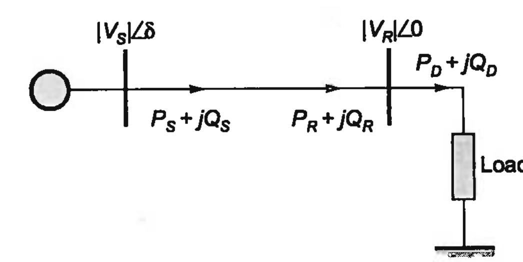


Figure-2.2 : *A two bus power system*

Real power demand is P_D where, $P_R = P_D$
Real power demand P_D can be controlled by changing torque angle δ.

The received reactive power of the line must remain fixed at Q_R^s given by equation (5) for fixed $|V_S|$ and specified $|V_R^s|$.

The line will operate with specified receiving end voltage only when

$$Q_D = Q_R^s$$

For $Q_D > Q_R^s$, the receiving end voltage must change from $|V_R^s|$ to some value $|V_R|$ to meet the required VARs demand.

Thus, $$Q_D = Q_R = \frac{|V_R|}{X}(|V_s| - |V_R|), \quad \text{for } Q_D > Q_R^s$$

Now, for $Q_D = Q_R > Q_R^s$, $|V_R| < |V_R^s|$

Hence, a larger VAR demand than Q_R^s is met by a consequent fall in receiving end voltage from the specified value.

Similarly, if the VAR demand is less than Q_R^s then, $|V_R| > |V_R^s|$.

Therefore, in order to regulate the line voltage under varying demands of reactive power (VARs), the following two methods are employed.

1. Reactive Power Injection Method

In order to keep the receiving end voltage at a specified value $|V_R^s|$, a fixed amount of reactive power (VARs) i.e. Q_R^s must be drawn from the line. For this a local VAR (reactive power) generator must be used as shown in Figure 2.3. The reactive power balance equation at the receiving end now becomes

$$Q_R^s + Q_C = Q_D$$

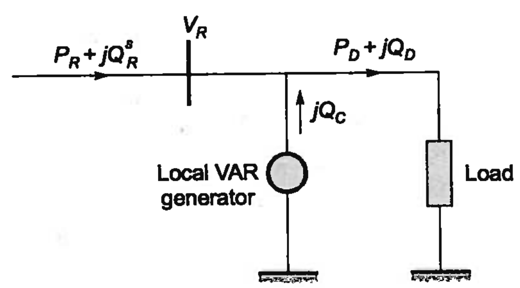


***Figure-2.3 :** Use of local reactive power generator at the load bus*

The receiving end voltage thus remain fixed at $|V_R^s|$.

There are two types of reactive power generators employed in practice namely static type and rotative type.

Static Type VAR Generators

A bank of three-phase static capacitors and/or inductors is used as a static VAR generator as shown in Figure 2.4.

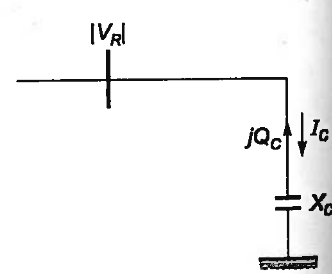


Figure-2.4
Static VAR generator/static capacitor bank

Let $|V_R|$ be the receiving end voltage in kV and X_C be the per-phase capacitive reactance of the capacitor bank on an equivalent star basis.

Then, reactive power fed into the line will be

$$Q_{C\,(3\text{-phase})} = \frac{|V_R|^2}{X_C}\ \text{MVAR} \quad \textbf{(When capacitor bank is used)}$$

and

$$Q_L(3\text{-phase}) = \frac{-|V_R|^2}{X_L}\ \text{MVAR} \quad \textbf{(When inductor are used)}$$

NOTE: Under high load condition, when positive VARs are needed, capacitor banks are employed, while under light load conditions, when negative VARs are required then, inductor banks are switched on.

Rotating VAR Generators

A rotating VAR generators is nothing but a synchronous motor running at no-load and having excitation adjustable over a wide range. When this synchronous motor is overexcited it feeds positive VARs (operates at leading p.f.) and when it is underexcited it feed negative VARs (operates at lagging p.f.) into the system. The other name of rotating VAR generator is ***"synchronous condenser"***.

Figure 2.5 shows a synchronous motor connected to the receiving end bus bars and running at no load.

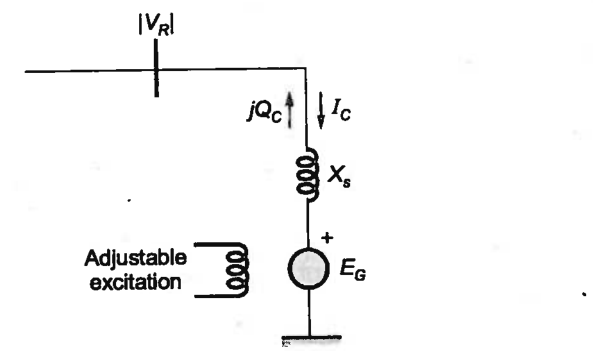


***Figure-2.5 :** Rotating VAR generator or synchronous condenser improving the voltage profile*

NOTE: When a large amount of reactive power injection is needed in the system then, only a rotating VAR generator is used due to the economic considerations, installation and maintenance problems.

2. Voltage Control by Means of Transformers

This method include mainly two types of control techniques discussed below.

On-load Tap Changing Transformers

On-load tap changing is the most common phenomenon in a power system network because minimum load is always existing in a power system network. Receiving end voltage which tends to sag owing to VARs demanded by the load, can be raised by simultaneously changing the taps of sending and receiving end transformers. The tap changes can be done automatically or manually.

Figure 2.6 shows a transmission line with a tap changing transformer at each end.

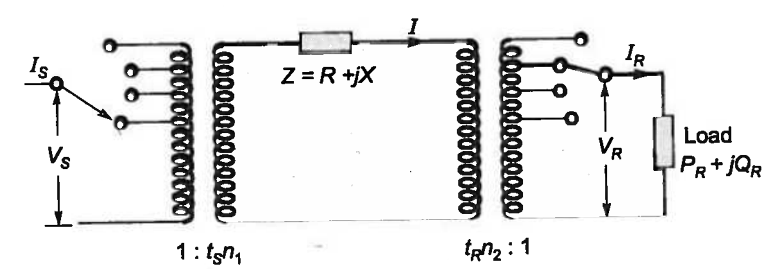


***Figure-2.6 :** Transmission line having tap changing transformer at each ends*

Generally, the tap changing is automatic and operated by motors which respond to relays set to hold the voltage at the prescribed level. Special circuit allow the change to be made without interrupting the current.

Control by Mid-line Boosters

When it is desired to increase the voltage at an intermediate point in a line rather than at the ends as with tap-changing transformers then, booster transformers are used.

Figure 2.7 shows a booster transformer for controlling the voltage profile.

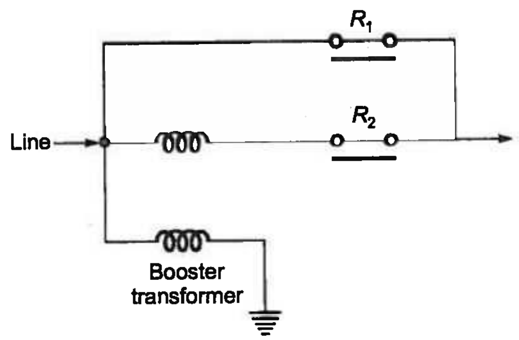


***Figure-2.7 :** Booster transformer*

Booster are generally used in distribution feeders where the cost of tap-changing transformer is not warranted.

The booster transformer shown in Figure 2.7 can be pressed into the circuit by closure of relay R_2 and the opening of relay R_1 and vice-versa.

Example - 2.3 **The Thevenin's equivalent impedance of a bus bar in a three-phase 400 kV system is 0.20 p.u. at a base of 500 MVA. Calculate the reactive power needed to (a) boost the voltage by 5 kV at the bus bar. (b) reduce the voltage by 4 kV at the bus bar. What equipment is needed in each case?**

[IES-2002 : 10 marks]

Solution:

We know that, reactive power is

$$Q = \frac{V}{X}\cdot\Delta V \quad \text{or} \quad \Delta V = \frac{QX}{V} \qquad ...(1)$$

Given, $X = 0.2$ p.u. $(\text{MVA})_{\text{base}} = 500$, $(\text{kV})_{\text{base}} = 400$

So, $$X_{\text{base}} = \frac{(\text{kV})^2_{\text{base}}}{(\text{MVA})_{\text{base}}} = \frac{(400)^2}{500}\ \Omega$$

and actual value of reactance, X = (p.u. value) × Base value

$$= X_{\text{p.u.}} \times X_{\text{base}} = 0.2 \times \frac{(400)^2}{500} = 64\ \Omega$$

(a) For boosting the voltage by 5 kV at the bus bar, we have

$$\Delta V = 5000 = \frac{Q \times 64}{400 \times 10^3} \qquad \text{[Using equation (1)]}$$

or, $$Q = \frac{5000 \times 400 \times 10^3}{64} = 31.25 \quad \text{MVAR (injected)}$$

Static shunt capacitor will be used for voltage boost.

(b) For reducing the voltage by 4 kV, reactor will be used where, $X_L = 64\ \Omega$

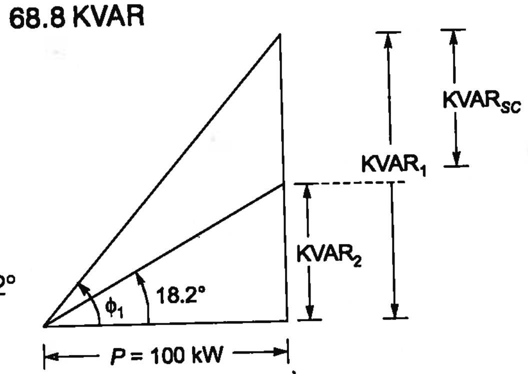
Now, $$4 \times 10^3 = \frac{Q \times 64}{400 \times 10^3} \qquad \text{[Using equation (1) and } \Delta V = 4\text{ kV]}$$

or, $$Q_L = \frac{4 \times 400 \times 10^6}{64} = 25\ \text{MVAR} \quad \text{(extracted/drawn)}$$

Example - 2.4 **An industry takes 100 kW at 0.7 p.f. lagging from a 3-ϕ 11 kV supply. It is required to increase the p.f. to 0.95 lagging using series capacitors. The rating of series capacitor required is given by**

(a) 28.88 KVAR **(b) 98.2 KVAR**
(c) 50 KVAR **(d) 68.8 KVAR**

Solution: (d)



Initial p.f. = 0.7 lag = or $\cos\phi_1 = 0.7$

or, $\phi_1 = \cos^{-1}(0.7) = 45.5°$

Final p.f. = 0.95 lag

or, $\cos\phi_2 = 0.95$

or, $\phi_2 = \cos^{-1}(0.95) = 18.2°$

Since power factor is improved therefore, series capacitor will inject lagging KVAR.

Let $(\text{KVAR})_{sc}$ be the reactive power produced by series capacitor.

Then, $(\text{KVAR})_{sc} = (\text{KVAR})_1 - (\text{KVAR})_2$

Now, $\tan\phi = \dfrac{\text{KVAR}}{\text{kW}}$ or KVAR = kW $\tan\phi$

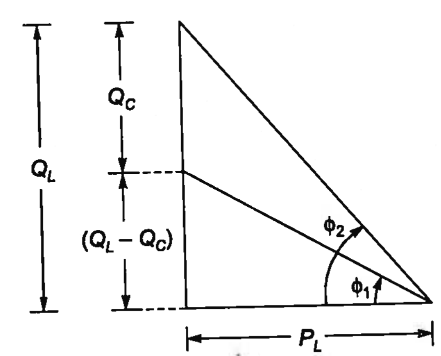
or, $(\text{KVAR})_{sc} = \text{kW}\tan\phi_1 - \text{kW}\tan\phi_2$
$= 100\,[\tan 45.5° - \tan 18.2°] = 68.8$ KVAR

Hence, rating of series capacitor required = 68.8 KVAR

Example - 2.5 **At an industrial sub-station with a 4 MW load, a capacitor of 2 MVAR is installed to maintain the load power factor at 0.97 lagging. If the capacitor goes out of service, the load power factor becomes**

(a) 0.85 **(b) 1.00**
(c) 0.80 lag **(d) 0.90 lag** [GATE-2005]

Solution: (c)



Load power, $P_L = 4$ MW

Rating of capacitor, $Q_C = 2$ MVAR

Let the reactive power demand of load be Q_L

Given, $\cos\phi_1 = 0.97$ lag or $\phi_1 = \cos^{-1}(0.97) = 14.06°$

Let ϕ_2 be the power factor angle of load when the capacitor goes out of service.

From above power triangle, $\tan\phi_1 = \left(\dfrac{Q_L - Q_C}{P_L}\right)$

or, $\tan(14.06)° = \dfrac{Q_L - Q_C}{P_L}$ or $0.25 = \dfrac{Q_L - Q_C}{P_L}$

or, $Q_L = 0.25 \times 4 + 2 = 3$ MVAR

Hence, total load demand of reactive power becomes 3 MVAR.

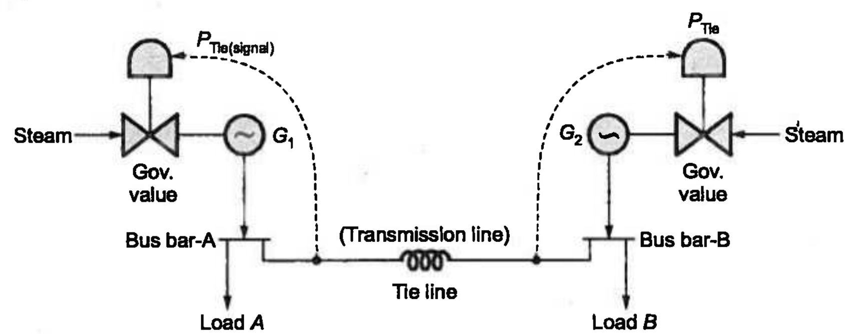
Now, $\tan\phi_2 = \dfrac{Q_L}{P_L} = \dfrac{3}{4}$ or $\phi_2 = 36.86°$

∴ New load p.f. = $\cos\phi_2 = \cos 36.86° = 0.80$ lag

2.3 Load Frequency Control

Load frequency control represents the change in the frequency due to change in the load demand. Load frequency control is used to control the power output of the generators of a electric area so as to maintain the scheduled frequency. All the generators in such an area constitute a coherent group so that all the generators speed up and slow down together maintaining their relative power angles. Such an area is defined as a ***"control area"***.

2.4 Area Frequencies Control



1. Flat Frequency Control

Consider two generator G_1 and G_{21} operating in parallel and interconnected by a tie line. The frequency of this system could be maintained at constant by regulating the generator G_1 without any regulation of generator G_2. If the load at Bus bar '*A*' or Bus bar '*B*' changes, the generation of station '*A*' would have to be altered accordingly to maintain a balance between generation and load on the system. In this manner, the frequency of the entire system could be maintained at a constant value. This type of regulation would be known as **flat frequency regulation.**

Advantage

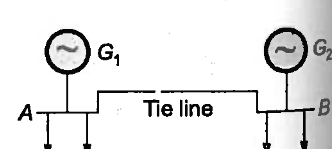
This type of control is advantageous when one station is much more efficient than the other station and it is desirable to obtain maximum output of the efficient station.

Disadvantage

Station '1' must absorb load changes for the entire system. Also the tie line between the two stations would have to absorb all load changes at station '2' since the generator '2' would maintain its output constant. The resulting wide swings in load for station 1 and on the tie line may result in uneconomical operation of the Generator-1.

Flat-Tie-Line-Regulation

In this method, the load changes of Bus bar '*B*' is supplied by generator G_1 without overloading the tie-line. The governing valve control signal is proportional to the frequency change and the tie-line power. In general this type of control is applied where a small system ties in with a large system and we want to maintain a definite load on that tie-line while the larger system maintain the frequency. This type of control is not generally used for large interconnections.



Tie-Line Load Bias Control or Parallel Frequency Control

In this method, both the generators (G_1 and G_2) simultaneously responding for the changes in the load of bus bar *A* and *B*. It is more efficient method for the frequency control of two areas. In general this type of control is applied for large interconnections.

Frequency Change Due to Sudden Load Change

Kinetic energy = $W \propto N^2 \propto f^2$

Load change = ΔP_D

Time lag or Delay in governor system = T_d

Inertia constant = H MW sec/MVA

Rating of generator = S, MVA

Initial frequency = f_i, new frequency = f_n

Change in frequency = $\Delta f = (f_n - f_i)$

$$W \propto f_2^2$$

$$\therefore \quad W_i \propto f_i^2 \text{ and } W_n \propto f_n^2$$

$$\frac{W_n}{W_i} = \left(\frac{f_n}{f_i}\right)^2 \Rightarrow \frac{f_n}{f_i} = \left(\frac{W_n}{W_i}\right)^{1/2}$$

Initial kinetic energy (W_i) = H.S.

$$W_n = W_i \pm (\Delta P_D)\, T_d$$

$$\frac{f_n}{f_i} = \left[\frac{W_i \pm (\Delta P_D) T_d}{W_i}\right]^{1/2}$$

$$\boxed{f_n = f_i\left[\frac{H.S \pm (\Delta P_D) T_d}{H.S}\right]^{1/2}}$$

$$f_n = f_i\left[\frac{H.S - (\Delta P_D) T_d}{H.S}\right]^{1/2}$$ ...(**Load demand** or **load increased**)

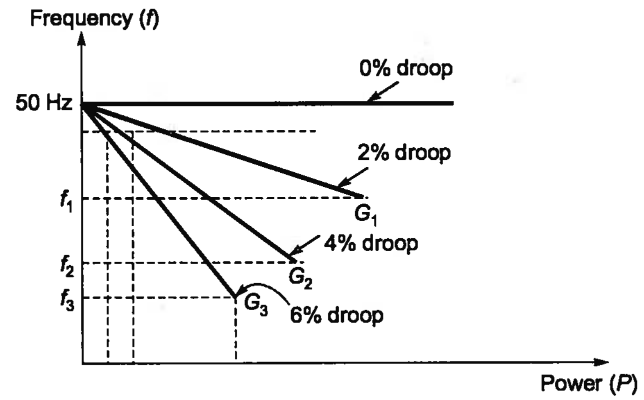
$$f_n = f_i\left[\frac{H.S + (\Delta P_D) T_d}{H.S}\right]^{1/2}$$ ...(**Load thrown off** or **load decreased**)

Disadvantages of Frequency Variation

1. The transformer voltage $V_{1(1-\phi)} = 4.44\, f \phi_m N$ that is, $V \propto f \phi_m N$.

   At constant voltage, if the frequency is reduced then the core flux is increased and core of the transformer may be saturated.
2. The transformer hysteresis and eddy current losses depend on frequency so, these losses are also increased if frequency of the system is increased.
3. AC electrical motor speed (N) is proportional to frequency of the system. If the frequency of the system is changed then the performance of electrical motor are also affected.
4. The thermal efficiency is affected because induced draft, force draft and primary air fan also depend on frequency.

Multiple Generator Parallel Operation



As the percentage (%) droop characteristic reduces, then the sharing of the load of the generator increases. A constant speed generator has zero (0%) percent speed regulation and shares entire load if it is connected parallel to other generators which have droop characteristic (2%, 4% and 6% respectively) greater than zero percentage characteristic.

Turbine Speed Governing System

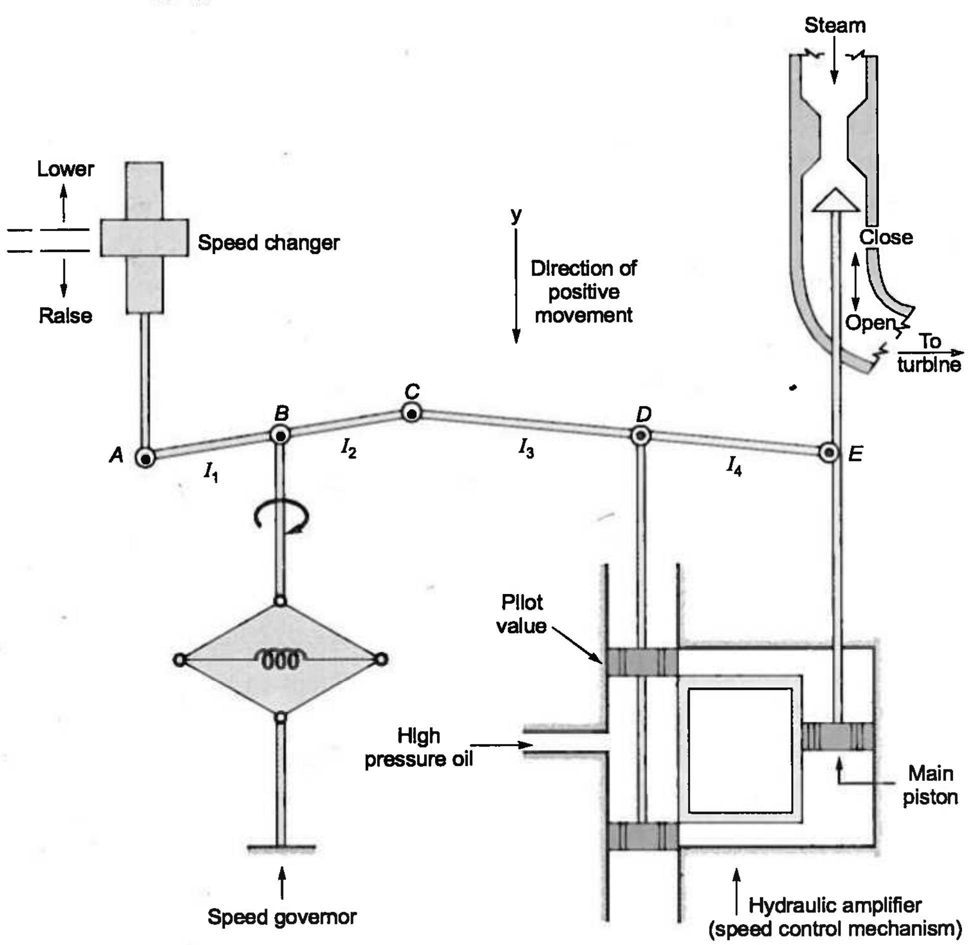


***Figure-2.8 :** Turbine speed governing system*

Figure 2.8 shows schematically the speed governing system of a steam turbine.

It consists of the following components:

(i) **Fly ball speed governor:**

It is the heart of governing system which senses the change in frequency (speed). When speed increases the fly ball moves outward and vice-versa.

(ii) **Speed changer:**

It provides a steady state power output setting for the turbine. For it's downward movement, upper pilot valve opens so that more steam is admitted to the turbine under steady state conditions and reverse happens for it's upward movement.

(iii) **Hydraulic amplifier:**

It ensures that the steam input to the turbine is constant till the required generation is obtained.

(iv) **Linkage mechanism:**

ABC is a rigid link pivoted at *B* and *CDE* is another rigid link pivoted at *D*. Linkage mechanism provides a movement to the control valve in proportion to change in speed.

Model of Speed Governing System

1. Design Model of Speed Governor

Let $\Delta P_C(s)$ be the signal given by speed governor to the speed changer. Point *E* in the linkage mechanism moves in the *y*-axis.

Hence, the change in the position of point *E* along *y*-axis is represented by $\Delta Y_E(s)$.

In order to make $\Delta F(s)$ equal to zero, it is applied as feedback to the speed governor by means of speed regulation $(1/R)$.

Figure 2.9 shows the block diagram of speed governor system.

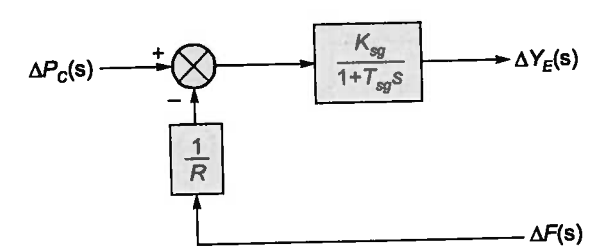


***Figure-2.9 :** Block diagram of speed governor system*

Here, K_{sg} = Gain constant of speed governor

T_{sg} = Time constant of speed governor

2. Turbine Model

Steam input to turbine depends on $\Delta Y_E(s)$

Output of turbine = Mechanical energy output = $\Delta P_t(s)$ = Turbine output

The input to the turbine depends on the position of point *E* of the linkage mechanism.

The block diagram for turbine model is shown in Figure 2.10 below.

Here, T_t is the time constant of turbine model.

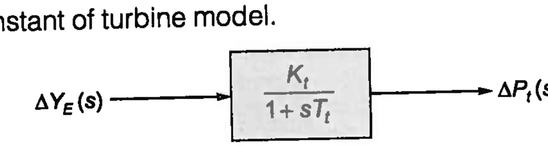


***Figure-2.10 :** Turbine transfer function mode*

3. Generator Load Model

Generator load model is also called *"Power system model"*.

The generator output must be equal to the load demand such that $\Delta F(s) = 0$.

Therefore, alternator output is expressed as $\Delta F(s)$.

The input to the alternator is $\Delta P_t(s)$ (= output of turbine).

The generator load model should operate only when $\Delta P_G(s) - \Delta P_D(s) = 0$.

Figure 2.11 shows the block diagram of generator load model.

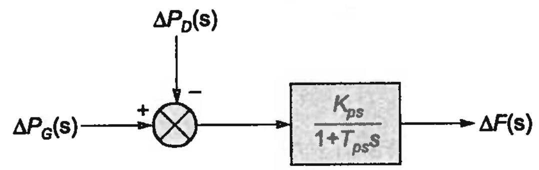


Figure-2.11 : *Block diagram of generator load model*

Complete Block Diagram Representation of Load Frequency Control of an Isolated Power System

By combining all the three block diagrams of speed governor, turbine and generators from Figure 2.9, 2.10 and 2.11 respectively a complete block diagram representation of an isolated power system can be obtained as shown in Figure 2.12 below.

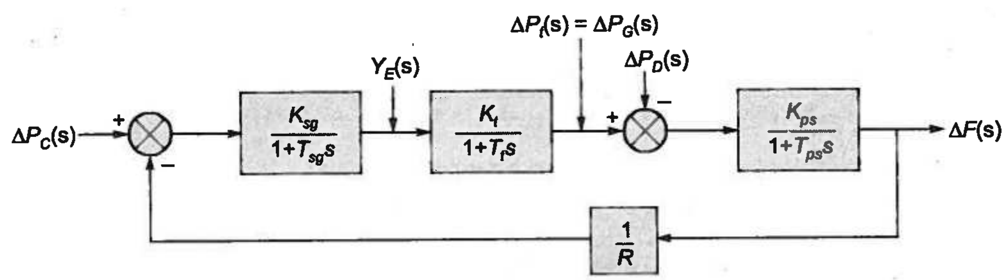


Figure-2.12 : *Block diagram model of load frequency control for an isolated power system*

Steady State Analysis

Steady state analysis deals with the small and gradual changes in the load demand. Steady state analysis is applicable for small step changes in the load demand. It gives the result in frequency domain.

Using block diagram of Figure 2.12, we have, change in frequency under steady state condition is

$$\Delta f = \Delta F(s)\big|_{\Delta P_D(s)=0} + \Delta F(s)\big|_{\Delta P_C(s)=0}$$

Case-I

Change in steady state frequency due to change in speed changer setting [$\Delta P_C(s)$] with change in load demand $\Delta P_D(s) = 0$.

When, $\Delta P_D(s) = 0$, the equivalent block diagram is reduced as shown below in Figure 2.13.

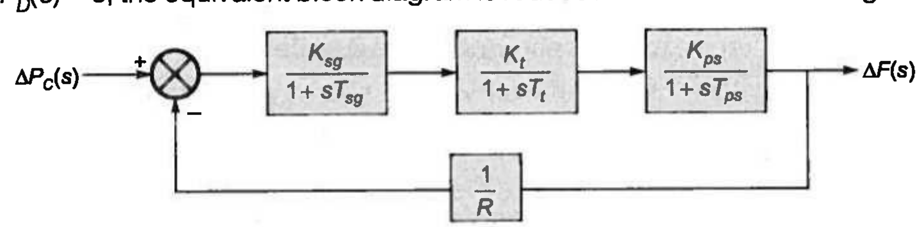


Figure-2.13 : *Block diagram of load frequency control for $\Delta P_D = 0$*

Here,

$$\frac{\Delta F(s)}{\Delta P_C(s)}\bigg|_{\Delta P_D(s)=0} = \frac{\left(\frac{K_{sg}}{1+sT_{sg}}\right)\left(\frac{K_t}{1+sT_t}\right)\left(\frac{K_{ps}}{1+sT_{ps}}\right)}{1+\left\{\left(\frac{K_{sg}}{1+sT_{sg}}\right)\left(\frac{K_t}{1+sT_t}\right)\left(\frac{K_{ps}}{1+sT_{ps}}\right)\right\}}$$

For step changes, $\Delta P_C(s) = \dfrac{\Delta P_C}{s}$

So,

$$\Delta F(s)\big|_{\Delta P_D(s)=0} = \frac{K_{sg}\cdot K_t \cdot K_{ps}}{(1+sT_{sg})(1+sT_t)(1+sT_{ps})+\left(\frac{K_{sg}\cdot K_t\cdot K_{ps}}{R}\right)}\left(\frac{\Delta P_C}{s}\right)$$

By readjusting the length of the linkage mechanism, $K_{sg}\,K_t = 1$

So,

$$\Delta F(s)\big|_{\Delta P_D(s)=0} = \frac{K_{ps}}{(1+sT_{sg})(1+sT_t)(1+sT_{ps})+\frac{K_{ps}}{R}}\left(\frac{\Delta P_C}{s}\right)$$

The steady state change in frequency is

$$\Delta f_{ss} = \underset{s\to 0}{Lt}\,[s\cdot \Delta F(s)]$$

$$\Delta f_{ss} = \underset{s\to 0}{Lt}\; s\left\{\frac{K_{ps}}{(1+sT_{sg})(1+sT_t)(1+sT_{ps})+\frac{K_{ps}}{R}}\right\}\left(\frac{\Delta P_C}{s}\right)$$

$$= \left(\frac{K_{ps}}{(1+0)(1+0)(1+0)+\frac{K_{ps}}{R}}\right)\cdot \Delta P_C = \left(\frac{K_{ps}}{1+\frac{K_{ps}}{R}}\right)\cdot \Delta P_C$$

The change in the load demand based on the change in frequency is

$$B = \left(\frac{\delta P_D}{\delta f}\right)\text{MW/Hz}$$

$$B_{pu} = \left(\frac{B}{P_{rated}}\right)\text{p.u.-MW/Hz} = \frac{1}{K_{ps}}$$

Now,

$$\Delta f_{ss} = \left\{\frac{1}{\frac{1}{K_{ps}}+\frac{1}{R}}\right\}\cdot \Delta P_C$$

$\therefore$

$$\Delta f_{ss} = \frac{1}{\left(B_{pu}+\frac{1}{R}\right)}\cdot \Delta P_C \qquad \text{...(Important result)} \qquad ...(1)$$

Case-II

Steady state change in frequency due to change in the load demand $\Delta P_D(s)$ with the change in the speed changer setting $\Delta P_C(s) = 0$.

When the speed governor fails to sense the change in the load demand it can't send the signal to the speed changer therefore, speed changer setting remains fixed i.e. $\Delta P_C(s) = 0$. This is called ***"free governor operation"***.

The block diagram of load frequency control for $\Delta P_C(s) = 0$ reduces to the block diagram as that shown in Figure 2.14.

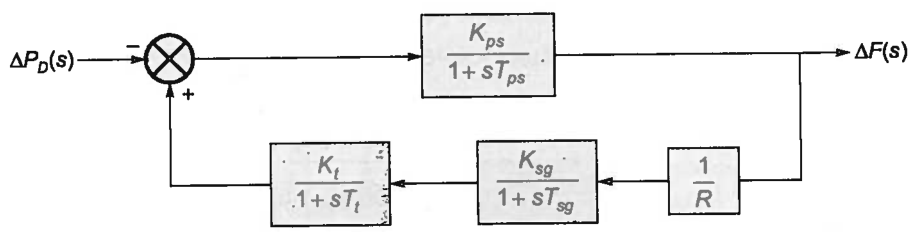


Figure-2.14: Equivalent block diagram of load frequency control for $\Delta P_C(s) = 0$

$$\left.\frac{\Delta F(s)}{\Delta P_D(s)}\right|_{\Delta P_C(s)=0} = \frac{-\left(\dfrac{K_{ps}}{1+sT_{ps}}\right)}{1-\left\{\left(\dfrac{K_{ps}}{1+sT_{sg}}\right)\left(\dfrac{K_t}{1+sT_t}\right)\left(\dfrac{K_{sg}}{1+sT_{sg}}\right)\left(-\dfrac{1}{R}\right)\right\}}$$

For step change in load demand,

$$\Delta P_D(s) = \frac{\Delta P_D}{s}$$

$$\therefore \quad \Delta F(s)\big|_{\Delta P_C(s)=0} = \left(\frac{-K_{ps}(1+sT_t)(1+sT_{sg})}{(1+sT_{sg})(1+sT_t)(1+sT_{ps})+\dfrac{(K_{sg}\cdot K_t)K_{ps}}{R}}\right)\cdot\left(\frac{\Delta P_D}{s}\right)$$

BY adjusting the length of linkage mechanism, $K_{sg}K_t = 1$

$$\therefore \quad \Delta F(s)\big|_{\Delta P_C(s)=0} = \left(\frac{-K_{ps}(1+sT_t)(1+sT_{sg})}{(1+sT_{sg})(1+sT_t)(1+sT_{ps})+\dfrac{K_{ps}}{R}}\right)\cdot\left(\frac{\Delta P_D}{s}\right)$$

Now,

$$\Delta f_{\text{steady-state}} = \underset{s\to 0}{Lt}\,[s\Delta F(s)]$$

$$= \underset{s\to 0}{Lt}\, s\left(\frac{-K_{ps}(1+sT_t)(1+sT_{sg})}{(1+sT_{sg})(1+sT_t)(1+sT_{ps})+\dfrac{K_{ps}}{R}}\right)\cdot\left(\frac{\Delta P_D}{s}\right)$$

$$= \frac{-K_{ps}(1+0)(1+0)}{(1+0)(1+0)(1+0)+\dfrac{K_{ps}}{R}}\cdot(\Delta P_D) = \frac{-K_{ps}}{\left(1+\dfrac{K_{ps}}{R}\right)}\cdot(\Delta P_D)$$

or,

$$\Delta f_{ss} = \frac{-K_{ps}}{\left(1+\dfrac{K_{ps}}{R}\right)}\cdot(\Delta P_D) = \left(\frac{-1}{\dfrac{1}{K_{ps}}+\dfrac{1}{R}}\right)\cdot\Delta P_D$$

or,

$$\Delta f_{ss} = \left(\frac{-1}{B_{pu}+\dfrac{1}{R}}\right)\cdot\Delta P_D \qquad \text{...(2)}$$

Combining equations (1) and (2), we get

$$\Delta f_{ss} = \Delta F(s)\big|_{\Delta P_D(s)=0} + \Delta F(s)\big|_{\Delta P_C(s)=0} = \left(\frac{1}{B_{pu}+\dfrac{1}{R}}\right)\cdot\Delta P_C + \left(\frac{-1}{B_{pu}+\dfrac{1}{R}}\right)\cdot\Delta P_D$$

or,

$$\Delta f_{\text{steady-state}} = \left(\frac{1}{B_{pu}+\dfrac{1}{R}}\right)\cdot(\Delta P_C - \Delta P_D) \qquad \text{...(Important result)} \qquad \text{...(3)}$$

Equation (3) is the final result to find the steady-state change in frequency which the change in ΔP_C or/and ΔP_D.

Example-2.6 **A 250 MW machine operates with a load of 125 MW. If the change in load be 1% for 1% change in frequency (scheduled frequency = 50 Hz) then, power system parameter B for load frequency control is given by**

(a) 0.5 pu-MW/Hz **(b) 0.01 pu-MW/Hz**
(c) 1.5 pu-MW/Hz **(d) 0.08 pu-MW/Hz**

Solution: (b)

$$\frac{\delta P_D}{\delta f} = \frac{1.25}{0.5} = 2.5 \text{ MW/Hz}$$

$$\therefore \quad B = \left(\frac{\delta P_D}{\delta f}\right)\Big/P_r = \frac{2.5}{250} = 0.01 \text{ pu-MW/Hz}$$

Example-2.7 **A power system having rated capacity of 1000 MW has a load demand of 500 MW. The percentage regulation is 5% and operating frequency is 50 Hz. The load demand decreases by 1 % due to decrease in the frequency by 1%. What is the change in the frequency when the load demand increases by 75 MW?**

Solution:

$P_{\text{rated}} = 1000$ MW, $P_D = 500$ MW, %regulation = 5%, $\Delta P_D = 75$ MW

For 1% decreases in load demand there is 1% decrease in frequency

So,
$$B = \frac{\delta P_D}{\delta f} = \frac{1\% \text{ of } 500 \text{ MW}}{1\% \text{ of } 50 \text{ Hz}} = \frac{500}{50} = 10 \text{ MW/Hz}$$

$$\therefore \quad B_{pu} = \frac{B}{P_{\text{rated}}} = \frac{10}{1000} = 0.01 \text{ pu-MW/Hz}$$

Now, percentage regulation = 5% of $f_{\text{scheduled}}$ or $R = \dfrac{5}{100}\times 50 = 2.5$ Hz/pu-MW

Now,
$$\Delta f = \left(\frac{1}{B_{pu}+\dfrac{1}{R}}\right)(\Delta P_C - \Delta P_D)$$

Since no-information is mentioned in question about ΔP_C. So, let $\Delta P_C = 0$

Then, $$\Delta f = \left(\frac{1}{B_{pu} + \frac{1}{R}}\right)(-\Delta P_D)$$

Now, $$\Delta P_{D(pu)} = \frac{75}{1000} = 0.075$$

∴ $$\Delta f = \left(\frac{1}{0.01 + \frac{1}{2.5}}\right)(-0.075) = -0.1829 \text{ Hz(pu)}$$

Hence, change in frequency is

$$\Delta f = -0.1829 \text{ Hz(pu)} = -9.146 \text{ Hz}$$

Important Expressions

1. Power transmitted from sending end to the receiving end is given by

$$P_W = \frac{|V_S||V_R|}{X_L}\sin\delta \quad \text{(Without series capacitor)}$$

$$P_{se} = \frac{|V_S||V_R|}{(X_L - X_C)}\sin\delta \quad \text{(With series capacitor)}$$

2. $$\frac{P_{se}}{P_W} = \left(\frac{X_L}{X_L - X_C}\right) = \frac{X_L}{X_L\left(1 + \frac{X_C}{X_L}\right)} = \frac{1}{(1-k_{se})} \quad (k_{se} = X_C/X_L = \text{degree of series compensation})$$

3. Change in steady-state frequency due to change in speed changer setting ($\Delta P_C(s)$ with change in load demand $\Delta P_D(s) = 0$ is given by $\left[\Delta f_{ss} = \frac{1}{\left(B_{pu} + \frac{1}{R}\right)} \cdot \delta P_C\right]$

where, $$B = \left(\frac{\partial P_D}{\partial f}\right)\text{MW/Hz and } B_{pu} = \left(\frac{B}{P_{\text{rated}}}\right)\text{pu-MW/Hz} = \frac{1}{k_{ps}}$$

4. Steady-state change in frequency due to change in the load demand $\Delta P_D(s)$ with the change in the speed changer setting $\Delta P_C(s) = 0$ is given by $\left[\Delta f_{ss} = \left(\frac{-1}{B_{pu} + \frac{1}{R}}\right) \cdot \Delta P_D\right]$

5. When ΔP_C and ΔP_D both are non-zero then, $\left[\Delta f_{ss} = \left(\frac{-1}{B_{pu} + \frac{1}{R}}\right)(\Delta P_C - \Delta P_D)\right]$

Student's Assignments 1

Q.1 Two 75 MW, 3-ϕ alternators are operating in parallel and are sharing equally a load of 150 MW corresponding to full load of each machine. The settings of the governors are such that the rise in speed from full load to no load is 2% in the first machine and 3% in the other machine. The speed regulation characteristics may be assumed to be straight line in both the cases. Determine the load on each machine when the total load is 100 MW.

Q.2 A 100 MVA synchronous generator operates on full load at a frequency of 50 Hz. The load is suddenly reduced to 50 MW. Due to time lag in governor system, the steam valve begins to close after 0.4 sec. Determine the change in frequency that occurs in this time.

Q.3 Describe the method of controlling
(*i*) the active power (kW) and
(*ii*) the reactive power (kVAR), between two inter connected power stations.

Q.4 A 3-ϕ, 400 kV transmission line has $Z_s = 300\ \Omega$
(*i*) Find surge impedance loading
(*ii*) If above transmission line is compensated with series capacitor and shunt reactor of 30% and 20% respectively, find the new surge impedance and new surge impedance loading.

Q.5 Considered previous problem. If this transmission line is connected to a generator which delivers power of 400 MW, find the load angle of generator
(*i*) without compensation
(*ii*) with compensation

Q.6 An area including two turbine generator units rated at 250 MVA and 450 MVA at 50 Hz frequency for which R_1 = 0.03 pu and R_2 = 0.04 pu based on their respective ratings. Each units carriers a 200 MVA steady-state load. The load on the system suddenly changes (or increased) by 150 MVA.
(*i*) Calculate β (Area frequency response characteristic) on a 750 MVA base.
(*ii*) Determine Δf on a 50 Hz base (in Hz).

Q.7 There are two generator in a power system. No load frequencies of the generator are 51.5 Hz and 51 Hz respectively and both are having droop constant of 1 Hz/MW. Total load in the system is 2.5 MW. Assuming that the generators are operating under their respective droop characteristics, the frequency of the power system in Hz in the steady-state is ______ .

Student's Assignments 1 Explanations

1. 60 MW, 40 MW

2. 1 Hz (Final frequency = 51 Hz)

4. **Solution:**

(*i*) $$SIL = \frac{V^2}{Z_S} = 533.33 \text{ MW}$$

(*ii*) $$Z_{S_1} = Z_S\sqrt{\frac{1-K_{se}}{1-K_{sh}}}$$
$$= 300\sqrt{\frac{1-0.3}{1-0.2}} = 300\sqrt{\frac{0.7}{0.8}}$$
$$Z_{S_1} = 280.62\ \Omega$$

Surge impedance loading,

$$(SIL)_1 = SIL\sqrt{\frac{1-K_{sh}}{1-K_{se}}} = 570.157 \text{ MW}$$

i.e. by using compensation, SIL is increased and $Z_{S_1} < Z_S$.

5. **Solution:**

Without compensation,

$$SIL = \frac{V^2}{Z_S} = \frac{(400)^2}{300} = 533.33 \text{ MW}$$

Delivered power,

$$P_R = 400 \text{ MW}$$

(*i*) $P_R = \frac{V_S V_R}{Z_S}\sin\delta_1$ ...(Without compensation)

$400 = (SIL)_1 \sin\delta_1$

$\Rightarrow \quad \delta_1 = \sin^{-1}\left(\frac{400}{533.33}\right) = 48.59°$

(*ii*) With compensation,

$P_R = (SIL)_2 \sin\delta_2$

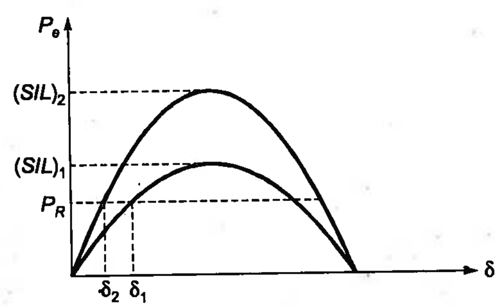
$(SIL)_2 = 570.157$ MW

...(Taken from previous problem)

$400 = (570.157)\sin\delta_2$

$\delta_2 = \sin^{-1}\left(\frac{400}{570.157}\right) = 44.55°$

$\delta_1 > \delta_2$ i.e. using compensation, load angle decreases and surge impedance loading increases. And also increases the stability of the system.



6. Solution:

(*i*) $R_{new} = R_{old} = \frac{S_{b(new)}}{S_{b(old)}}$

$R_{1_{new}} = 0.03 \times \frac{750}{250} = 0.09$ pu

$R_{2_{new}} = 0.04 \times \frac{750}{450} = 0.067$ pu

β = Area frequency response characteristic

$\beta = \sum_{k=1}^{n} \frac{1}{R_K}$

$= \frac{1}{R_{1_{new}}} + \frac{1}{R_{2_{new}}} = \frac{1}{0.09} + \frac{1}{0.067}$

$\beta = 26.11$ pu

(*ii*) Per unit increase in load $= \frac{150}{750} = 0.2$ pu

$\Delta P_{m(total)} = \Delta P_{ref(total)} - \beta\Delta f$

with $\Delta P_{ref(total)} = 0$ for steady-state condition.

$\Delta P_m = -\beta\Delta f \;\Rightarrow\; \Delta f = -\frac{1}{\beta}\Delta P_m$

$\Delta f = -\frac{1}{26.11}(0.2) = -7.66 \times 10^{-3}$ pu

$\Delta f = -7.66 \times 10^{-3} \times 50$

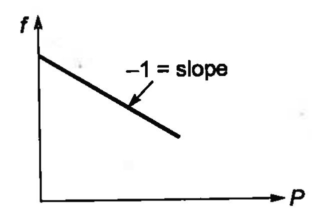
$= -0.383$ Hz

7. Solution:

Given that, two generator in a power system has no load frequency of 51.5 and 51 Hz respectively. Droop constant = 1 Hz/MW.

i.e. slope $= \frac{\Delta f}{\Delta P}$

Total load = 2.5 MW



For generator '1',

$f = -P_1 + 51.5$ (Use $y = mx + C$)

For Generator '2' $f = -P_2 + 51$

$-P_1 + 51.5 = -P_2 + 51$

$P_1 - P_2 = 0.5$ ...(*i*)

$P_1 + P_2 = 2.5$ ...(*ii*)

Solving equation (*i*) and (*ii*),

$P_1 = \frac{3}{2} = 1.5$

and $P_2 = 1$

$f = -1.5 + 51.5 = 50$ Hz

i.e. steady-state frequency of the power system,

$f = 50$ Hz

Student's Assignments 2

Q.1 A synchronous phase modifier supplies
(a) both active and reactive powers
(b) both lagging and leading reactive power
(c) inductive reactive power only
(d) active power only

Q.2 Full load compensation in a line requires
(a) shunt capacitors (b) series capacitors
(c) transformers (d) shunt reactors

Q.3 For a good voltage profile under no load condition, a long line needs
(a) shunt capacitor at receiving end
(b) shunt reactors at the receiving end
(c) shunt resistance at receiving end
(d) none of the above

Q.4 Over excited synchronous phase modifier
(a) draws a lagging current
(b) draws a leading current
(c) supplies a leading current
(d) supplies a lagging current

Q.5 The reactive power transfer over a line mainly depends on
(a) power angle δ (b) $|V_S| - |V_R|$
(c) V_S (d) V_R

Q.6 To increase the transmission capability of a high voltage long line
(a) the resistance can be increased
(b) the resistance can be decreased
(c) the series reactance can be reduced
(d) the shunt admittance can be reduced

Q.7 A booster is inserted in the circuit to
(a) reduce current
(b) increase current
(c) reduce voltage drop
(d) compensate for voltage drop

Q.8 The injection of VARs is required to
(a) compensate for line losses
(b) get a good voltage profile
(c) increase the voltage at the receiving end
(d) all of the above

Q.9 For a system used for load frequency control which of the following option is true?
(a) $k_{sg} \times k_T$ is nearly equal to 1
(b) $k_{sg} \times k_T$ is nearly equal to zero
(c) $k_{sg} \times k_T$ is equal to ∞
(d) $k_{sg} \times k_T$ is equal to any value

Q.10 The change in reactive power at a bus have a great effect on the voltage magnitude
(a) of that bus (b) of distant busses
(c) of all the busses (d) none of these

Direction of Questions (11 to 13):

Each of the following question consists of two statements, one labelled the **'Assertion (A)'** and the other labelled the **'Reason (R)'**. Examine the two statements carefully and decide if the Assertion (A) and Reason (R) are individually true and if so whether the Reason (R) is correct explanation of the Assertion (A). Select your answers to these questions using the codes given below:

Codes:
(a) Both A and R are true and R is the correct explanation of A.
(b) Both A and R are true but R is not a correct explanation of A.
(c) A is true but R is false.
(d) A is false but R is true.

Q.11 Assertion (A): Control of reactive power is essential for maintaining a desired voltage profile.
Reason (R): The reactive power transferred over a transmission line depends on load or power angle.

Q.12 Assertion (A): Synchronous condensers are used for pf improvement only when kVAR requirement exceeds 5000.
Reason (R): Initial as well as operating costs of synchronous condensers are much higher than those of static capacitors and do not justify their installation for low ratings.

Q.13 Assertion (A): The best location for the pf correction equipment to be installed is the generating end.
Reason (R): Generators are relieved of carrying excessive current due to poor power factor.

Q.14 A capacitor bank is supplying 50 MVAR at a voltage of 132 kV. If the voltage is rised by 20% and frequency drops by 5%, what is the reactive power supplied by capacitor bank?

(a) 68.4 MVAR (b) 75.6 MVAR
(c) 33.6 MVAR (d) None of these

Q.15 Transmission line has an electrical line length of 9°. What is the length in km if it is a 100 Hz system?
(a) 100 km (b) 50 km
(c) 125 km (d) 75 km

Q.16 A transmission line has length of 500 km and operating at frequency of 60 Hz has V_s = 1 pu. Find the receiving end voltage V_R at no load
(a) 1.8 pu (b) 1.1 pu
(c) 1.4 pu (d) 1.3 pu

Q.17 The load of 20 MVA, 0.8 pf (lag) is connected at a substation. If a load of 4 MW, 0.95 pf (lead) is shaded, the remaining load connected will be
(a) 12 MVA, 0.85 lag
(b) 16 MVA, 0.96 lag
(c) 14 MVA, 0.74 lead
(d) 17.9 MVA, 0.67 lag

Q.18 Two system areas are connected by a tie-line.
Area 1 : R_1 = 0.03 pu, B_1 = 0.6 pu,
Base MVA = 1000
Area 2 : R_2 = 0.05 pu, B_2 = 0.9 pu,
Base MVA = 1000
A change of 20 MW occur in Area 1.
What is the steady state frequency?
(Take, f = 50 Hz)
(a) 48.721 Hz (b) 51.278 Hz
(c) 49.817 Hz (d) 50.18 Hz

Answer Key:

1. (b)	**2.** (a)	**3.** (b)	**4.** (b)	**5.** (b)
6. (c)	**7.** (d)	**8.** (b)	**9.** (a)	**10.** (a)
11. (c)	**12.** (a)	**13.** (d)	**14.** (a)	**15.** (d)
16. (c)	**17.** (d)	**18.** (c)		

Student's Assignments 2 Explanations

1. (b)
A synchronous phase modifier is a synchronous motor operating under no load condition under wide variation of excitation. Depending upon nature of the load, it may be over-excited (leading pf operation) or under-excited (lagging pf operation).

2. (a)
Shunt capacitors are used at the receiving end of the transmission line (across loads) to improve the power factor of the system.

3. (b)
Under no load condition for a long line (and medium line) receiving end voltage becomes greater than the sending end voltage (Ferranti effect). Hence, shunt reactor (inductor) is needed to improve the voltage profile which is connected in parallel across the load.

5. (b)
The reactive power delivered by the line for a fixed sending end and receiving end voltage $|V_S|$ and $|V_R|$ respectively is given by

$$Q_R = \frac{|V_R|}{X}\left[|V_S| - |V_R|\right]$$

Hence, $Q_R \; \alpha \; \alpha\left[|V_S| - |V_R|\right]$

6. (c)
The power transmitted from sending to the receiving end is given by

$$P = \frac{|V_S| - |V_R|}{X}\sin\delta$$

(X = Net reactance of the line)

Hence, $P \; \alpha \; \frac{1}{X}$

Therefore, by reducing series reactance (X), power transmission capability can be increased.

9. (a)
k_{sg} = Gain constant of speed governor
k_T = Gain constant of turbine
By readjusting the length of the linkage mechanism, $k_{sg} \times k_T = 1$

13. (d)
The best location for the pf correction equipment to be installed is the receiving end (load end). Hence, assertion is false.

14. (a)

$$Q \propto f V^2$$

$$\frac{Q_2}{Q_1} = \frac{f_2 V_2^2}{f_1 V_1^2} \qquad Q_2 = 68.4 \text{ MVAR}$$

15. (d)

$$\beta = \frac{2\pi}{\lambda} \text{ and } v = \lambda f$$

$$\beta = \frac{2\pi f}{v}, \; v = \text{velocity of propagation}$$

$$= 3 \times 10^8 \text{ m/s}$$

βl = electrical line length

$$= 9° = \frac{9 \times \pi}{180} \text{ rad}$$

$$l = \frac{9 \times \pi}{180 \times \beta} = \frac{9 \times \pi}{180} \times \frac{3 \times 10^8}{2\pi \times 100}$$

$$l = 75 \text{ km}$$

∴ The length is 75 km.

16. (c)

$$\Delta V_R = \frac{4\pi^2 l^2 f^2 V_S^2}{(v)^2} = 0.4 \text{ pu}$$

$$v = 3 \times 10^8 \text{ m/s}$$

$$V_R = V_S + \Delta V_R$$

18. (c)

$$\Delta f = -\frac{\Delta P_D}{\frac{1}{R_1} + \frac{1}{R_2} + B_1 + B_2}$$