POWER SYSTEM OPERATION AND CONTROL (15EE81 / 17EE81)

MODULE – 03

MODULE – 03:

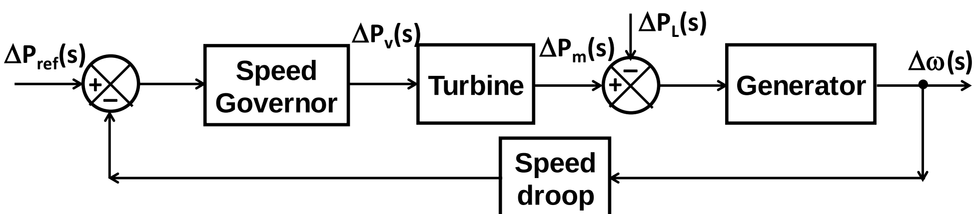
- **AUTOMATIC GENERATION CONTROL (Continued) (AGC)**
- **AUTOMATIC GENERATION CONTROL IN INTER-CONNECTED POWER SYSTEM**

Prepared by A. DHAMODARAN, Asst. Prof., SAPTHAGIRI COLLEGE OF ENGG., BANGALORE.

AUTOMATIC GENERATION CONTROL (Continued):

MATHEMATICAL MODEL OF ALFC :

- **Let us derive a mathematical model for ALFC.**
- **This can be achieved by developing transfer function models for each element in the ALFC loop.**
- **The functional diagram of the ALFC loop is as shown.**



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AUTOMATIC GENERATION CONTROL (Continued):

MATHEMATICAL MODEL OF ALFC :

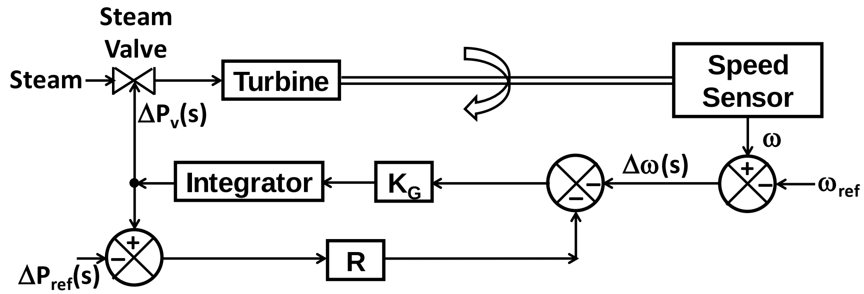
- **The inputs to the ALFC loop are**
  - **The output power reference ΔP_{ref} and**
  - **The change in active power of the load ΔP_L.**
- **The mathematical model of ALFC can be obtained by deriving mathematical model of each of the following blocks in ALFC loop.**

  1) Speed Governor
  2) Generator
  3) Load
  4) Generator + Load
  5) Turbine

Prepared by A. DHAMODARAN, Asst. Prof., SAPTHAGIRI COLLEGE OF ENGG., BANGALORE.

1) GOVERNOR MODEL:

- The block diagram of the speed governor with a speed droop mechanism is as shown.



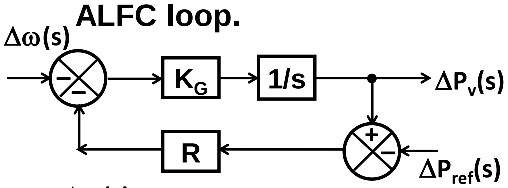
- Here, output of speed sensor ‘ω’ is compared with reference speed ‘ω_{ref}’ to produce speed error ‘Δω’.

1) GOVERNOR MODEL:

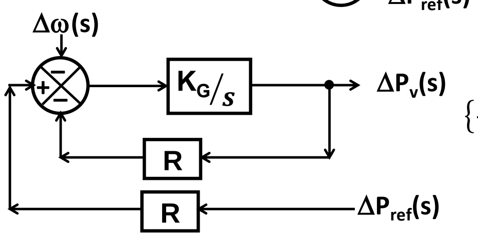
- By adjusting reference set point for power output on the unit, the output power can be varied while holding system frequency close to the standard frequency.
- The error due to difference between actual power output and a reference set point of power output is fed back through speed regulation R.
- Let us derive the transfer functional model of the speed governor.
- Using block diagram reduction techniques, let us simplify the functional block diagram as follows.

1) GOVERNOR MODEL:

- Let us consider the bottom loop of functional block diagram of ALFC loop.

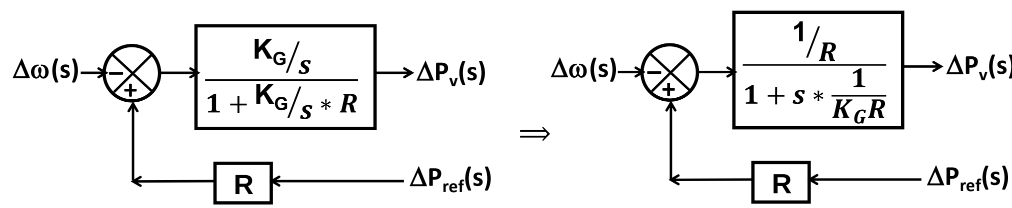


$$-\{[\Delta P_V(s) - \Delta P_{ref}(s)] * R + \Delta\omega(s)\} * K_G * {}^{1}/_{s} = \Delta P_V(s)$$



$$\{-\Delta P_V(s) * R + \Delta P_{ref}(s) * R - \Delta\omega(s)\} * K_G * {}^{1}/_{s} = \Delta P_V(s)$$

1) GOVERNOR MODEL:

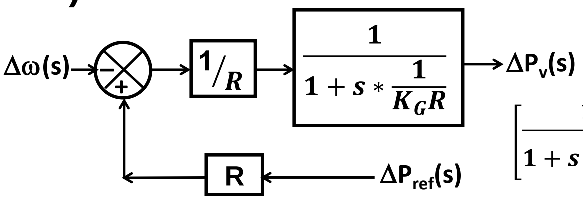


$$\left[\frac{K_G/s}{1 + K_G/s * R}\right] * \left(-\Delta\omega(s) + \Delta P_{ref}(s) * R\right) = \Delta P_V(s)$$

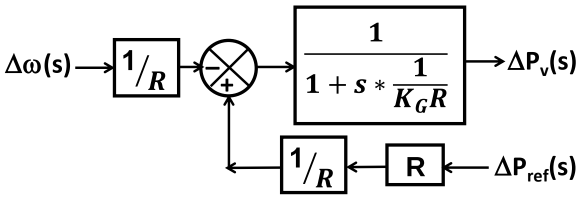
$$\Rightarrow \left[\frac{1/R}{1 + s * \frac{1}{K_G R}}\right] * \left(-\Delta\omega(s) + \Delta P_{ref}(s) * R\right) = \Delta P_V(s)$$

[Multiplying both sides by $\frac{s}{K_G * R}$]

1) GOVERNOR MODEL:



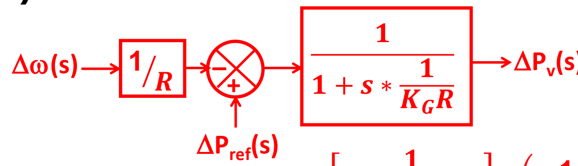
$$\left[\frac{1}{1+s*\frac{1}{K_G R}}\right] * {}^{1}/_{R} * \left(-\Delta\omega(s) + \Delta P_{ref}(s) * R\right) = \Delta P_V(s)$$



[Moving a summing block away the block (1/R)]

$$\left[\frac{1}{1+s*\frac{1}{K_G R}}\right] * \left(-{}^{1}/_{R} * \Delta\omega(s) + {}^{1}/_{R} * \Delta P_{ref}(s) * R\right) = \Delta P_V(s)$$

1) GOVERNOR MODEL:



$$\left[\frac{1}{1+s*\frac{1}{K_G R}}\right] * \left(-{}^{1}/_{R} * \Delta\omega(s) + \Delta P_{ref}(s)\right) = \Delta P_V(s)$$

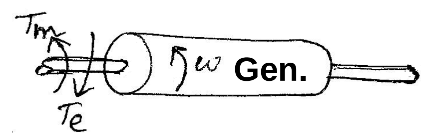
- The above simplified transfer functional block diagram is the mathematical model of speed governor with hydraulic amplifier.
- Let the time constant of speed governor be T_G.
- It can be expressed as $T_G = \frac{1}{K_G * R}$.
- It depends on speed regulation R and gain of hydraulic amplifier K_G.

2) GENERATOR MODEL:

- Let us consider the generator in the ALFC loop.
- There are two torques acting on the generator;
  - Shaft torque which is due to prime mover
  - Electromagnetic torque which is developed at the generator, internally, neglecting losses.
- The shaft torque tends to accelerate the generator in the direction of rotation of the shaft.
- The electromagnetic torque in the tends to accelerate the generator in the opposite direction of rotation of the shaft.

2) GENERATOR MODEL:

- The net accelerating torque is given by, $T_a = T_m - T_e$---------- (1)



- Applying Newton's laws of motion for rotary motion,

$T = I * \alpha$ -------------------------- (2)

Where, $T = T_a$ = Total accelerating torque or net torque.

I = Moment of Inertia

α = Angular acceleration $= \frac{d^2\theta_m}{dt^2}$ --------------- (3)

$\theta_m =$ rotor angle

From equations (1), (2) and (3), $I * \frac{d^2\theta_m}{dt^2} = T_m - T_e$ -------- (4)

2) GENERATOR MODEL:

Let the rotor angle θ_m be measured in radians.

Let the synchronous speed be ω_{sm} and measured in rad/sec.

The rotor angle θ_m is measured with respect to a synchronously rotating reference axis ω_{sm}.

Hence, the difference between the rotor speed and synchronous speed is,

$$\delta_m = \theta_m - \omega_{sm}\, t \text{ -------------------- (5)}$$

Where, δ_m is angular displacement called torque angle or load angle in rad.

From eqn. (5), $\frac{d\delta_m}{dt} = -\omega_{sm} + \frac{d\theta_m}{dt}$ **and** $\frac{d^2\delta_m}{dt^2} = \frac{d^2\theta_m}{dt^2}$ **------- (6)**

2) GENERATOR MODEL:

Substituting (6) in (4), $I * \frac{d^2\delta_m}{dt^2} = T_m - T_e$ **Nm**

Multiplying both sides by ω_m,

$$I * \omega_m * \frac{d^2\delta_m}{dt^2} = \omega_m\,(T_m - T_e) \text{ ------------------------- (7)}$$

Where, $I\,\omega_m = M$ = Angular momentum or inertia constant.

$\omega_m\, T_m = P_m$ = Mechanical power developed at the shaft.

$\omega_m\, T_e = P_e$ = Electrical power output.

Hence, equation (7) can be written as,

$$M \frac{d^2\delta_m}{dt^2} = P_m - P_e = P_a \text{ W -------------------------- (8)}$$

2) GENERATOR MODEL:

- **The angular momentum M depends on angular speed of rotor ω_m.**
- **However, since the speed deviation is limited, the angular momentum M can be assumed to be a constant.**
- **Values of M varies over a wide range depending on the rating and type of generator.**
- **Let us define another constant H which is used to specify the energy stored in the machine.**
- **It is also called as inertia constant.**
- **It is defined as the ratio of kinetic energy stored in the machine at synchronous speed to the machine rating.**

2) GENERATOR MODEL:

$$\therefore\ H = \frac{\text{Kinetic energy stored at synchronous speed in MJ}}{\text{Machine rating in MVA}}\ MJ/MVA$$

The inertia constants M and H are related as,

$$M = \frac{2GH}{\omega_{sm}} \text{ MJ–Sec./mech. Rad --------------- (9)}$$

where, G – Machine rating in MVA.

Substituting (9) in (8), $\frac{2GH}{\omega_{sm}} * \frac{d^2\delta_m}{dt^2} = P_m - P_e$ **W ---------- (10)**

Where, P_m and P_e are in W. Let G be the base power and angular parameters be expressed in electrical radians.

Hence, equation (10) in pu, $\frac{2H}{\omega_s} * \frac{d^2\delta_m}{dt^2} = P_m - P_e$ **pu ------------ (11)**

Where, P_m and P_e are in pu. Equation (11) is called as swing equation.

ω_s is synchronous speed in electrical rad/sec. $\omega_s = \frac{P}{2}\,\omega_{sm}$

2) GENERATOR MODEL:

Let us assume there is a small deviation in variables in swing equation.

$$\frac{2H}{\omega_s} * \frac{d^2\Delta\delta_m}{dt^2} = \Delta P_m - \Delta P_e \text{ -------------------------- (12)}$$

Let ω be the angular velocity of the motor.

$$\therefore \quad \omega = \frac{d\delta}{dt} \qquad \Longrightarrow \qquad \Delta\omega = \frac{d\Delta\delta}{dt}$$

Further, $\frac{d\Delta\omega}{dt} = \frac{d^2\Delta\delta}{dt^2}$ ------------------- (13)

Substituting (13) in (12), $\frac{2H}{\omega_s} * \frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e$

Let ω_s be the basic angular speed.

$$\therefore 2H * \frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e \text{ pu}$$

$$\Longrightarrow \frac{d\Delta\omega}{dt} = \frac{1}{2H}\left[\Delta P_m - \Delta P_e\right] \text{ -------------------------------------- (14)}$$

2) GENERATOR MODEL:

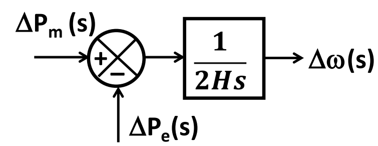
Taking laplace transforms on both sides of equation (14),

$$s\,\Delta\omega(s) = \frac{1}{2H}\left[\Delta P_m(s) - \Delta P_e(s)\right]$$

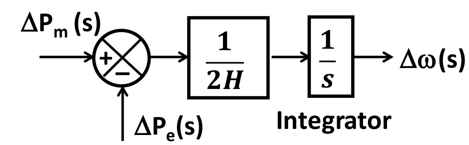
$$\Longrightarrow \Delta\omega(s) = \frac{1}{2Hs}\left[\Delta P_m(s) - \Delta P_e(s)\right] \text{ ------------------------ (15)}$$

The above equation (15) gives the transfer function model of generator.

From equation (15), let us write the transfer function model as shown.



OR



3) LOAD MODEL:

- Some loads exhibit variation in active power drawn with respect to frequency variations.
- This is expressed by a parameter called Damping Constant.
- Damping Constant is defined as the ratio of a change in active power drawn by the load which is dependent on frequency to the change in frequency.
- It is expressed as "D".

$\therefore$ Load Damping Constant $D = \frac{(\Delta P_L)_{freq}}{\Delta\omega}$ -------------- (1)

Where, $(\Delta P_L)_{freq}$ is the frequency dependent load change in MW

$\Delta\omega$ is the change in frequency in Hz.

3) LOAD MODEL:

- By neglecting losses, the change in electrical power output of a generator is equal to the change in load.

$$\therefore \quad \Delta P_e = [\Delta P_L]_{Total} \qquad \Longrightarrow \qquad \Delta P_e = \left[\Delta P_L + (\Delta P_L)_{freq}\right] \text{ --------- (2)}$$

Where, ΔP_L is the non-frequency sensitive load change.

$(\Delta P_L)_{freq}$ is the frequency sensitive load change.

From (1) and (2), $\Delta P_e = \Delta P_L + D\,\Delta\omega$ ------------------ (3)

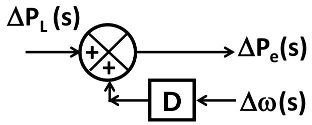
Taking laplace transforms on both sides,

$$\Delta P_e(s) = \Delta P_L(s) + D\,\Delta\omega(s) \text{ -------------------- (4)}$$

Equation (4) gives mathematical model for the load.

3) LOAD MODEL:

- A transfer functional model of the load can be derived from equation (4) as shown.



4) GENERATOR + LOAD MODEL:

- Let us derive a mathematical model for a generator and load together by combining their individual models.
- The mathematical model of generator is,

$$\Delta\omega(s) = \frac{1}{2Hs}[\Delta P_m(s) - \Delta P_e(s)] \text{ ------------------- (1)}$$

- The mathematical model of load is,

$$\Delta P_e(s) = \Delta P_L(s) + D\,\Delta\omega(s) \text{ ------------------- (2)}$$

4) GENERATOR + LOAD MODEL:

- Substituting equation (2) in equation (1) gives,

$$\Delta\omega(s) = \frac{1}{2Hs}[\Delta P_m(s) - \Delta P_e(s)] = \frac{1}{2Hs}[\Delta P_m(s) - \Delta P_L(s) - D\,\Delta\omega(s)] \text{ ----- (3)}$$

$$\Rightarrow \quad \left[1 + \frac{D}{2Hs}\right]\Delta\omega(s) = \frac{1}{2Hs}[\Delta P_m(s) - \Delta P_L(s)]$$

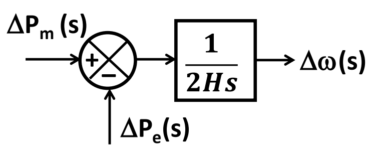
$$\Rightarrow \quad \left[\frac{2Hs + D}{2Hs}\right]\Delta\omega(s) = \frac{1}{2Hs}[\Delta P_m(s) - \Delta P_L(s)]$$

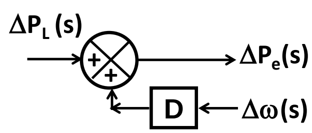
$$\Rightarrow \quad [2Hs + D]\,\Delta\omega(s) = [\Delta P_m(s) - \Delta P_L(s)]$$

$$\Rightarrow \quad \Delta\omega(s) = \frac{1}{2Hs + D}[\Delta P_m(s) - \Delta P_L(s)] \text{ ------------------- (4)}$$

The above equations (3) and (4) gives mathematical model of combined Generator and Load. The transfer functional model of them can be derived from (3) or (4) as shown.

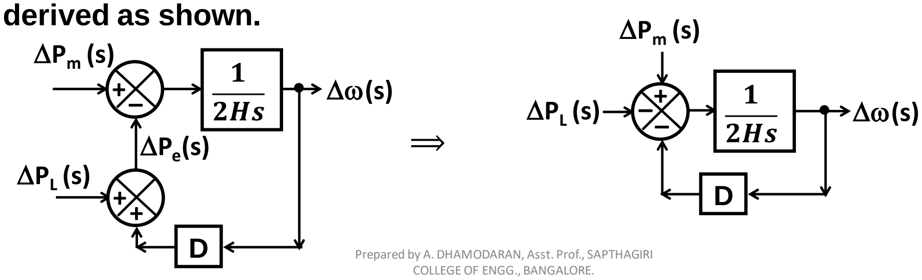
4) GENERATOR + LOAD MODEL:



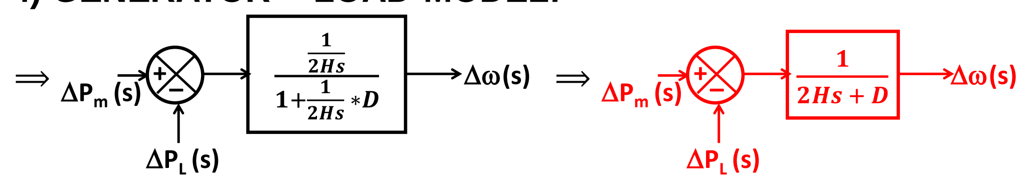


Transfer function model of generator   Transfer function model of Load

The combined transfer function model of generator and load can be derived as shown.



4) GENERATOR + LOAD MODEL:



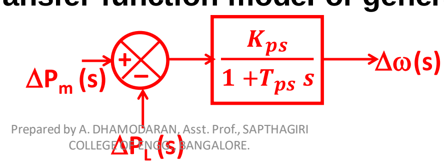
This is the combined transfer function model of generator and load.

Let $F(s) = \frac{1}{2Hs+D} = \frac{1/D}{1+(2H/D)s} = \frac{K_{ps}}{1+T_{ps}\,s}$

Where, $K_{ps} = 1/D$ is power system gain.

$T_{ps} = 2H/D$ is power system time constant.

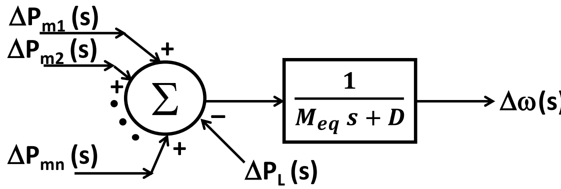
Hence, the combined transfer function model of generator and load can be modified as,



COMPOSITE GENERATOR + LOAD MODEL:

- While building the complete ALFC model of the power system, the collective performance of all generators connected is to be considered.
- All the generators connected to the system are assumed to swing coherently.
- Hence, it can be represented as a single equivalent generator with an equivalent inertia constant M_{eq} driven by combined mechanical outputs of the turbines connected to the generators.
- Let there be 'n' no. of generators in a power system.
- The block diagram of the composite generator + load model is as shown.

COMPOSITE GENERATOR + LOAD MODEL:



- The effects of all frequency dependent loads are lumped into a single damping constant D.

The inertia constants M and H are related as,

$$M = \frac{2GH}{\omega_{sm}} \text{ MJ–Sec./mech. Rad}$$

Let G be the base power and ω_{sm} be the base angular speed.

Hence inertia constants M and H are related in pu as,

M = 2 H pu

Hence, $M_{eq} = 2\,H_{eq} = M_1 + M_2 + M_3 + \ldots + M_n = 2*(H_1 + H_2 + H_3 + \ldots + H_n)$

Now, the speed of the complete equivalent system determines the frequency of the complete system.

COMPOSITE GENERATOR + LOAD MODEL:

- For this power system with 'n' generators, the steady state frequency deviation after a change in load ΔP_L is determined by combined characteristics of speed regulation and damping constant D.

  Speed regulation $R = \frac{\Delta f}{\Delta P}$ Damping constant $D = \frac{\Delta P_L}{\Delta f}$

- Since, both the characteristics are inverse to each other, R and D are combined as, $\frac{1}{R} + D$
- Hence, the steady state frequency deviation after a change in load ΔP_L is determined by,

$$\Delta f_{ss} = \frac{-\Delta P_L}{\frac{1}{R_{eq}} + D} = \frac{-\Delta P_L}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \cdots \frac{1}{R_n}\right) + D} \text{ -------------------- (1)}$$

Here speed droop R is taken as positive value as the equation (1) contains negative sign.

COMPOSITE GENERATOR + LOAD MODEL:

- let us define the composite frequency response of the system as,

$$\beta = \frac{-\Delta P_L}{\Delta f_{ss}} = \frac{1}{R_{eq}} + D \text{ --------------------- (2)}$$

- Here, β is also referred as stiffness of the system or frequency bias characteristics.
- The unit of β is MW / Hz.
- Let us assume that there is an increase of load by ΔP_L at a nominal frequency.
- Then, there will be an increase in generation by ΔP_G and the reduction in frequency by Δf.
- This will cause a reduction of frequency dependent loads by ΔP_D.

$$\therefore \quad \Delta P_L = \Delta P_G - \Delta P_D \text{ ------------------------------ (3)}$$

COMPOSITE GENERATOR + LOAD MODEL:

- The increase in power output of the generator depends on the speed regulation of its speed governor.

  i.e., $R = \frac{-\Delta f}{\Delta P_G}$ $\quad \Rightarrow \Delta P_G = \frac{-\Delta f}{R}$ --------------- (4)

- Since, the load damping constant is, $D = \frac{(\Delta P_L)_{freq}}{\Delta \omega}$, the composite load damping constant is, $D = \frac{\Delta P_D}{\Delta f}$ $\quad \Rightarrow \quad \Delta P_D = \mathrm{D} * \Delta f$ --------- (5)

- Substituting eqn. (4) and eqn. (5) in eqn. (3),

$$\Delta P_L = \Delta P_G - \Delta P_D = \frac{-\Delta f}{R} - \mathrm{D} * \Delta f = \Delta f\left[\frac{-1}{R} - D\right]$$

$$\Rightarrow \Delta f = \frac{-\Delta P_L}{\left[\frac{1}{R} + D\right]}$$ ------------------ (6)

- This equation is identical to equation (1), steady state frequency deviation in composite generator + Load model.

PROBLEMS:

1) Consider an isolated generator of 500 MVA, M = 8 puMW/puHz/sec. on the machine base. The unit is supplying a load of 400 MVA. The load changes by 1.5% for a 1% change in frequency. Draw the block diagram for the equivalent generator + load system. For an increase of 10 MVA in the load, determine the steady state frequency deviation and frequency deviation characteristics.

Sol.: Given, G = 500 MVA, M = 8 puMW/puHz/sec. Load P_L = 400 MVA.

M is defined on base power G=500 MVA.

Given that, the load changes (ΔP_L) by 1.5% for a 1% change in frequency (Δf).

$\therefore$ Load damping constant $D = \frac{(\Delta P_L)_{freq}}{\Delta f} = \frac{1.5}{1} = 1.5\,pu$ on a load base of 400 MVA

PROBLEMS:

Let us consider a common base power of 1000 MW and base frequency of 50 Hz.

$\therefore$ Inertia constant M = 8 puMW/puHz/sec on machine base of 500 MVA

$\Rightarrow$ M = 8*500 MW / puHz/sec = 4000 MW/ puHz/sec.

For a common base of 1000 MW,

M = 4000 / 1000 puMW/puHz/sec. = 4 puMW/puHz/sec.

Similarly, Damping constant D = 1.5 puMW/puHz

D= 1.5 * 400 MW/puHz = 600 MW/pu Hz

For a common base of 1000 MW, D = 600/1000 puMW/pu Hz

$\therefore$ D = 0.6 puMW/pu Hz.

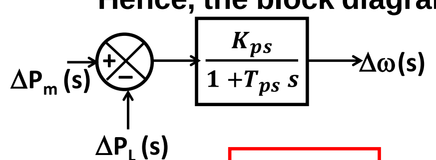
PROBLEMS:

Inertia constants M and H are related as, $M = \frac{2GH}{\omega_{sm}}$ MJ–sec./mech. rad

In pu, with a base power of G and base synchronous speed of ω_{sm},

$M = 2H$

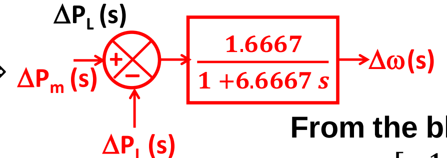
Hence, the block diagram of Generator + Load system is,



Where, $K_{ps} = {}^{1}/_{D} = {}^{1}/_{0.6} = 1.6667$

$T_{ps} = {}^{2H}/_{D} = {}^{M}/_{D} = {}^{4}/_{0.6} = 6.6667\ sec$

$\Rightarrow$



From the block diagram,

$$\Delta\omega(s) = \left[\frac{1.6667}{1+6.6667\,s}\right] * (\Delta P_m(s) - \Delta P_L(s))$$ ---------- (1)

PROBLEMS:

Given that the load is increased by 10 MVA, i.e. ΔP_L = 10 MVA = 0.01 pu (common base power of 1000 MW)

Hence, $\Delta P_L(s) = \frac{0.01}{s}$ ------------------ (2)

- Since, it is given, only the increase in load, it is implied that mechanical power output remains constant.

i.e., $\Delta P_m = 0$, and hence, $\Delta P_m(s) = 0$ ---------------- (3)

Substituting (2) and (3) in (1) gives,

$$\Delta\omega(s) = \left[\frac{1.6667}{1 + 6.6667\, s}\right] * (\Delta P_m(s) - \Delta P_L(s)) = \left[\frac{1.6667}{1 + 6.6667\, s}\right] * \left(0 - \frac{0.01}{s}\right)$$

$$\Rightarrow \Delta\omega(s) = \frac{-0.01}{s} * \left[\frac{1.6667}{1 + 6.6667\, s}\right] = \frac{-0.01}{s} * \left[\frac{0.25}{s + 0.15}\right] = \frac{-2.5 * 10^{-3}}{s\,(s + 0.15)}$$

PROBLEMS:

- Using partial fraction, $\Delta\omega(s) = \frac{-2.5*10^{-3}}{s\,(s+0.15)} = \frac{A}{s} + \frac{B}{s+0.15} = \left[\frac{-0.01667}{s} + \frac{0.01667}{s+0.15}\right]$
- Taking inverse laplace transform on both sides,

$$\Delta\omega(t) = -0.01667 + 0.01667\, e^{-0.15t}\ pu \text{ -------------- (4)}$$

- Let us assume initially the system is running at nominal frequency of 50 Hz, i.e., f_0 = 50 Hz = 1 pu.
- At steady state, i.e., t = ∞, $\Delta\omega(\infty)$ = – 0.01667 pu

Hence, steady state frequency deviation $\Delta\omega_{ss}$ = – 0.01667 pu

But, $\Delta\omega_{ss} = f_1 - f_0$ where, f_1 is the steady state frequency.

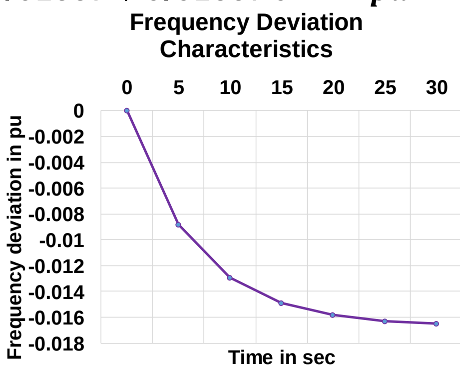
$$\Rightarrow f_1 = \Delta\omega_{ss} + f_0 = -0.01667 + 1 = 0.9833\ pu = 49.1665\ Hz$$

∴ Steady state frequency = 49.1665 Hz.

PROBLEMS:

- Let us plot the frequency deviation characteristics using equation (4) at various time t as shown.
- Equation (4) is, $\Delta\omega(t) = -0.01667 + 0.01667\, e^{-0.15t}\ pu$

Time (t) sec	Frequency deviation Δω (pu)
0	0
5	– 0.0088
10	– 0.01295
15	– 0.01491
20	– 0.01584
25	– 0.01628
30	– 0.01648



PROBLEMS:

2) A power system consists of four identical generators of 100 MVA capacity each, feeding a load of 250 MW. The inertia constant H = 5 pu for each machine on its own base. The load varies 1.2 % for a 1% change in frequency. If there is a drop of 10 MW of load, determine the speed deviation in pu and the new frequency at steady state. Plot the frequency deviation (pu) Vs time (sec.) curve.

Sol.: Given, $G_1 = G_2 = G_3 = G_4$ = 100 MVA = G, Total Load P_L = 250 MW.

Let base power be 100 MVA. ∴ G = 1 pu

$H_1 = H_2 = H_3 = H_4$ = 5 pu = H (on generator base of 100 MVA)

∴ $H_{eq} = H_1 + H_2 + H_3 + H_4$ = 20 pu ⇒ $M_{eq} = 2\, H_{eq}$ = 2 * 20 = 40 pu

Change in load, ΔP_L = – 10 MW = – 0.1 pu

Total Load after the change = 250 – 10 = 240 MW

PROBLEMS:

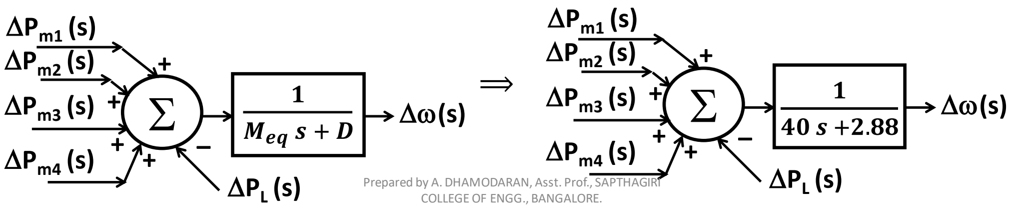
Given that, the load changes (ΔP_L) by 1.2% for a 1% change in frequency (Δf).

$\therefore$ **Damping constant** $D = \frac{(\Delta P_L)_{freq}}{\Delta f} = \frac{1.2}{1} = 1.2\ pu$ **on load base of 240 MVA**

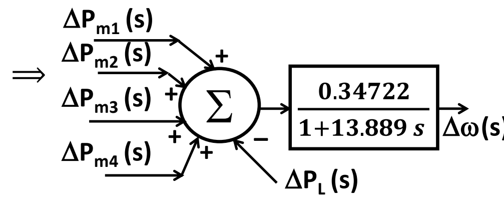
$$\Rightarrow \quad D = 1.2 * 240\ MW/puHz = 288\ MW/puHz$$

Hence, for a new base of 100 MVA, $D = \frac{288}{100}\ pu = 2.88\ pu$

Hence, the mathematical model of composite generator + Load is given by,



PROBLEMS:



Given that, change in load, ΔP_L = – 10 MW = – 0.1 pu

$$\Rightarrow \Delta P_L(s) = \frac{-0.1}{s}$$

Let the mechanical power outputs be constant.

$$\Rightarrow \Delta P_{m1} = \Delta P_{m2} = \Delta P_{m3} = \Delta P_{m4} = 0$$

From the block diagram,

$$\Delta\omega(s) = \left[\frac{0.34722}{1 + 13.889\ s}\right] * (\Delta P_{m1}(s) + \Delta P_{m2}(s) + \Delta P_{m3}(s) + \Delta P_{m4}(s) - \Delta P_L(s)\ )$$

$$\Rightarrow \Delta\omega(s) = \left[\frac{0.34722}{1 + 13.889\ s}\right] * \left(\frac{0.1}{s}\right) = \left[\frac{0.025}{s + 0.072}\right] * \left(\frac{0.1}{s}\right) = \left[\frac{0.0025}{s\ (s + 0.072)}\right]$$

By partial fraction, $\Delta\omega(s) = \left[\frac{0.0025}{s\ (s+0.072)}\right] = \frac{A}{s} + \frac{B}{s+0.072} = \frac{0.03472}{s} - \frac{0.03472}{s+0.072}$

PROBLEMS:

$$\therefore \Delta\omega(s) = \frac{0.03472}{s} - \frac{0.03472}{s+0.072}$$

Taking inverse laplace transforms,

$$\Delta\omega(t) = 0.03472 - 0.03472\ \ e^{-0.072t} \text{--------------------- (1)}$$

$\therefore$ **Steady state frequency deviation** $\Delta\omega_{ss} = \Delta\omega(\infty) = 0.03472\ pu$

$\therefore$ **Steady state speed deviation = steady state frequency deviation**

$$= \Delta\omega_{ss} = 0.03472 \text{ pu}$$

Let the frequency of the system be nominal at 50 Hz before the change in load. $\Rightarrow$ **f_0 = 50 Hz = 1 pu (Base frequency = 50 Hz)**

$\therefore$ **Steady state frequency deviation = f_1 – f_0 = $\Delta\omega_{ss}$**

Where, f_1 is the steady state frequency in pu

$\therefore$ **Steady state frequency f_1 = $\Delta\omega_{ss}$ + f_0**

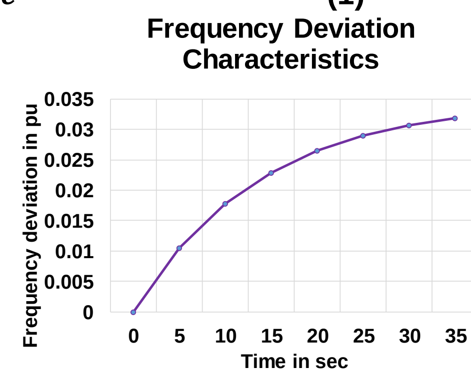
= 0.034722 + 1 = 1.034722 pu = 51.7361 Hz

PROBLEMS:

The frequency deviation (pu) Vs time (sec.) curve can be plotted using equation (1) as follows.

$$\Delta\omega(t) = 0.03472 - 0.03472\ \ e^{-0.072t} \text{--------------------- (1)}$$

Time (t) sec	Frequency deviation $\Delta\omega$ (pu)
0	0
5	0.0105
10	0.0178
15	0.0229
20	0.0265
25	0.02899
30	0.0307
35	0.0319



PROBLEMS:

3) A power system has a total load of 1400 MW at 50 Hz, D = 1.2 pu. A load of 50 MW is tripped. Find the steady state speed or frequency deviation if, (i) there is no speed control, and (ii) the system has a spinning reserve of 250 MW with a speed regulation of 4% on this capacity. Due to governor dead band, only 75% of the generators respond to the change in load.

Sol.: Given, Total Load P_L = 1400 MW, frequency f = 50 Hz

Damping constant D = 1.2 pu on a base of new load.

Change in load, ΔP_L = – 50 MW

Total Load after the change = 1400 – 50 = 1350 MW

Let the base power be 1350 MW and base frequency be 50 Hz.

$\therefore$ D = 1.2 pu = 1.2 *(1350 / 50) MW / Hz = 32.4 MW / Hz

PROBLEMS:

(i) When there is no speed control, $R \to \infty$. $\Rightarrow (1/R) = 0$

$\therefore$ frequency deviation $\Delta f = \frac{-\Delta P_L}{\frac{1}{R}+D} = \frac{-\Delta P_L}{D} = \frac{50}{32.4} = 1.5432\ Hz$

But, steady state frequency deviation $\Delta f = f_1 - f_0$

$\Rightarrow$ steady state frequency $f_1 = \Delta f + f_0$ = 1.5432 + 50 = 51.5432 Hz.

(ii) Given, the spinning reserve = 250 MW.

Let us assume that the load is met by the system with a generation of 1400 MW.

$\therefore$ Total generation capacity = 1400 + 250 = 1650 MW.

Given that only 75% of the generators responds.

Hence, generation capacity available for control=75%*1650 MW = 1237.5 MW

PROBLEMS:

Let the base power be 1237.5 MW and base frequency be 50 Hz.

A system speed regulation R = 4 % = 0.04 pu

$$\Rightarrow R = 0.04 * \frac{50}{1237.5} = 0.001616\ Hz/MW$$

$$\therefore \text{frequency deviation } \Delta f = \frac{-\Delta P_L}{\frac{1}{R}+D} = \frac{50}{\frac{1}{0.001616}+32.4} = 0.07678\ Hz$$

$\Rightarrow$ steady state frequency $f_1 = \Delta f + f_0$ = 0.07678 + 50 = 50.0768 Hz

Conclusion:

From the above (i) and (ii) cases, it is inferred that the steady state frequency deviation is reduced with speed governor control.

5) TURBINE MODEL:

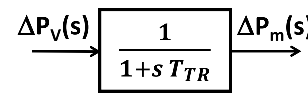
- Steam turbines and hydro turbines are the most commonly used prime movers for generators.
- In both type of turbines, the speed governor regulates the speed of the turbines, which is essential to maintain the system frequency.
- To study the dynamic behaviour of the system, suitable mathematical models for the turbines have to be incorporated.
- Steam turbines are generally of compound type with more than one pressure level.
- The steam flow at the inlet to the high pressure turbine is controlled by governor system.

5) TURBINE MODEL:

- There are various sections in steam turbines such as, steam chest, inlet piping to the first cylinder, re-heaters and crossover piping downstream
- These sections introduces time delays after the valve movement to change the steam flow.
- Mathematical models have to take into account these time delays.
- The time delays are represented by first-order transfer functions with suitable time constants.
- There are various turbine configurations available. They are,
  (i) Non-reheat (ii) Tandem compound single reheat,
  (iii) Tandem compound double reheat
  (iv) Cross compound single reheat, type-2 and
  (v) Cross compound double reheat.

5) TURBINE MODEL:

- For simplicity, let us consider a non-reheat steam turbine configuration which can be modelled by a simple transfer function of first order as shown.

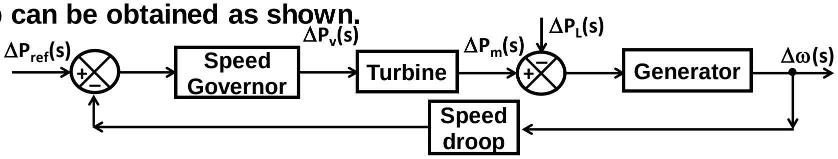


- In this turbine model, T_{TR} is the turbine time constant which can be specified based on type of turbine.
- From the block diagram, the transfer function of a simple non-reheat steam turbine is given by,

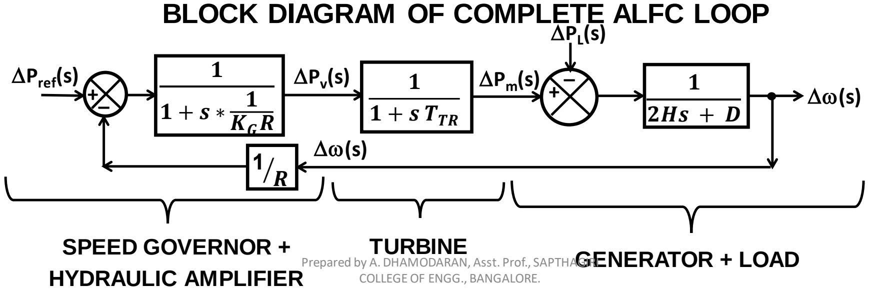
$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1+s\,T_{TR}} \text{ ------------------------------ (1)}$$

COMPLETE ALFC MODEL:

- With the mathematical models of speed governor with hydraulic amplifier, generator + Load, and turbine, the mathematical model of complete ALFC loop can be obtained as shown.



BLOCK DIAGRAM OF COMPLETE ALFC LOOP



COMPLETE ALFC MODEL:

- In the complete ALFC loop model shown above, let the reference set point be constant, i.e., $\Delta P_{ref} = 0$.
- Now, the ALFC loop without change in reference set point will become primary ALFC loop.
- From the above mathematical model, let us derive the transfer function of primary ALFC loop as follows.

$$\Delta\omega(s) = \left[\frac{1}{2Hs+D}\right] * [\Delta P_m(s) - \Delta P_L(s)]$$

$$= \left[\frac{1}{2Hs+D}\right] * \left[\Delta P_v(s) * \left(\frac{1}{1+s\,T_{TR}}\right) - \Delta P_L(s)\right]$$

$$= \left[\frac{1}{2Hs+D}\right] * \left[\left(\Delta P_{ref}(s) - \frac{1}{R} * \Delta\omega(s)\right) * \left(\frac{1}{1+s\,T_G}\right) * \left(\frac{1}{1+s\,T_{TR}}\right) - \Delta P_L(s)\right]$$

Where, $\Delta P_{ref} = 0$ and $T_G = \frac{1}{K_G\,R}$

$$\therefore \Delta\omega(s) = \left[-\frac{1}{R} * \Delta\omega(s) * \left(\frac{1}{1+s\,T_G}\right) * \left(\frac{1}{1+s\,T_{TR}}\right) * \left(\frac{1}{2Hs+D}\right) - \Delta P_L(s) * \left(\frac{1}{2Hs+D}\right)\right]$$

COMPLETE ALFC MODEL:

$$\left[1+\frac{1}{R}*\left(\frac{1}{1+sT_G}\right)*\left(\frac{1}{1+sT_{TR}}\right)*\left(\frac{1}{2Hs+D}\right)\right]\Delta\omega(s) = -\Delta P_L(s)*\left(\frac{1}{2Hs+D}\right)$$

Multiplying both sides by $(1+s\,T_G)*(1+s\,T_{TR})*(2Hs+D)$,

$$\left[\frac{1}{R}+(1+s\,T_G)(1+s\,T_{TR})(2Hs+D)\right]\Delta\omega(s) = -\Delta P_L(s)\left(\frac{1}{2Hs+D}\right)(1+s\,T_G)(1+s\,T_{TR})(2Hs+D)$$

$$\Longrightarrow \Delta\omega(s) = -\Delta P_L(s)*\left[\frac{(1+s\,T_G)(1+s\,T_{TR})}{\frac{1}{R}+(1+s\,T_G)(1+s\,T_{TR})(2Hs+D)}\right]$$

$\therefore$ **Transfer function of primary ALFC loop** $T(s) = \frac{\Delta\omega(s)}{-\Delta P_L(s)}$

$$\Longrightarrow T(s) = \frac{\Delta\omega(s)}{-\Delta P_L(s)} = \left[\frac{(1+s\,T_G)(1+s\,T_{TR})}{\frac{1}{R}+(1+s\,T_G)(1+s\,T_{TR})(2Hs+D)}\right] \text{----------------------- (1)}$$

COMPLETE ALFC MODEL:

- **This transfer function can also be rewritten in terms of power system gain and time constant.**
- **Dividing both sides of T(s) by D gives,**

$$T(s) = \left[\frac{(1/D)(1+s\,T_G)(1+s\,T_{TR})}{\frac{1}{D*R}+(1+s\,T_G)(1+s\,T_{TR})\left(\frac{2H}{D}s+1\right)}\right] = \left[\frac{K_{ps}\,(1+s\,T_G)(1+s\,T_{TR})}{\frac{K_{ps}}{R}+(1+s\,T_G)(1+s\,T_{TR})(1+s\,T_{ps})}\right]$$

Where, $K_{ps} = (1/D)$ **is a power system gain.**

$T_{ps} = \frac{2H}{D}$ **is a power system time constant.**

$$\therefore T(s) = \left[\frac{K_{ps}\,(1+s\,T_G)(1+s\,T_{TR})}{\frac{K_{ps}}{R}+(1+s\,T_G)(1+s\,T_{TR})(1+s\,T_{ps})}\right] \text{-------------------- (2)}$$

- **The above equations (1) and (2) gives the transfer function of primary ALFC loop.**

STEADY-STATE ANALYSIS:

- **Let us compute the steady state frequency deviation of the primary ALFC loop.**
- **From the transfer function of the primary ALFC loop,** $T(s) = \frac{\Delta\omega(s)}{-\Delta P_L(s)}$

$$\Longrightarrow \quad \Delta\omega(s) = -\Delta P_L(s)*T(s) \text{ ---------------- (1)}$$

- **Let us assume that there is a step change in load demand by 'M' MW. i.e.,** $\Delta P_L = M$ **MW** $\Longrightarrow \Delta P_L(s) = \frac{M}{s}$ **------------ (2)**
- **Using final value theorem, the steady state frequency deviation is given by,**

$$\Delta\omega_{ss} = \lim_{s\to 0} s\,\Delta\omega(s)$$

$$= \lim_{s\to 0} s*[-\Delta P_L(s)*T(s)] = \lim_{s\to 0} s*\left[-\frac{M}{s}*T(s)\right]$$

$$\Delta\omega_{ss} = \lim_{s\to 0}\,[-M*T(s)] \text{ ------------------- (3)}$$

STEADY-STATE ANALYSIS:

- **The transfer function of primary ALFC loop is,**

$$T(s) = \left[\frac{(1+s\,T_G)(1+s\,T_{TR})}{\frac{1}{R}+(1+s\,T_G)(1+s\,T_{TR})(2Hs+D)}\right]$$

$$\therefore \lim_{s\to 0} T(s) = \lim_{s\to 0}\left[\frac{(1+s\,T_G)(1+s\,T_{TR})}{\frac{1}{R}+(1+s\,T_G)(1+s\,T_{TR})(2Hs+D)}\right]$$

$$= \left[\frac{(1+0)(1+0)}{\frac{1}{R}+(1+0)(1+0)(0+D)}\right] = \frac{1}{\frac{1}{R}+D}$$

$$\therefore \lim_{s\to 0} T(s) = \frac{1}{\frac{1}{R}+D} \text{ ------------------- (4)}$$

- **Substituting equation (4) in equation (3),**

$$\Delta\omega_{ss} = \lim_{s\to 0}\,[-M*T(s)] = -M*\lim_{s\to 0}\,[T(s)]$$

$$\Delta\omega_{ss} = -M*\frac{1}{\frac{1}{R}+D} = \frac{-M}{\frac{1}{R}+D} = \frac{-M}{\beta}$$

STEADY-STATE ANALYSIS:

$\therefore$ steady state frequency deviation $\Delta\omega_{ss} = \frac{-M}{\frac{1}{R}+D} = \frac{-M}{\beta}$

- For a composite system with 'n' no. of generators,

$$\Delta\omega_{ss} = \frac{-M}{\frac{1}{R_{eq}}+D} \qquad \text{Where, } \frac{1}{R_{eq}} = \frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\cdots+\frac{1}{R_n}$$

$R_1, R_2, R_3, \ldots, R_n$ - Speed regulation of generators

PROBLEMS:

4) An isolated unit has the following parameters.
Turbine time constant = 0.3 sec, governor time constant = 0.2 sec.
Inertia constant M = 10 sec., Damping constant D = 1.0 pu,
Speed regulation R = 0.05 pu
For a unit step decrease in load demand, determine the steady state frequency deviation and the transfer function of primary ALFC loop of the unit.

Sol.: Given, $T_{TR} = 0.3$ sec. $\quad T_G = 0.2$ sec.

M = 10 sec.= 2 H $\quad$ D = 1 pu $\quad$ R = 0.05 pu

The transfer function of primary ALFC loop is,

$$T(s) = \left[\frac{(1+s\,T_G)(1+s\,T_{TR})}{\frac{1}{R}+(1+s\,T_G)(1+s\,T_{TR})(2Hs+D)}\right] = \left[\frac{(1+0.2\,s)(1+0.3\,s)}{\frac{1}{0.05}+(1+0.2\,s)(1+0.3\,s)(10s+1)}\right]$$

PROBLEMS:

$$\therefore \quad T(s) = \left[\frac{(1+0.2\,s)(1+0.3\,s)}{(1+0.2\,s)(1+0.3\,s)(1+10\,s)+20}\right]$$

Given that, Change in load demand ΔP_L = M = – 1 pu

Steady state frequency deviation, $\Delta\omega_{ss} = \frac{-M}{\frac{1}{R}+D}$

$$\Delta\omega_{ss} = \frac{-(-1)}{\frac{1}{0.05}+1} = \frac{1}{21} = 0.04762 \text{ pu}$$

Let the base frequency be 50 Hz.

$\therefore \Delta\omega_{ss} = 0.04762 \text{ pu} = 0.04762 * 50 = 2.381 \text{ Hz.}$

5) A single area consists of two generators as follows.
G_1: 200 MW, R_1 = 4% (on machine base)
G_2: 400 MW, R_2 = 5% (on machine base).
They are connected in parallel and share a load of 600 MW in proportion to their ratings at 50 Hz. The load of 200 MW is tripped.

PROBLEMS:

What is the generation from both generators to meet the new load if D = 0? What is the frequency at the new load? Repeat the same for D = 1.5 pu.

Sol.: Given, P_1= 200 MW, R_1 = 4%= 0.04 pu on 200 MW base
P_2= 400 MW, R_2 = 5%= 0.05 pu on 400 MW base
Load demand P_L = 600 MW, frequency f_0 = 50 Hz.
Change in load demand ΔP_L = – 200 MW = M
Let the base power be 100 MW and base frequency be 50 Hz.
$\therefore$ frequency f_0 = 50 Hz = 1 pu, $\quad$ M = ΔP_L = – 200 MW = – 2 pu.
Now, let us convert the regulations R_1 and R_2 to a new base.
R_1 = 4%= 0.04 pu = 0.04 * (100 / 200) = 0.02 pu.
R_2 = 5%= 0.05 pu = 0.05 * (100 / 400) = 0.0125 pu.

PROBLEMS:

Case (i) If D = 0:

Let f_1 be the frequency after tripping of the load.

Steady state frequency deviation, $\Delta\omega_{ss} = \frac{-M}{\frac{1}{R_{eq}}+D} = \frac{-M}{\left(\frac{1}{R_1}+\frac{1}{R_2}\right)+0} = \frac{-M}{\left(\frac{1}{R_1}+\frac{1}{R_2}\right)}$

$\Longrightarrow \Delta\omega_{ss} = \frac{-M}{\left(\frac{1}{R_1}+\frac{1}{R_2}\right)} = \frac{-(-2)}{\left(\frac{1}{0.02}+\frac{1}{0.0125}\right)}$

$\therefore \Delta\omega_{ss} = 0.01539\ pu = 0.7692\ Hz.$

Steady state frequency deviation $\Delta\omega_{ss} = f_1 - f_0 \quad \Longrightarrow f_1 = \Delta\omega_{ss} + f_0$

$\therefore f_1 = 0.7692 + 50 = 50.7692\ Hz = 1.01539\ pu$

Given that, the load is shared in proportion to their ratings.

$\therefore$ Share of generator-1, $\Delta P_1 = \frac{-\Delta f}{R_1} = \frac{-\Delta\omega_{ss}}{R_1} = \frac{-0.01539}{0.02} = -0.7695\ pu$

$\therefore \Delta P_1 = -0.7695 * 100 = -76.95\ MW$

$\therefore$ New power output of generator-1, $P_1{}' = P_1 + \Delta P_1$

$\Longrightarrow P_1{}' = 200 - 76.95 = 123.05\ MW$

PROBLEMS:

Now, share of generator-2, $\Delta P_2 = \frac{-\Delta f}{R_2} = \frac{-\Delta\omega_{ss}}{R_2} = \frac{-0.01539}{0.0125} = -1.2312\ pu$

$\therefore \Delta P_2 = -1.2312 * 100 = -123.12\ MW$

$\therefore$ New power output of generator-2, $P_2{}' = P_2 + \Delta P_2$

$\Longrightarrow P_2{}' = 400 - 123.12 = 276.88\ MW$

[Check: $\Delta P_1 + \Delta P_2 = -76.95 - 123.12 = -200.07\ MW = \Delta P_L$

and $P_1{}' + P_2{}' = 123.05 + 276.88 = 399.93\ MW = P_L{}'$]

Case (ii) If D = 1.5 pu:

Given D = 1.5 pu on load base of ΔP_L = 200 MW

$\therefore$ D = 1.5 * (200 / 50) = 6 MW / Hz

Now, for a new base power of 100 MW, D = 6 / (100 / 50) pu = 3 pu

Let f_1 be the frequency after tripping of the load.

Steady state frequency deviation, $\Delta\omega_{ss} = \frac{-M}{\frac{1}{R_{eq}}+D} = \frac{-M}{\left(\frac{1}{R_1}+\frac{1}{R_2}\right)+D}$

PROBLEMS:

$\therefore \Delta\omega_{ss} = \frac{-(-2)}{\left(\frac{1}{0.02}+\frac{1}{0.0125}\right)+3} = 0.01504\ pu = 0.752\ Hz.$

$\therefore$ New frequency $f_1 = \Delta\omega_{ss} + f_0 = 0.752 + 50 = 50.752\ Hz$

Now, share of generator-1, $\Delta P_1 = \frac{-\Delta f}{R_1} = \frac{-\Delta\omega_{ss}}{R_1} = \frac{-0.01504}{0.02} = -0.752\ pu$

$\therefore \Delta P_1 = -0.752 * 100 = -75.2\ MW$

$\therefore$ New power output of generator-1, $P_1{}' = P_1 + \Delta P_1$

$\Longrightarrow P_1{}' = 200 - 75.2 = 124.8\ MW$

Now, share of generator-2, $\Delta P_2 = \frac{-\Delta f}{R_2} = \frac{-\Delta\omega_{ss}}{R_2} = \frac{-0.01504}{0.0125} = -1.2032\ pu$

$\therefore \Delta P_2 = -1.2032 * 100 = -120.32\ MW$

$\therefore$ New power output of generator-2, $P_2{}' = P_2 + \Delta P_2$

$\Longrightarrow P_2{}' = 400 - 120.32 = 279.68\ MW$

PROBLEMS:

Increase in frequency dependent load $\Delta P_D = (\Delta P_L)_{freq} = D * \Delta\omega$

$\Rightarrow \Delta P_D$ = 3*0.01504 = 0.04512 pu = 4.512 MW

[Check: $\Delta P_1 + \Delta P_2 - \Delta P_D = -75.2 - 120.32 - 4.512 = -200.032\ MW = \Delta P_L$

and $P_1{}' + P_2{}' - P_D{}' = 124.8 + 279.68 - 4.512 = 399.968\ MW = P_L{}'$]

6) A single control area has the following data.

Total generation capacity = 2000 MW Normal load = 1500 MW

Inertia constant H = 4.8 sec. Damping constant D = 1.2%

Frequency f = 50 Hz Regulation R = 2.5 Hz / pu MW

a) Determine the primary ALFC loop parameters.

b) For an increase of 0.02 pu in the load, find the frequency drop without governor control. (c) Repeat (b) with governor control

PROBLEMS:

d) Repeat (b) with governor control and neglecting the frequency dependence of loads.

Sol: Given, Total capacity = 2000 MW, Normal Load P_L^0 = 1500 MW

H = 4.8 sec. D = 1.2% on load base f = 50 Hz

R = 2.5 Hz / pu MW on generation base

Let the base power be 2000 MW and base frequency be 50 Hz.

∴ D = 1.2 * (1500/50) MW/Hz = 36 MW/Hz

For a common base of 2000 MW,

D = 36 / 2000 pu MW / Hz = 0.018 pu MW / Hz

In pu, D = 36 / (2000/50) = 0.9 pu

(a) The primary ALFC loop parameters are, K_{ps} and T_{ps}.

PROBLEMS:

Power System gain K_{ps} = 1 / D = 1 / 0.018 = 55.5556 Hz / pu MW

K_{ps} = 1 / D = 1 / 0.9 = 1.1111 pu

Power system time constant T_{ps}= 2H / D = 2*4.8 / 0.9 = 10.6667 sec.

(b) Given, change in load ΔP_L = +0.02 pu and

no governor control, i.e., R = ∞

∴ Frequency deviation $\Delta f = \frac{-\Delta P_L}{\frac{1}{R}+D} = \frac{-0.02}{0+0.018} = -1.1111\ Hz$

(c) With speed governor control, i.e., R = 2.5 Hz / pu MW

∴ Frequency deviation $\Delta f = \frac{-\Delta P_L}{\frac{1}{R}+D} = \frac{-0.02}{\frac{1}{2.5}+0.018} = -0.04785\ Hz$

(d) Given that neglecting frequency dependent loads, i.e., D = 0

∴ Frequency deviation $\Delta f = \frac{-\Delta P_L}{\frac{1}{R}+D} = \frac{-0.02}{\frac{1}{2.5}+0} = -0.05\ Hz$

PROBLEMS:

7) A 1000 MVA generator operates on Full Load at the rated frequency of 50 Hz. The load is reduced to 800 MW. The steam valve has an operating time lag of 0.6 sec. If H = 5 sec., then determine the change in frequency.

Sol.: Given, Full load generation capacity = 1000 MVA.

Load = 1000 MW at rated frequency f = 50 Hz

New Load = 800 MW time delay in steam valve = 0.6 sec

H = 5 sec.

The kinetic energy generated is directly proportional to square of the frequency.

Let the kinetic energy generated initially be KE_0 at frequency f_0

PROBLEMS:

Let the kinetic energy generated after change in load be KE_1 at frequency f_1.

∴ $KE_0 \propto f_0^2$ and $KE_1 \propto f_1^2$

$$\Rightarrow \frac{KE_1}{KE_0} = \frac{f_1^2}{f_0^2} \quad \Rightarrow f_1 = f_0 * \sqrt{\frac{KE_1}{KE_0}} \text{ --------------- (1)}$$

Initially, the generator is operating at full load.

Hence, kinetic energy stored KE_0 = G * H W-sec

∴ KE_0 = 1000 *5 MW-sec = 5000 MW-sec = 5000 MJ

When the load reduced to 800 MW, the mechanical power output remains constant at 1000 MW (instant). Hence the excess power output of 200 MW is converted into kinetic energy and applied to rotating shaft till the time lag of steam valve, 0.6 sec.

PROBLEMS:

$\therefore$ Excess kinetic energy generated =Excess power output * time lag

= 200 * 0.6 = 120 MW-sec. = 120 MJ

$\therefore$ Total kinetic energy generated after the change in load demand is,

KE_1 = Initial kinetic energy generated + Excess kinetic energy generated

KE_1 = 5000 + 120 = 5120 MW-sec = 5120 MJ

Hence, from (1) $\quad f_1 = f_0 * \sqrt{\frac{KE_1}{KE_0}} = 50 * \sqrt{\frac{5120}{5000}} = 50.5964\ Hz.$

$\therefore$ Change in frequency $\Delta f = f_1 - f_0 = 50 - 50.5964 = 0.5964$ Hz.

PROBLEMS:

8) An isolated control area consists of a 500 MW generator with an inertia constant of H = 5 sec. with the following parameters. K_{ps} = 100, T_{ps} = 20 sec., R = 5%, f = 50 Hz, T_G = 0.45 sec., and T_{TR} = 0.5 sec.

(a) Draw the block diagram of the primary ALFC loop and obtain its transfer function.

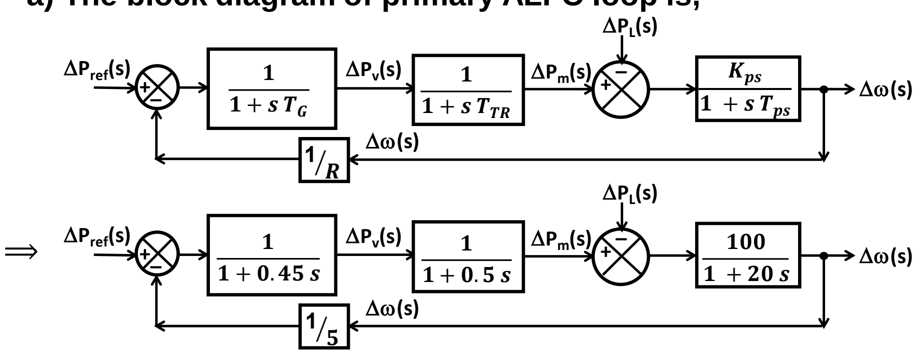
(b) Obtain the steady state frequency deviation of the approximate first order system of the ALFC loop by neglecting the turbine and governor dynamics for a load reduction of 0.1 pu.

Sol.: Given, G = 500 MW. H = 5 sec. K_{ps} = 100 T_{ps} = 20 sec

R = 5% f = 50 Hz T_G = 0.45 sec T_{TR} = 0.5 sec

PROBLEMS:

a) The block diagram of primary ALFC loop is,



The transfer function of primary ALFC loop is,

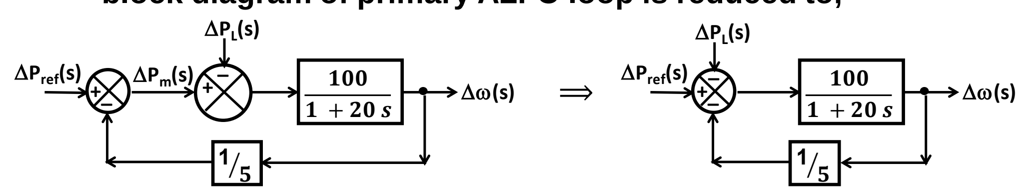
$$T(s) = \left[\frac{K_{ps}\,(1+s\,T_G)(1+s\,T_{TR})}{\frac{K_{ps}}{R}+(1+s\,T_G)(1+s\,T_{TR})(1+s\,T_{ps})}\right] = \left[\frac{100\,(1+0.45\,s)(1+0.5\,s)}{\frac{100}{5}+(1+0.45\,s)(1+0.5\,s)(1+20\,s)}\right]$$

$$\Rightarrow \quad T(s) = \frac{22.5\,s^2 + 95\,s + 100}{4.5\,s^3 + 19.225\,s^2 + 20.95\,s + 21}$$

PROBLEMS:

b) Given that, turbine and governor dynamics should be neglected. Change in load ΔP_L = – 0.1 pu.

Hence, by neglecting the turbine and governor dynamics, the block diagram of primary ALFC loop is reduced to,



From the above block diagram, the approximate first order transfer function is given by,

$$T(s) = \frac{\Delta\omega(s)}{-\Delta P_L(s)} = \frac{100/(1+20s)}{1+[100/(1+20s)]*(1/5)} = \frac{100}{(20\,s+1)+[100/5]} = \frac{100}{20\,s+21} \quad \text{-- (1)}$$

PROBLEMS:

Change in load $\Delta P_L = -0.1$ pu $\quad \Longrightarrow \quad \Delta P_L(s) = \frac{-0.1}{s}$

The steady state frequency deviation $\quad \Delta\omega_{ss} = \lim_{s\to 0} s * \Delta\omega(s)$

$$\Longrightarrow \Delta\omega_{ss} = \lim_{s\to 0} s * \left(-\Delta P_L(s)\right) * \left[\frac{100}{20\,s+21}\right] \text{ (From (1))}$$

$$= \lim_{s\to 0} s * \left(\frac{0.1}{s}\right) * \left[\frac{100}{20\,s+21}\right]$$

$$\Delta\omega_{ss} = \lim_{s\to 0} \left[\frac{10}{20\,s+21}\right] = \frac{10}{21} = 0.4762\ Hz$$

AUTOMATIC GENERATION CONTROLLER:

- With the speed control of primary ALFC loop, there is a steady state frequency or speed deviation for a change in system load.
- The amount of deviation in frequency depends on governor droop characteristics (R) and frequency sensitivity of the load (D).

Frequency deviation $\Delta f = \frac{-\Delta P_L}{\frac{1}{R}+D}$

- In response to the change in load, all the generating units will change their generation irrespective of the location of the load.
- For restoration of system frequency to the scheduled value, a Supplementary control is required to change the power reference set point (P_{ref}).

AUTOMATIC GENERATION CONTROLLER:

- This secondary control in ALFC loop is called as Automatic Generation Controller (AGC).
- This controller becomes the basic means of controlling the prime mover power output (P_m) to match with the variations of system load.
- The AGC should satisfy the following.

(i) Stable closed loop control operations.

(ii) Keep the frequency deviation to a minimum value.

(iii) Limit the integral of frequency error.

(iv) Share the load economically.

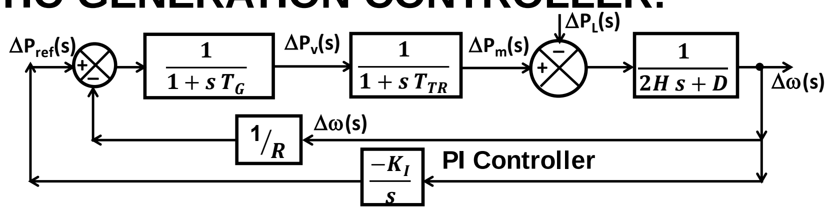
AUTOMATIC GENERATION CONTROLLER:

- In an isolated system, the function of AGC is to maintain the frequency at the scheduled value.
- This is achieved by adding a Proportional Integral Controller (PI) in the feedback path to change the reference power setting (P_{ref}) depending on the frequency deviation.
- The steady state error of a PI controller is zero.

PROPORTIONAL INTEGRAL CONTROLLER:

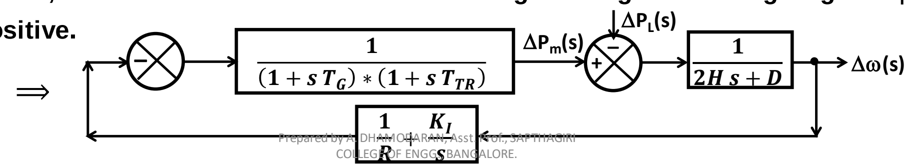
- Let us add a PI controller to the primary ALFC loop in its feedback path as shown.
- This is required to maintain the frequency at the scheduled value by changing the reference power setting (P_{ref}).

AUTOMATIC GENERATION CONTROLLER:



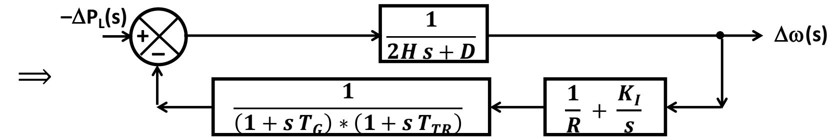
- For a decrease in frequency $\Delta f(s)$, the power generation must increase, $\Delta P_m(s)$ and hence, reference power setting $\Delta P_{ref}(s)$ must be positive.
- So, output signal of PI controller must be of opposite sign to frequency deviation $\Delta f(s)$.
- Hence, PI controller block is shown with negative sign with integral gain K_I is positive.

$\Longrightarrow$



AUTOMATIC GENERATION CONTROLLER:

$\Longrightarrow$

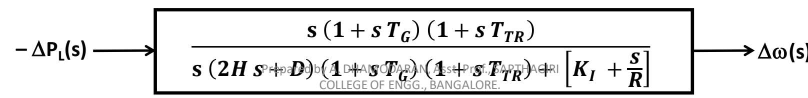


Where, $G(s) = \frac{1}{2H\,s+D}$ and $H(s) = \left[\frac{1}{(1+s\,T_G)*(1+s\,T_{TR})}\right]*\left[\frac{1}{R}+\frac{K_I}{s}\right]$

$\therefore$ Transfer function $T(s) = \frac{\Delta\omega(s)}{-\Delta P_L(s)} = \frac{\left(\frac{1}{2H\,s+D}\right)}{1+\left(\frac{1}{2H\,s+D}\right)*\left[\frac{1}{(1+s\,T_G)*(1+s\,T_{TR})}\right]*\left[\frac{1}{R}+\frac{K_I}{s}\right]}$

Multiplying both sides by $s*(2H\,s+D)*(1+s\,T_G)*(1+s\,T_{TR})$,

$\Longrightarrow$ $T(s) = \frac{s\,(1+s\,T_G)\,(1+s\,T_{TR})}{s\,(2H\,s+D)\,(1+s\,T_G)\,(1+s\,T_{TR})+\left[K_I+\frac{s}{R}\right]}$ --------------- (1)



AUTOMATIC GENERATION CONTROLLER:

- For a step change in load demand of '± M' MW, ($\Delta P_L = \pm M$) the frequency deviation is given by,

$$\Delta\omega(s) = -\Delta P_L(s) * T(s) = \frac{\mp M}{s} * T(s) \text{ (From transfer function)}$$

- $\therefore$ Steady state frequency deviation $\Delta\omega_{ss} = \lim_{s\to 0} s\,\Delta\omega(s)$

$$\Delta\omega_{ss} = \lim_{s\to 0} s * \frac{\mp M}{s} * T(s) = \lim_{s\to 0} \mp M * T(s)$$

$$\Longrightarrow \Delta\omega_{ss} = \mp M \lim_{s\to 0} T(s) = 0 \text{ (From the transfer function)}$$

- Hence, the steady state frequency deviation $\Delta\omega_{ss} = 0$
- The frequency error $\Delta\omega(s) = \omega_{ref}(s) - \omega(s)$ is called as Area Control Error (ACE) for an isolated generator.

AUTOMATIC GENERATION CONTROLLER:

- The steady state frequency deviation $\Delta\omega_{ss}$ is driven to zero, irrespective of the values of integral gain K_I and speed regulation R.
- Hence, to control the dynamic response of the system, the two parameters are used; K_I and R.
- The output of the PI controller is zero only when the speed deviation is $(\Delta\omega)$ zero.
- At this stage, $\Delta P_{ref} = 0$.

$$\Delta P_{ref}(s) = \frac{-K_I}{s}\Delta\omega(s) \Longrightarrow \Delta P_{ref}(t) = -K_I \int \Delta\omega(t)\,dt$$

AUTOMATIC GENERATION CONTROLLER:

- The AGC with Integral controller can also be represented in terms of power system parameters K_{ps} and T_{ps} as follows.

  Dividing both sides of (1) by D gives,

$$T(s) = \frac{(1/D) * s\,(1+s\,T_G)\,(1+s\,T_{TR})}{s\left((2H/D)\,s+1\right)(1+s\,T_G)\,(1+s\,T_{TR}) + (1/D) * \left[K_I + \frac{s}{R}\right]}$$

$$\therefore T(s) = \frac{K_{ps}\,s\,(1+s\,T_G)\,(1+s\,T_{TR})}{s\,(1+s\,T_{ps})\,(1+s\,T_G)\,(1+s\,T_{TR}) + K_{ps}\left[K_I + \frac{s}{R}\right]} \text{ --------(2)}$$

PRIMARY CONTROL VS SUPPLEMENTARY (SECONDARY) CONTROL:

- The supplementary control is much slower than the primary speed control action.
- The supplementary control comes into action only after the primary control has stabilized the system frequency.
- The primary control acts on all units with speed regulation.
- The secondary control adjusts the load reference settings in only a few selected units.
- The output power generations of these units will override the effect of Composite Frequency Response (CFR) characteristics of the system.
- In this process, the output power generations of all the units are forced to the scheduled values.

PROBLEMS:

9) A 500 MW generator has a speed regulation of 3%. The frequency drops by 0.1 Hz due to increased load. Find the increase in turbine power if the reference setting is not changed. What would be the change in reference power setting if the turbine power is to remain unchanged?

Sol.: Given, G = 500 MW. R = 3% = 0.03 pu $\Delta f = -0.1$ Hz

In the complete ALFC loop model,

$$\Delta P_m(s) = \left(\frac{1}{1+s\,T_{TR}}\right) * \Delta P_V(s) = \left(\frac{1}{1+s\,T_{TR}}\right)\left(\frac{1}{1+s\,T_G}\right) * \left(\Delta P_{ref}(s) - \frac{1}{R}\Delta f(s)\right)$$

At steady state, s→0, $\therefore \Delta P_m = \Delta P_{ref} - \frac{1}{R}\Delta f$ --------------- (1)

PROBLEMS:

Case (i): Given, Reference setting is not changed, i.e., $\Delta P_{ref} = 0$.

R = 0.03 pu on generation base. Let base frequency f_0 be 50 Hz.

∴ R = 0.03 * (50 / 500) = 0.003 Hz / MW.

From (1), $\Delta P_m = \Delta P_{ref} - \frac{1}{R}\Delta f = 0 - \frac{1}{0.003}(-0.1) = 33.3333\ MW$.

Hence, if the reference power setting is not changed, the turbine power output should be increased by 33.3333 MW.

Case (ii): Given, the turbine power remain unchanged, i.e., $\Delta P_m = 0$

From (1), $\Delta P_m = \Delta P_{ref} - \frac{1}{R}\Delta f$

$\Longrightarrow \quad 0 = \Delta P_{ref} - \frac{1}{0.003}(-0.1) \qquad \Longrightarrow \Delta P_{ref} = -33.3333\ MW$

Hence, if the turbine power output is to remain unchanged, the reference power setting should be lowered by 33.3333 MW.

PROBLEMS:

10) An isolated power system has the following parameters.

T_G = 0.2 sec T_{TR} = 0.5 sec H = 5 sec D = 0.8 pu and R = 0.05 pu

The turbine output power is 250 MW at the nominal frequency of 50 Hz. A load increase of 50 MW occurs. What is the steady state frequency deviation? Obtain the transfer function of complete ALFC loop. If the system is equipped with an integral controller whose gain is 7, then determine the transfer function of AGC.

Sol.: Given, T_G = 0.2 sec T_{TR} = 0.5 sec H = 5 sec D = 0.8 pu and R = 0.05 pu, ΔP_L = M = 50 MW, P_m = 250 MW at f = 50 Hz.

Let us choose a base power of 250 MW and base frequency of 50 Hz

∴ ΔP_L = M = 50 MW = 50 / 250 pu = 0.2 pu.

PROBLEMS:

∴ Steady state frequency deviation $\Delta f = \frac{-M}{\frac{1}{R}+D} = \frac{-0.2}{\frac{1}{0.05}+0.8} = -0.009615\ pu$

$$\Rightarrow \quad \Delta f = -0.009615\ pu = -0.009615 * 50\ Hz = -0.4808\ Hz$$

∴ Steady state frequency $f_1 = f_0 + \Delta f$ = 50 – 0.4808 = 49.5192 Hz

Transfer function of complete ALFC loop (primary) is,

$$T(s) = \frac{\Delta\omega(s)}{-\Delta P_L(s)} = \left[\frac{(1+s\,T_G)(1+s\,T_{TR})}{\frac{1}{R}+(1+s\,T_G)(1+s\,T_{TR})(2Hs+D)}\right] = \left[\frac{(1+0.2\,s)(1+0.5\,s)}{\frac{1}{0.05}+(1+0.2\,s\,)(1+0.5\,s)(10\,s+0.8)}\right]$$

$$\therefore\ T(s) = \frac{0.1\,s^2+0.7\,s+1}{s^3+7.08\,s^2+10.56\,s+20.8}$$

Given that, Integral gain of PI controller KI = 7.

∴ Transfer function of AGC (supplementary or secondary loop),

$$T(s) = \frac{s\,(1+s\,T_G)\,(1+s\,T_{TR})}{s\,(2H\,s+D)\,(1+s\,T_G)\,(1+s\,T_{TR})+\left[K_I+\frac{s}{R}\right]} = \frac{s\,(1+0.2\,s)\,(1+0.5\,s)}{s\,(10\,s+0.8)\,(1+0.2\,s)\,(1+0.5\,s)+\left[7+\frac{s}{0.05}\right]}$$

$$T(s) = \frac{s\,(1+0.2\,s)\,(1+0.5\,s)}{s\,(10\,s+0.8)\,(1+0.2\,s)\,(1+0.5\,s)+(7+20\,s)} = \frac{0.1\,s^3+0.7\,s^2+s}{s^4+7.08\,s^3+10.56\,s^2+20.8\,s+7}$$

THANK YOU