Load frequency control is the basic control mechanism in Power system operation. whenever there is a variation in load demand on a generating unit then unbalance takes place between real Power input and output ($\Delta P_G - \Delta P_D$). This difference is being supplied by stored energy of rotating Parts of the unit.

Therefore Kinetic energy of any unit is given by

$$K.E = \frac{1}{2} I \omega^2$$

where 'I' is moment of inertia of the rotating Part

'ω' is angular speed of rotating Part

If K.E reduces, 'ω' reduces then the speed falls, hence the frequency decreases

the change in frequency 'Δf' is sensed through a speed governing sensor system, it is fedback to control the position of inlet valve of primemover which is connected to generating units.

It changes the input of primemover and tries to bring back the balance between real Power input and output.

Therefore it states that frequency variation is dependant on real Power of system.

A load frequency control also controls the real Power through interconnecting transmission lines by sensing change in Power flow through Tie lines.

Necessity of Keeping frequency constant:

Generally generators using in generating stations are alternators (or) ac generators.

Speed of alternator is $N_S = \frac{120f}{P}$.

Therefore frequency $f = \frac{N_s \cdot P}{120}$

Frequency of Power system depends on speed. The frequency needs to be maintained constant i.e., 50 Hz ($\pm 2\%$) but due to continuous variation of real and reactive power demands, frequency is not constant.

To supply the load as per variations, steam input to turbo generators (or) water input to hydro generators must be regulated otherwise speed will vary results in change in frequency.

Frequency should be maintained constant due to the following reasons:

1. For synchronous operation of various units, it is necessary to maintain frequency constant.

2. All AC motors should require constant frequency to maintain constant speed

3. Frequency effects the amount of power transmitted through interconnecting lines

   i.e $P = \frac{V_S \cdot V_R}{X} \sin \delta$ where $X = 2\pi f l$

4. If the frequency decreases then speed of generator exciter decreases which results generated emf falls, resulting drooping voltage in the network i.e $e = 4.44 f \phi_m T_{ph} K_c \cdot K_d$

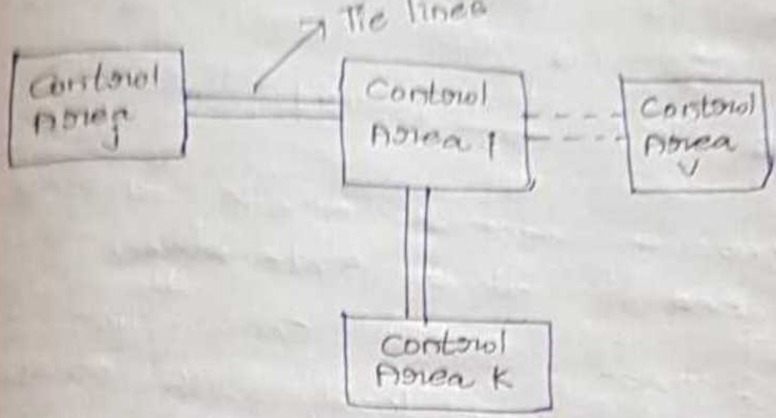
   where T_{ph} = No. of turns per phase

   K_c = Pitch factor

   K_d = Distribution factor.

5. In the thermal power station, the efficiency of auxiliary mechanism is highly effected with decrease in frequency.

Control Area Concept:



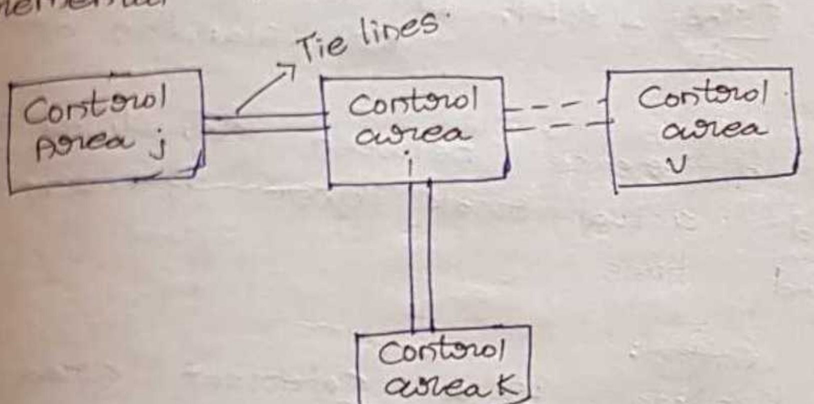
Generally several generators located at different location are connected in parallel to meet load demand of large area.

All generators may have same response cycle per second to changes in load demand.

Very large power systems are divided into subareas in which all generators are tightly coupled such that they swing in unison with change in load, such an area is called control area.

A control area consist of a turbine, generator, speed governer and a load system.

Incremental Power balance of Control Area:



Above figure shows interconnected control area. Let us assume that the control area "i" experiences a change in real power demand ΔP_D.

Due to turbine controller action there is a small change in output of real power generation ΔP_G

Therefore the net Power in control area 'i' is $\Delta P_{Gi} - \Delta P_{Di}$ which is observed by the $\left[\Delta P_{Gi} - \Delta P_{Di} = \frac{dW_{KE}}{dt} + B\Delta f\right]$ system in three ways

By increasing stored Kinetic energy of Control area 'i' at a rate $\frac{dW_{KEi}}{dt}$

By an increased load consumption i.e., the rate of change of load with respect to frequency is considered as constant for small changes in frequency i.e $\left(\frac{dP_{Di}}{dF}\right)\Delta F_i = B_i \Delta F_i$

By increasing the flow of Power via lines with total amount (ΔP_{Tiei}) which is defined positive for outflow from area.

Therefore net surplus Power in control area is given by

$$\Delta P_{Gi} - \Delta P_{Di} = \frac{dW_{KEi}}{dt} + B_i \Delta f_i + \Delta P_{tiei}$$ (Interconnected system)

$$\Delta P_{Gi} - \Delta P_{Di} = \frac{dW_{KEi}}{dt} + B_i \Delta f_i$$ [single area (or) Isolated (or) Islanding area]

Note:

ΔP_{tie} is difference between scheduled real Power and actual real Power through interconnected lines.

Single Area Control:

A single area is a coherent area in which all the generators swing in unison to the changes in load.

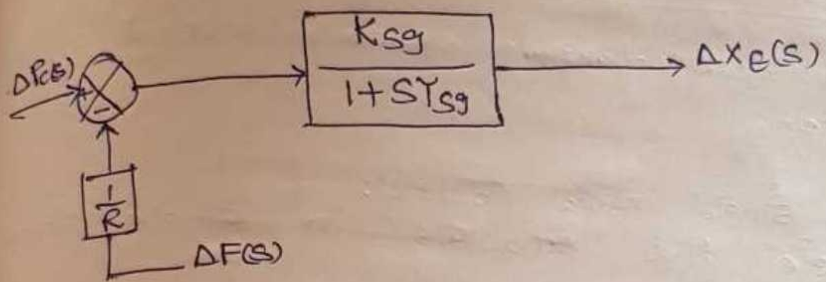
In this area frequency is assumed to be constant both in static and dynamic condition. The single area is represented by isolated power system consisting of an turbine, generator, speed governor and load.

change in tie line Power ... and from now is absent in single area.

Therefore net surplus power of single area is $\Delta P_G - \Delta P_D = \frac{dW_{KE}}{dt} + B\Delta f$

Block diagram of single (or) Isolated area speed Governor model:

$$\Delta X_E(S) = \frac{K_{sg}}{1+ST_{sg}}\left[\Delta P_C(S) - \frac{1}{R}\Delta F(S)\right]$$

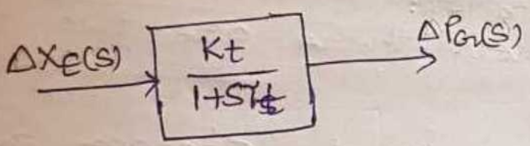


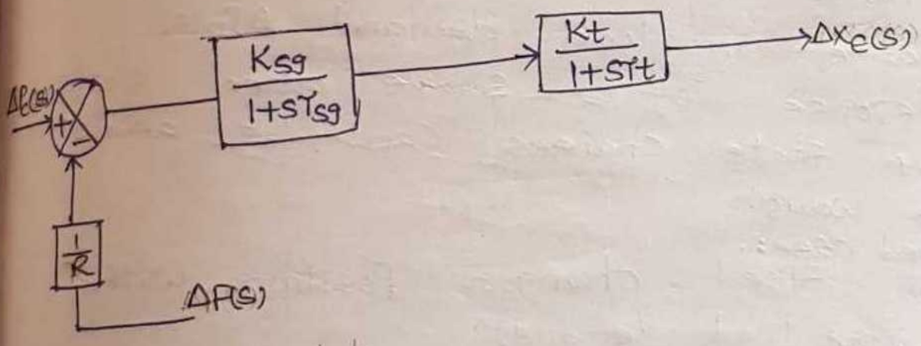
Turbine model:

Transfer function of turbine model is given by

$$\Delta P_G(S) = \frac{K_t}{1+ST_{st}} \cdot \Delta X_E(S)$$

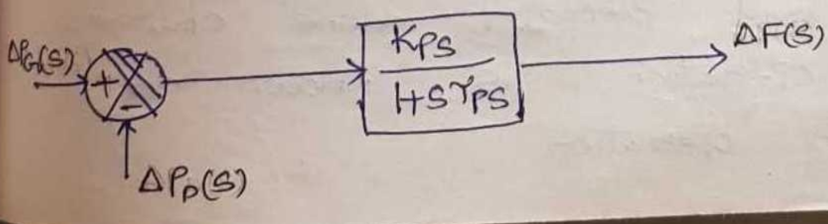
$$\Rightarrow \frac{\Delta P_G(S)}{\Delta X_E(S)} = \frac{K_t}{1+ST_t}$$





Generator model:

$$\Delta F(S) = \frac{K_{ps}}{1+ST_{ps}}\left[\Delta P_G(S) - \Delta P_D(S)\right]$$



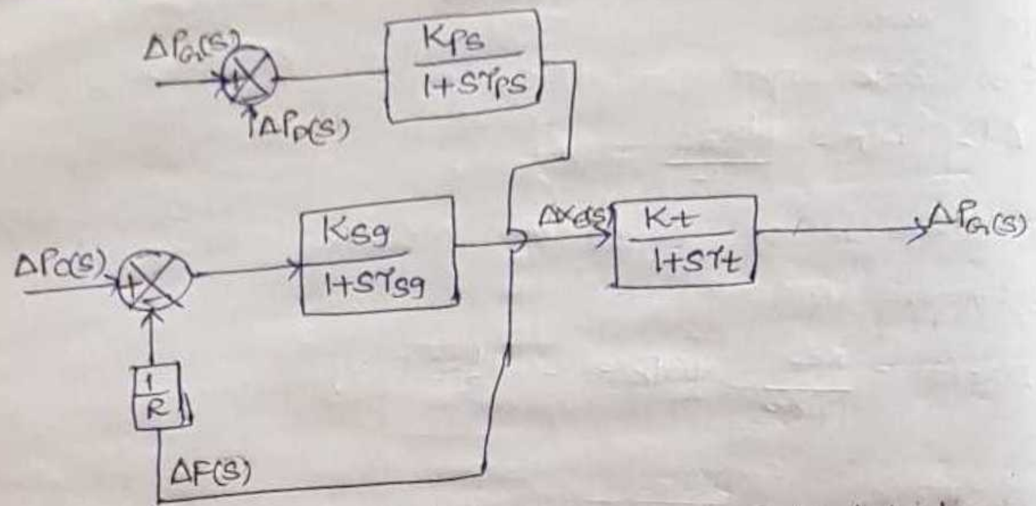


Fig. overall block diagram of an isolated Power system

Analysis of single Area Control:

There are two analysis in Single area control

1. Steady State Analysis:

Uncontrolled case (constant spee

Controlled Case

By Varying $\Delta P_{C}(s)$ and $\Delta P_{D}(s)$

2. Dynamic state Analysis:

For this model, there are two incremental inputs

The change in speed changer position $\Delta P_{C}(s)$

The change in load demand $\Delta P_{D}(s)$.

The response of a single area system to steady state changes can be analysed in three ways.

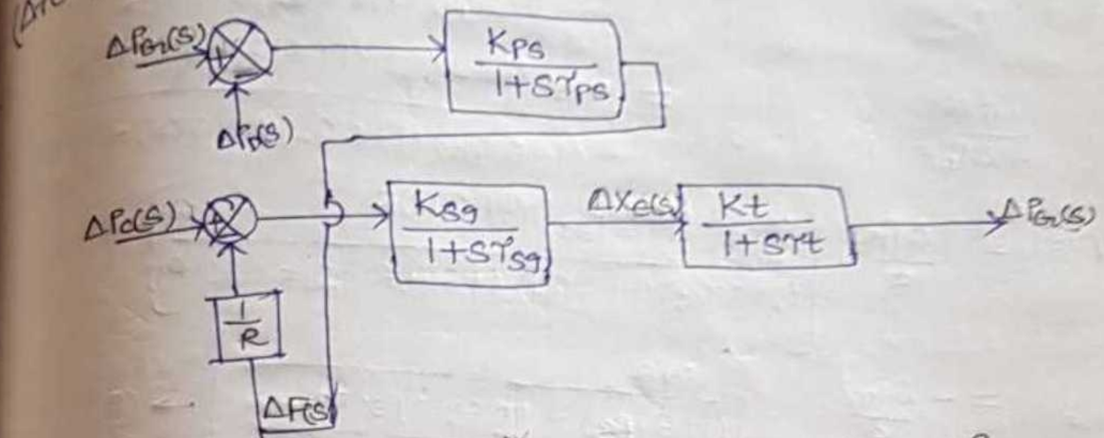
Uncontrolled Case:

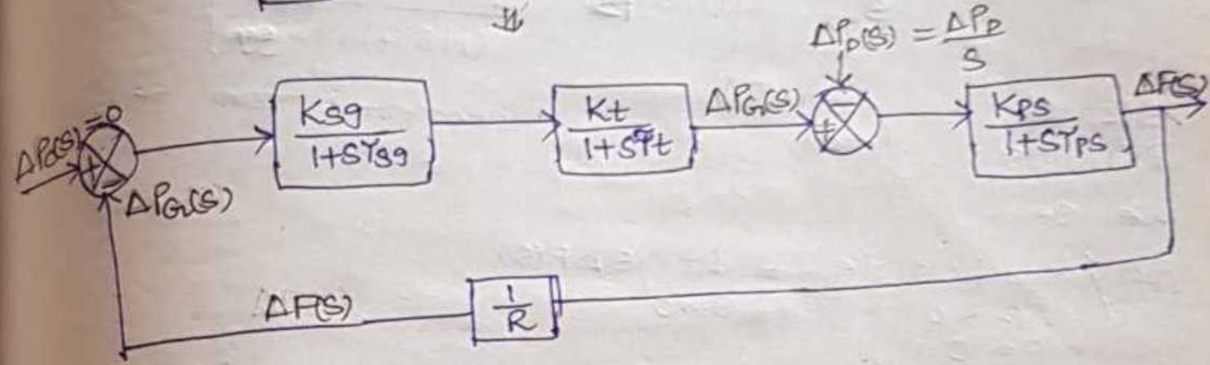
(Constant speed changer position with variable ~~input~~ load demand)

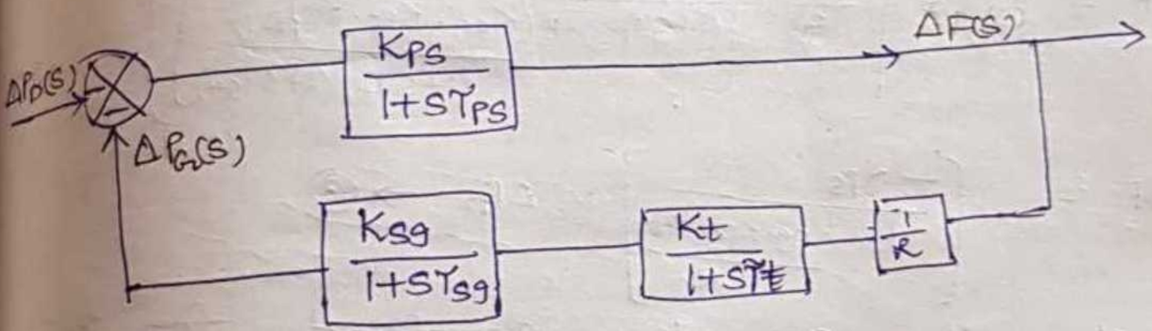
Let us consider the speed changer has fixed setting which means $\Delta P_{C}(s)=0$ and the load demand alone changes. such an operation is known as free governor operation step I:

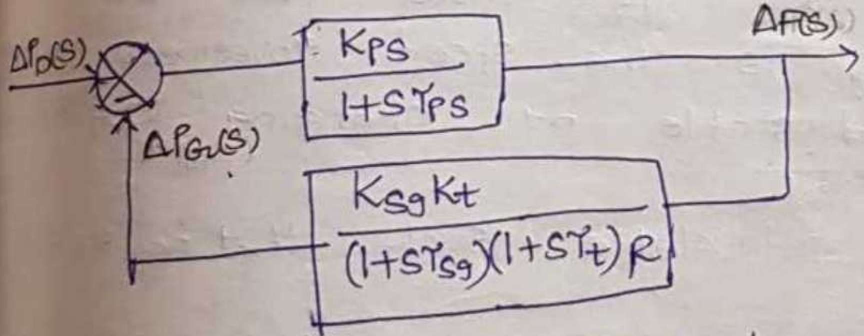
Let us consider a sudden step change in load demand i.e $\Delta P_D(s) = \frac{\Delta P_D}{s}$ → (1)

The steady state change of frequency ($\Delta F(s)$) is determined from block diagram.









Transfer function $= \frac{\Delta F(s)}{-\Delta P_D(s)}\Big|_{\Delta P_C(s) = 0}$

$$\text{Transfer function} = \frac{G(s)}{1+G(s)H(s)}$$

$$= \frac{\dfrac{K_{ps}}{1+sT_{ps}}}{1+\dfrac{K_{ps}}{1+sT_{ps}} \cdot \dfrac{K_{sg}K_t}{(1+sT_{sg})(1+sT_t)R}}$$

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

$$\Delta F(s) = \frac{\Delta P_D}{s}\left[\frac{K_{ps}(1+sT_{sg})(1+sT_t)R}{(1+sT_{ps})(1+sT_{sg})(1+sT_t)R+K_{ps}K_{sg}\cdot K_t}\right]$$

$$= -\frac{\Delta P_D}{s}\left[\frac{K_{ps}}{(1+sT_{ps})+\dfrac{(K_{sg}\cdot K_{ps}\cdot K_t/R)}{(1+sT_t)(1+sT_{sg})}}\right] \rightarrow (2)$$

Step II: Applying final Value theorem for eq (2), we get

$$\Delta f \Big/_{\substack{\Delta P_C=0 \\ s=0}}^{\text{steady state}} = \lim_{s\to 0} s\Delta F(s)$$

$$\Delta F = \lim_{s\to 0} s\left[-\frac{\Delta P_D}{s}\left[\frac{K_{ps}}{(1+sT_{ps})+\dfrac{(K_{sg}\cdot K_{ps}\cdot K_t/R)}{(1+sT_t)(1+sT_{sg})}}\right]\right]$$

$$\Delta F = \left[\frac{-K_{ps}}{1+\dfrac{K_{sg}\cdot K_{ps}\cdot K_t}{R}}\right] \times \Delta P_D \rightarrow (3)$$

while the gain K_t is fixed for the turbine and K_{ps} is fixed for the generator, K_{sg} is the speed governor gain which is adjustable by changing lengths of various links

$\therefore$ K_{sg} is adjustable such that $K_{sg}\cdot K_t \simeq 1$

$$\therefore \quad \Delta F = \left[\frac{-K_{ps}}{1+\dfrac{K_{ps}}{R}}\right]\Delta P_D \rightarrow (4)$$

Put $K_{ps} = \frac{1}{B}$, substitute in eq ④ then it is also recognized that $K_{ps} = \frac{1}{B}$ where $B = \frac{dP_D}{df} / P.u$ [per unit MW/unit change in frequency]

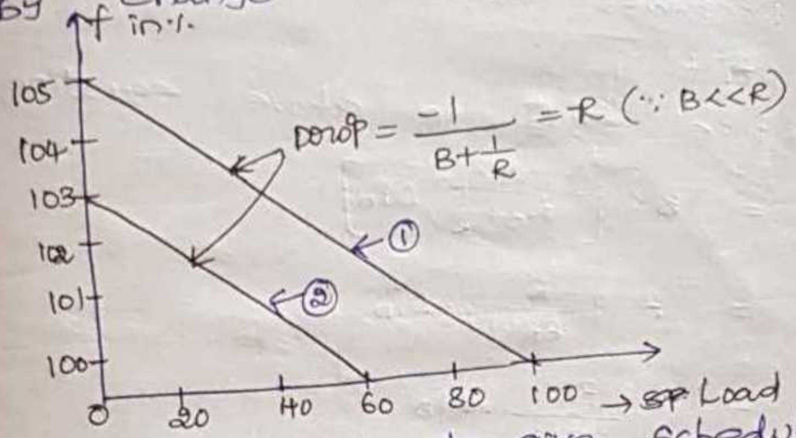
$$\therefore \Delta F = \left[\frac{\frac{-1}{BB}}{1+\frac{1}{BR}}\right] \Delta P_D \rightarrow ⑤$$

$$\Delta F = \left[\frac{-1}{B+\frac{1}{R}}\right] \Delta P_D \rightarrow ⑤$$

where $B + \frac{1}{R} = B + \frac{1}{R} = \beta$ is known as frequency response (or) regulation characteristics.

step III:

eq ⑤ gives steady state change in frequency caused by change in load.



speed changer set to give scheduled frequency at

1. 100% Load – ①
2. 60% Load – ②

Speed regulation 'R' is adjusted that changes in frequency are small (5% from no load to full load). The above graph shows the linear characteristics between frequency and load for free governer operation.

The droop (or) slope is '$\frac{-1}{B+\frac{1}{R}}$'.

when $B<<R$, then droop (or) slope = '$-R$'

Then eq ⑤ will becomes $\Delta f = -R \Delta P_D \rightarrow ⑥$

Step IV:

From the above increase in load demand

ΔP_D is met under steady state cond
Partly by increasing power generation

i.e $\Delta P_G = \frac{-1}{R} \Delta f$

Substitute eq ⑤ in eq ⑥, we get

$$\Delta P_G = \frac{-1}{R}\left[-\left(\frac{1}{B+\frac{1}{R}}\right)\Delta P_D\right]$$

$$= \left(\frac{1}{R} \cdot \frac{1}{B+\frac{1}{R}}\right)\Delta P_D$$

$$= \frac{1}{\cancel{R}} \times \frac{\cancel{R}}{BR+1} \cdot \Delta P_D$$

$$\Delta P_G = \frac{1}{BR+1} \cdot \Delta P_D$$

~~Dose~~ Decrease in system load is expressed as $B\Delta f$

Substitute eq ⑤ in above equation, we get

$$B\Delta f = B \times \left[-\left(\frac{1}{B+\frac{1}{R}}\right)\Delta P_D\right]$$

$$= B\left(\frac{-R}{BR+1}\right) \cdot \Delta P_D$$

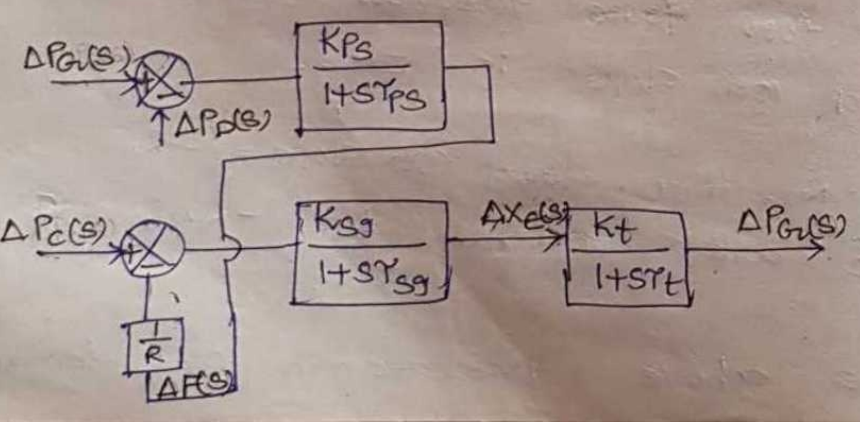
$$= \frac{-BR}{BR+1} \cdot \Delta P_D$$

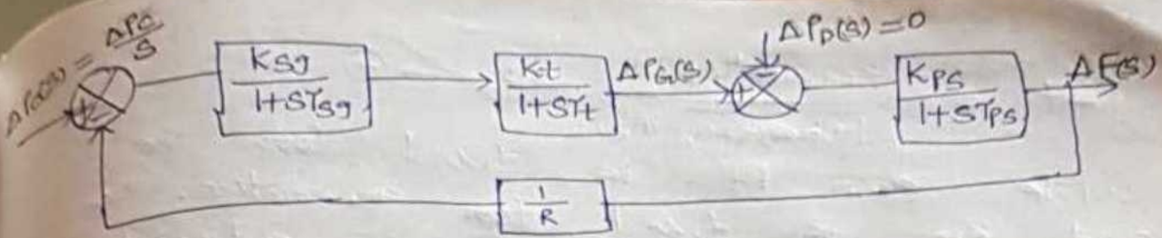
Controlled case (constant load demand with variable speed changer position):

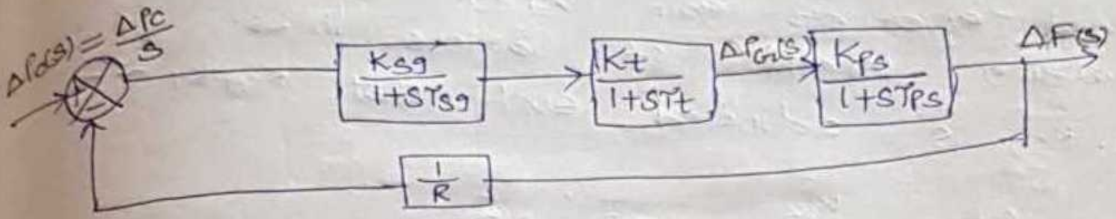
Step I:
Consider a step change in a speed changer position with a load demand remaining fixed

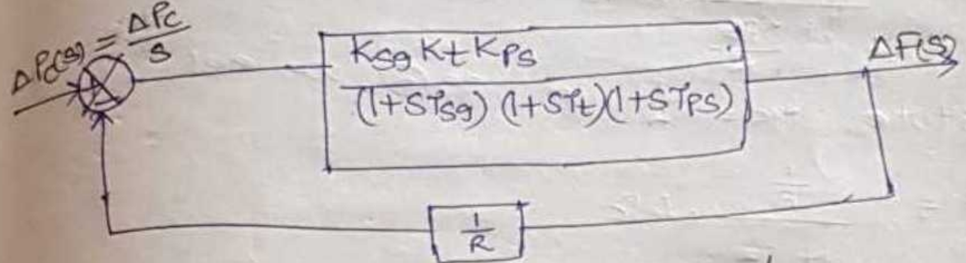
i.e $\Delta P_C(s) = \frac{\Delta P_C}{s} \rightarrow$ ①

$\Delta P_D(s) = 0 \rightarrow$ ②









$$\text{Transfer function} = \frac{\Delta F(s)}{\Delta P_c(s)} \Big|_{\Delta P_D(s)=0}$$

$$= \frac{G(s)}{1+G(s)H(s)}$$

$$= \frac{\dfrac{K_{sg} \cdot K_t \cdot K_{ps}}{(1+sT_{sg})(1+sT_t)(1+sT_{ps})}}{1 + \dfrac{K_{sg} \cdot K_t \cdot K_{ps}}{(1+sT_{sg})(1+sT_t)(1+sT_{ps})} \times \dfrac{1}{R}}$$

$$\Delta F(s) = \frac{\dfrac{K_{sg} \cdot K_t \cdot K_{ps}}{(1+\cancel{sT_{sg}})(1+\cancel{sT_t})(1+\cancel{sT_{ps}})}}{\dfrac{R(1+sT_{sg})(1+sT_t)(1+sT_{ps}) + K_{sg} \cdot K_t \cdot K_{ps} \times (\frac{1}{R})}{(1+\cancel{sT_{sg}})(1+\cancel{sT_t})(1+\cancel{sT_{ps}})R}} \cdot \frac{\Delta P_c}{s}$$

$$\Delta F(s) = \frac{K_{sg} \cdot K_t \cdot K_{ps} \; R}{R(1+sT_{sg})(1+sT_t)(1+sT_{ps}) + K_{sg} \cdot K_t \cdot K_{p} \times (\frac{1}{R})} \frac{\Delta P_c}{s} \rightarrow \text{eq} \; ③$$

Step II:

The steady state value is obtained by applying the final value theorem.

i.e $\lim_{s \to 0} s \cdot \Delta F(s) \Rightarrow \Delta f \,/\, \Delta P_D(s) = 0$

$$\Delta f = \frac{K_{sg} \cdot K_t \cdot K_{ps}}{1 + K_{sg} K_t K_{ps} \times (\frac{1}{R})} \cdot \Delta P_c \rightarrow (4)$$

while gain K_t is fixed for the turbine and K_{ps} is fixed for generator, K_{sg} is speed governor gain which is adjustable by changing lengths of various links.

$\therefore K_{sg}$ is adjusted such that $K_{sg} \cdot K_t \approx 1$

$$\therefore \Delta f = \frac{K_{ps}}{1 + \frac{K_{ps}}{R}} \cdot \Delta P_c \rightarrow (5)$$

substitute $K_{ps} = \frac{1}{B}$ in eq(5), we get

$$\Delta f = \frac{\frac{1}{B}}{1 + \frac{\frac{1}{B}}{R}} \cdot \Delta P_c$$

$$\Delta f = \frac{1}{B + \frac{1}{R}} \cdot \Delta P_c \rightarrow (6)$$

$$\Delta f = \frac{1}{\beta} \cdot \Delta C \rightarrow (7) \quad \text{where } \beta = B + \frac{1}{R}$$

3. speed changer and load demands are variable:

If speed changer setting is changed by ΔP_c while load demand changes by ΔP_D, the steady state frequency change is obtained as shown below

$$\Delta f = \frac{1}{B + \frac{1}{R}} [\Delta P_c - \Delta P_D]$$

$$= \frac{1}{B + \frac{1}{R}} \Delta P_c - \frac{1}{B + \frac{1}{R}} \cdot \Delta P_D$$

$$\Delta f = -\left(\frac{1}{B + \frac{1}{R}}\right) \Delta P_D + \left(\frac{1}{B + \frac{1}{R}}\right) \Delta P_c$$

According to above equation the frequency change caused by load demand can be compensated by changing the setting of speed changer

If $\Delta P_c = \Delta P_D$ then $\Delta f = 0$

H. Dynamic analysis of single area control:

step I: The dynamic response means changes in frequency as a function of time immediately after disturbance before it reaches the new steady state condition.

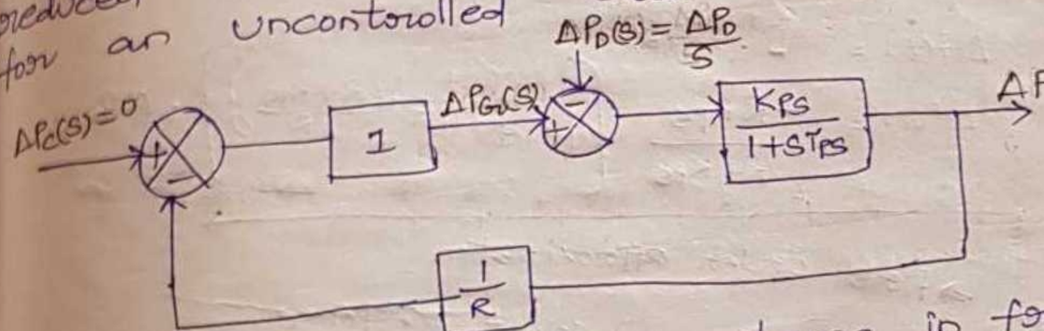
The analyzation of dynamic response requires the solution of dynamic equation of system for a given disturbance

step II: The inverse laplace transforms of $\Delta F(s)$ gives variation of frequency with respective to time for a given step change in load demand for a load frequency control system,

For a $T_{sg} < T_t < T_{ps}$

The typical values are $T_{sg} = 0.4$ sec, $T_t = 0.5$ sec, $T_{ps} = 20$ sec

step III: If T_{sg} and T_t are considered negligible compared to T_{ps} and by adjusting $K_{sg} \cdot K_t \simeq 1$, the block diagram of load frequency control of power system of an isolated system is reduced to a first order system with $\Delta P_C(s)=0$ for an uncontrolled case.



From the above figure, change in frequency is given by

$$\left.\frac{\Delta F(s)}{\Delta P_D(s)}\right|_{\Delta P_C(s)=0} = \frac{G(s)}{1+G(s)H(s)}$$

$$\frac{\Delta F(s)}{\Delta P_D(s)} = \frac{\frac{K_{ps}}{1+sT_{ps}}}{1+\frac{K_{ps}}{1+sT_{ps}}\cdot\frac{1}{R}}$$

$$\Delta F(s) = \frac{\frac{K_{ps}}{1+sT_{ps}}}{1+\frac{K_{ps}}{1+sT_{ps}}\cdot\frac{1}{R}} \cdot \Delta P_D(s)$$

$$= \frac{\frac{K_{ps}}{1+sT_{ps}}}{1+\frac{K_{ps}}{1+sT_{ps}}\cdot\frac{1}{R}} \cdot \frac{-\Delta P_D}{s}$$

$$\Delta F(s) = \frac{-K_{ps}}{sT_{ps}+\left(\frac{K_{ps}+R}{R}\right)} \cdot \frac{\Delta P_D}{s} \rightarrow (1)$$

Divide both numerator and denominator by T_{ps}, we get

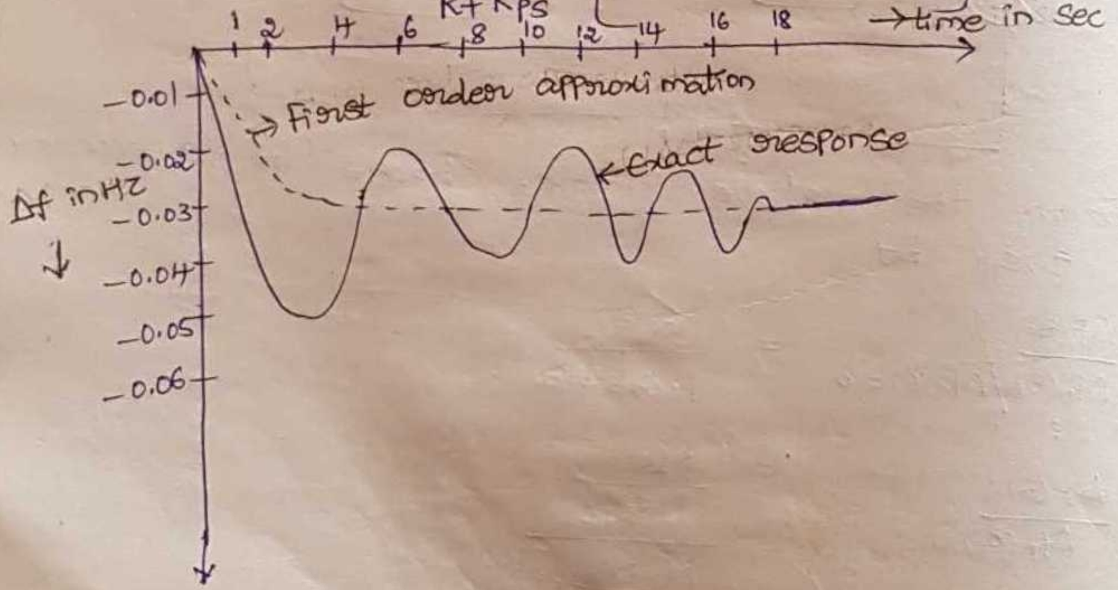
$$\Delta F(s) = \frac{\frac{-K_{ps}}{T_{ps}}}{\frac{sT_{ps}+\left(\frac{K_{ps}+R}{R}\right)}{T_{ps}}} \cdot \frac{\Delta P_D}{s}$$

$$= \frac{\frac{-K_{ps}}{T_{ps}}}{s+\frac{K_{ps}+R}{RT_{ps}}} \cdot \frac{\Delta P_D}{s} \rightarrow (2)$$

Apply inverse laplace transform, we get

$$\Delta f(t) = L^{-1}\cdot \Delta f(s)$$

$$\Delta f(t) = \frac{-RK_{ps}}{R+K_{ps}}\left[1-e^{\left(\frac{-t}{T_{ps}}\right)\left(\frac{R+K_{ps}}{R}\right)}\right]\cdot \Delta P_D$$



$$\Delta F(s) = \left[\frac{\frac{-K_{ps}}{T_{ps}}}{s+\left(\frac{K_{ps}+R}{R T_{ps}}\right)}\right] \frac{\Delta P_D}{s}$$

$$= \frac{-K_{ps}\cdot\Delta P_D}{T_{ps}} \times \frac{1}{s\left[s+\frac{K_{ps}+R}{R\cdot T_{ps}}\right]}$$

$$= \frac{-K_{ps}\cdot\Delta P_D}{T_{ps}} \times \frac{R T_{ps}}{K_{ps}+R}\left[\frac{1}{s} - \frac{1}{s+\frac{K_{ps}+R}{R T_{ps}}}\right]$$

$$\frac{1}{s\left(s+\frac{K_{ps}+R}{R T_{ps}}\right)} = \frac{1}{s(s+\alpha)}$$

$$\frac{1}{s(s+\alpha)} = \frac{A}{s} + \frac{B}{s+\alpha}$$

$$\frac{1}{\cancel{s(s+\alpha)}} = \frac{A(s+\alpha)+Bs}{\cancel{s(s+\alpha)}}$$

$$1 = (A+B)s + A\alpha$$

There are no s-coefficients, so $A+B=0$
$A=-B$

Constant term, $A\alpha = 1 \Rightarrow A = \frac{1}{\alpha}$

$A=-B \Rightarrow B = \frac{-1}{\alpha}$

$$\therefore \frac{1}{s(s+\alpha)} = \frac{1}{\alpha s} - \frac{1}{\alpha(s-\alpha)}$$

$$= \frac{1}{\alpha}\left[\frac{1}{s} - \frac{1}{s+\alpha}\right]$$

$$= \frac{1}{\frac{K_{ps}+R}{R T_{ps}}}\left[\frac{1}{s} - \frac{1}{s+\frac{K_{ps}+R}{R T_{ps}}}\right]$$

$$= \frac{R T_{ps}}{K_{ps}+R}\left[\frac{1}{s} - \frac{1}{s+\frac{K_{ps}+R}{R T_{ps}}}\right]$$

$L^{-1}\left(\frac{1}{s}\right) = 1$; $L(1) = \frac{1}{s} \Rightarrow \frac{1}{s+\frac{K_{ps}+R}{R T_{ps}}}$

$$L^{-1}\left(\frac{1}{s+a}\right) = e^{-at} = e^{-\left(\frac{K_{ps}+R}{R T_{ps}}\right)t}$$
$$= e^{-\frac{t}{T_{ps}}\left(\frac{R+K_{ps}}{R}\right)}$$

$$\Delta f(t) = L^{-1}\Delta f(s)$$

$$\Delta f(t) = \frac{-RK_{ps}}{R+K_{ps}}\left[1-e^{-\left(\frac{K_{ps}+R}{R\,T_{ps}}\right)t}\right]\Delta P_D$$

$$= \frac{-RK_{ps}}{R+K_{ps}}\left[1-e^{\left[\frac{-t}{T_{ps}}\left(\frac{R+K_{ps}}{R}\right)\right]}\right]\Delta P_D$$

Problems:

1. A 500mw generator has a speed regulation of 4%. If the frequency drops by 0.12Hz with an uncharge reference. Determine the increase in turbine power.

Sol

$\Delta f = -0.12$ Hz

$$\Delta P_G = \frac{-1}{R}\Delta f$$

$$R = \frac{4}{100}\times 50$$

$$R = 2 \text{ Hz/mw}$$

$$R = \text{Hz/p.u.mw}$$

$$R = \frac{2}{500} = 0.004 \text{ Hz/p.u.mw}$$

$$\therefore \Delta P_G = \frac{-1}{0.004}\times -0.12$$

$$\Delta P_G = 30 \text{ mw}$$

2. A single area system has the following data. Speed regulation $R = 4$ Hz/p.u.mw. Damping co-efficient $B = 0.1$ p.u.mw/Hz. Power system time constant $T_{ps} = 10$ sec. Power system gain $K_{ps} = 75$ Hz/p.u.mw. when a 2% load change occurs, determine the area frequency regulation controller and the static frequency error. What is the value of steady state error if the governor was blocked.

Sol Given data,

Speed regulation, $R = 4$ Hz/p.u.mw

Damping Coefficient $B = 0.1$ p.u.mw/Hz

Power system time constant $T_{ps} = 10$ sec

Power system gain $K_{ps} = 75$ Hz/p.u.mw

Change in load $\Delta P_D = 2\%$

Case I: Power frequency regulation controller, AFRC (β)

$$\beta = B + \frac{1}{R}$$

$$= 0.1 + \frac{1}{4}$$

$$\beta = 0.35 \text{ pu mw/HZ}$$

Static frequency error, $\Delta f_{ss} = -\left(\frac{1}{B+\frac{1}{R}}\right) \Delta P_D$

$$= \frac{-1}{0.35} \times \frac{2}{100}$$

$$\Delta f_{ss} = -0.05714 \text{ HZ}$$

New frequency, $f' = f + \Delta f_{ss}$

$$= 50 - 0.05714$$

$$f' = 49.942 \text{ HZ}$$

Case II:

when governor is blocked, feedback loop is not present, therefore $R \to \infty$

$$\therefore \frac{1}{R} = 0$$

AFRC, $\beta = B + \frac{1}{R} = 0.1 + 0 = 0.1$ pu mw/HZ

Static frequency error, $\Delta f_{ss} = \frac{-1}{B+\frac{1}{R}} \cdot \Delta P_D$

$$= \frac{1}{0.1+0} \times \frac{2}{100}$$

$$= 0.2$$

3. A 100 mVA synchronous generator operates initially at no load at 3000 rpm at 50HZ. A 25mw load is suddenly applied to system. Due to time lag in governor system, steam value of turbine commences to open after 0.6 seconds. Determine the frequency of system before steam flow commenses to increase to meet given load. Given $H = 5$ mw-sec per mVA of generator capacity.

Sol Given data,

Rated capacity of synchronous generator, $P_R = 100$m

No load speed $N_s = 3000$rpm

Frequency $f = 50\,Hz$

Load supplied to machine, $\Delta P_D = 25\,mw$.

$H = 5\,mw\,sec/mVA$

$t = 0.6\,sec$

$W_{KE}^{\circ} = H \cdot P_r$

Kinetic energy of rotating parts of generator and turbine before disturbance occurs.

$W_{KE}^{\circ} = 5 \times 100 = 500\,mw\text{-}sec$

Excess energy input to rotating parts in 0.6 sec

$W_{KE} = \Delta P_D \times t = 25 \times 0.6 = 15\,mw\text{-}sec$

Since stored kinetic energy proportional to frequency^2 i.e f^2. Frequency at end of 0.6 sec is

$$f' = f\sqrt{\frac{W_{KE}^{\circ} - W_{KE}}{W_{KE}^{\circ}}} = 50 \times \sqrt{\frac{500-15}{500}} = 49.24\,Hz$$

4. A 100 mVA synchronous generator is running on full load at 50 Hz frequency. A 40 mw load is suddenly removed. Due to time lag in governor system, steam valve of turbine begins to close after 0.5 sec. Determine change in frequency that occurs in this time $H = 5\,mw\,sec$ of generator capacity.

Sol Given data,

$P_r = 100\,mVA$

$f = 50\,Hz$

$\Delta P_D = 40\,mw$

$t = 0.5\,sec$

$H = 5\,mw\,sec.$

$W_{KE}^{\circ} = 5 \times 100 = H \cdot P_r = 500\,mw\text{-}sec$

$W_{KE} = \Delta P_D \times t = 40 \times 0.5 = 20\,mw.sec$

$$f' = f\sqrt{\frac{W_{KE}^{\circ} - W_{KE}}{W_{KE}^{\circ}}} = 50 \times \sqrt{\frac{500+20}{500}} = 50.99\,Hz$$

Two Generators rated 300 MW and 600 MW are operating in Parallel. These governors have a droop characteristics of 4% and 5% respectively from no load to full load. Assuming that generators are operating at 50Hz at no load. Determine how would a load of 750 MW be shared between them. What will be system frequency at this load. Assuming free governor operation.

Sol Given data

Rated Capacity of generator I, $P_{r1} = 300$ MW

Rated Capacity of generator II, $P_{r2} = 600$ MW.

Speed regulation of generator I, $r_1 = 4\%$ of rated frequency.

Speed regulation of Generator II, $r_2 = 5\%$ of rated frequency.

Total load, $P_D = 750$ MW (It has to share between two generators).

Change in supply (or) system frequency, $\Delta f = ?$

Load on generator I be 'x'

Load on generator II is '$750-x$'

change in frequency for generator I,

$$\frac{\Delta f}{x} = \frac{\frac{4}{100} \times 50}{300}$$

$$\Rightarrow \Delta f = 0.0067x \rightarrow (1)$$

change in frequency for generator II,

$$\frac{\Delta f}{750-x} = \frac{\frac{5}{100} \times 50}{600}$$

$$\Delta f = (750-x)\,0.0042$$

$$\Delta f = 3.15 - 0.0042x \rightarrow (2)$$

Equating (1) and (2), we get

$$3.15 - 0.0042x = 0.0067x$$

$$3.15 - 0.0042x - 0.0067x = 0$$

$$\Rightarrow 3.15 - 0.0042x$$

$$\Rightarrow 3.15 - 0.0109x = 0$$

$3.15 = 0.0109x$

$x = \frac{3.15}{0.0109} = 288.990$ mw

$\therefore$ Load on generator I = 288.99 mw

Load on generator II = $750 - x = 750 - 288.99 = 461.01$ mw

change in frequency for generator I is

$$\Delta f = 50 - \frac{\frac{4}{100} \times 50}{300} \cdot \Delta P_D = 50 - \frac{\frac{4}{100} \times 50}{300} \times 288.99$$

$\Delta f =$ ~~49.99~~ 48.07 HZ

6. Two generators rated 200 mw and 400 mw are operating in Parallel. The droop characteristics of their goverrners are 4% and 5% respectively from no load to full load. Assuming that goverrners operating at 50HZ at no load. How would a load of 600mw be shared between them, what will be system frequency at this load by assuming free goverrner operation.

Sol Given data,

Rated Capacity of generator I, $P_{r1} = 200$ mw

Rated Capacity of generator II, $P_{r2} = 400$ mw.

speed regulation of generator I, $r_1 = 4\%$ of rated frequency

II, $r_2 = 5\%$ of rated frequency.

Load, $P_D = 600$ mw

Change in supply frequency, $\Delta f = ?$

Load on generator I be 'x'

Load on generator II = 600 − x

change in frequency for generator I

$$\frac{\Delta f}{x} = \frac{\frac{4}{100} \times 50}{200}$$

$$\Delta f = 0.01x \rightarrow ①$$

change in frequency for generator II,

$$\frac{\Delta f}{600-x} = \frac{\frac{5}{100}\times 50}{400}$$

$$\Delta f = (600-x)\,0.0063$$

$$\Delta f = 3.78 - 0.0063x \rightarrow ②$$

Equating ① and ②, we get

$$0.01x = 3.78 - 0.0063x$$

$$\Rightarrow 3.78 - 0.0163x = 0$$

$$\Rightarrow x = \frac{3.78}{0.0163} = 231.901\ \text{mw}$$

The rated capacity of generator I is 200mw but generator is exceeding that. So unit is violating its constraint limit.

∴ Load on generator $I = x = 231.901$ mw

7. The following data is available for an isolated area, capacity of 4000mw, frequency of 50Hz operating load of 2500mw, speed regulation constant = 2Hz/p.u. mw, Inertia constant is 5sec, 2% of change in load takes place for 1% of change in frequency. Find

(i) Largest change in step load. It steady state frequency is not to exceed by more than 0.2Hz

(ii) change in frequency as a function of time after a step change in load.

Sol Given data,

Generator capacity, $P_r = 4000$ mw

operating Load, $P_D = 2500$ mw

Frequency $f = 50$ Hz

Speed regulation constant, $R = 2$ Hz/p.u.mw

Inertial constant, H = 5 sec

$\partial P_D = \frac{2}{100} \times 2500 = 50$ mw

$\partial f = \frac{1}{100} \times 50 = 0.5$ Hz

(i) ΔP_D at $\Delta f = 0.2$ Hz:

$$\Delta f = \frac{-1}{\beta} \cdot \Delta P_D$$

$$\Delta P_D = -\beta \Delta f$$

$$= -\left(B + \frac{1}{R}\right) \cdot \Delta f$$

$$B = \frac{\partial P_D}{\partial f} = \frac{50}{0.5} = 100 \text{ mw/Hz}$$

$$B = \frac{100}{4000} = 0.025 \text{ p.u mw/Hz}$$

$$\Delta P_D = -\left(0.025 + \frac{1}{2}\right) \times 0.2$$

$$\Delta P_D = -0.105 \text{ p.u. mw}$$

$$\Delta P_D = -0.105 \times 4000 = -420 \text{ mw}$$

(ii) $$\Delta f = \frac{-R \cdot K_{PS}}{R + K_{PS}} \left[1 - e^{-t/\tau_{PS}\left(\frac{R + K_{PS}}{R}\right)}\right] \cdot \Delta P_D$$

$$K_{PS} = \frac{1}{B} = \frac{1}{0.025} = 40 \text{ Hz/p.u.mw}$$

$$\tau_{PS} = \frac{2H}{Bf} = \frac{2 \times 5}{0.025 \times 50} = 8 \text{ sec.}$$

$$\Delta f = -\frac{2 \times 40}{2 + 40} \left[1 - e^{-t/8\left(\frac{2+40}{2}\right)}\right] \times -420.$$

8. A control area has a total rated capacity of 10000 mw. The regulation for all units in area is 2Hz/p.u.mw. A 1% change in frequency causes a 1% change in load. If system operates at half of rated capacity and load increased by 2%. Find
(i) Static frequency drop.
(ii) If speed governor loop were open, what would be frequency drop.

Given data,

Capacity of the unit = 10000 mw.

Regulation, r = 2 Hz/P.u.mw

at half rated capacity, $P_D = \frac{10000}{2} = 5000$ mw

$B = \frac{\partial P_D}{\partial f}$

$\partial P_D = \frac{1}{100} \times 5000 = 50$ mw

$\partial f = \frac{1}{100} \times 50 = 0.5$ Hz

$B = \frac{50}{0.5} = 100$ mw/Hz

B in Per Unit $= \frac{100}{10000} = 0.01$ P.u. mw/Hz.

Finding terms:

(i) Δf:

$\Delta f = \frac{-1}{\beta} \cdot \Delta P_D$

$= \frac{-1}{B + \frac{1}{R}} \cdot \Delta P_D$

$\Delta P_D = \frac{2}{100} \times 5000 = 100$ mw $\quad \Delta P_D$ in Per Unit mw $= \frac{100}{10000} = 0.01$ P.u

$\Delta f = \frac{-1}{0.01 + \frac{1}{2}} \times \frac{100}{10000} = -0.0196$ P.u.Hz

(ii) when speed governer loop is open, $\frac{1}{R} = 0$

$\therefore \Delta f = \frac{-1}{0.01} \times 0.01 = -1$ P.u.Hz.

Area control Error (ACE) of an isolated system,

(or) Proportional + Integral controller of an isolated system:

In the steady state characteristics of load frequency, with speed changer adjustment, the speed changer move downwards to a large extent due to sudden change in load. Therefore frequency changes due to sudden change in speed. For better performance the frequency must be maintain constant. In the load frequency control area, change in frequency (Δf) is known as area control error

$\therefore$ ACE = Δf

Under steady state condition, ACE = $\Delta f = 0$

Ex: For small variations in frequency error reading synchronous clock shows time error = $\int (ACE)\, dt$

because frequency error Due to the integration, and will will get added up accumulatively frequency error rise to significant value of so control strategies are used to reduce the errors.

Integral Controller Action:

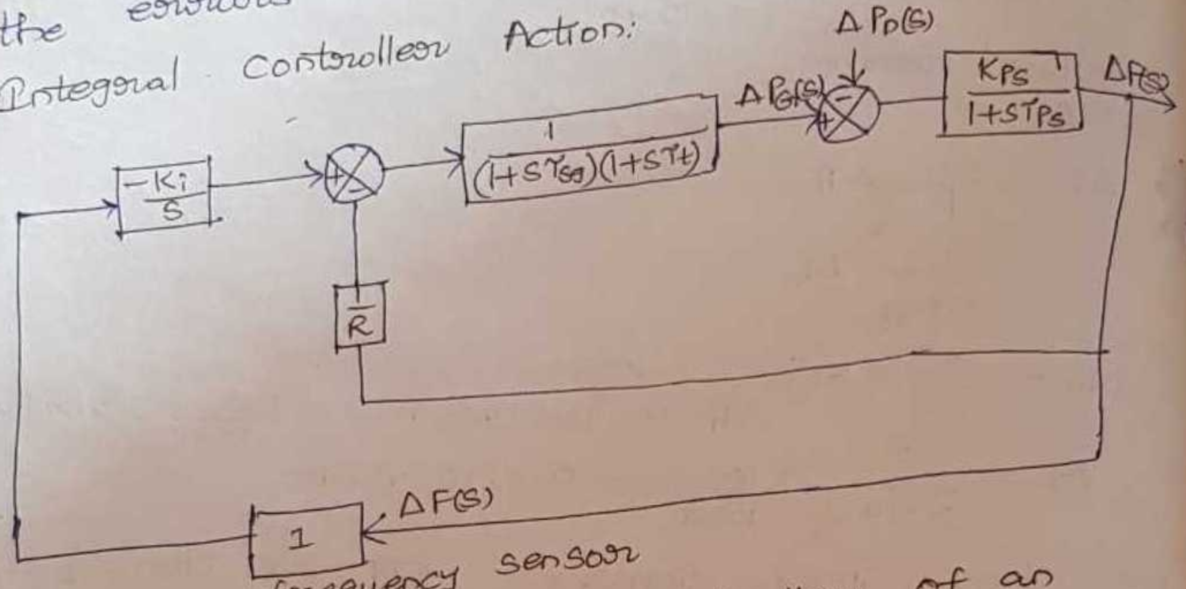


Fig. proportional + Integral controller of an isolated system.

The integral controller is composed of a frequency sensor and an integrator. The frequency sensor measures the frequency error (Δf) and this error signal is fed into integrator. The input to the integrator is called area control error i.e., a signal from Δf is fed through integrator to speed changer as shown in the above block diagram.

The integrator produces $\Delta P_C = -K_i \int \Delta f \cdot dt$

$= -K_i \int ACE \cdot dt$

The system now modifies the proportional+ integral controller gives zero steady state error.

i.e., Δf / steady state error $= 0$

The signal $\Delta P_c(s)$ generated by the integral controller must be of opposite sign to $\Delta f(s)$ which accounts for negative sign in a block for integral controller.

Assumptions:

1. The time constant of speed governer (τ_{sg}) and time constant of turbine (τ_t) are both neglected i.e., $\tau_{sg} = \tau_t = 0$
2. The speed changer is an electro mechanical device and hence its response is not instantaneous. However it is assumed to be instantaneous in present analysis.
3. All non-linearities in equipment such as dead zone, dead time etc., are neglected.
4. The generator can change its generation (ΔP_G) has fast as it is commanded by the speed changer.
5. The ACE is a continuous signal.

$$\Delta P_c = -K_I \int(\Delta f)\,dt$$

Taking laplace transform to above equation, we get

$$\Delta P_c(s) = -\frac{K_I}{s} \cdot \Delta f(s)$$

For a sudden step change of load demand,

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

From the above block diagram, we can write the equation as

$$\left[-\frac{K_i}{s}\Delta F(s) - \frac{1}{R}\Delta F(s)\right] \frac{1}{(1+s\tau_{sg})(1+s\tau_t)} = \Delta P_G(s)$$

$$-\left[\frac{1}{R} + \frac{K_i}{s}\right] \frac{1}{(1+s\tau_{sg})(1+s\tau_t)} \cdot \Delta F(s) = \Delta P_G(s)$$

But we know that,

$$\Delta F(s) = \frac{K_{PS}}{1+s\tau_{PS}}\left[\Delta P_G(s) - \Delta P_D(s)\right]$$

$$\Delta F(S) = \frac{K_{PS}}{1+ST_{PS}} \Delta P_G(S) - \frac{K_{PS}}{1+ST_{PS}} \cdot \Delta P_D(S)$$

substitute $\Delta P_G(S)$ value in above equation, we get

$$\Delta F(S) = \frac{K_{PS}}{1+ST_{PS}} \left[\left[-\frac{1}{R}+\frac{K_i}{S}\right] \frac{1}{(1+ST_{sg})(1+ST_t)} \Delta F(S)\right] - \frac{K_{PS}}{1+ST_{PS}} \cdot \Delta P_D(S)$$

$$\Delta F(S) \cdot \left[1+ \frac{K_{PS}}{1+ST_{PS}} \left(\frac{1}{R}+\frac{K_i}{S}\right)\left(\frac{1}{(1+ST_{sg})(1+ST_t)}\right)\right] = \frac{-K_{PS}}{1+ST_{PS}} \cdot \Delta P_D(S)$$

$$\Delta F(S) = \frac{\frac{-K_{PS}}{1+ST_{PS}} \cdot \frac{\Delta P_D(S)}{S}}{1+\frac{K_{PS}}{1+ST_{PS}}\left(\frac{1}{R}+\frac{K_i}{S}\right)\left(\frac{1}{(1+ST_{sg})(1+ST_t)}\right)}$$

By applying steady state final value theorem,

$$\Delta f(t)\Big|_{\text{steady state}} = \lim_{S\to 0} S \cdot \Delta f(S)$$

and also consider the first assumption. $T_{sg} = T_t = 0$, then the equation becomes

$$\Delta F(S) = \frac{-K_{PS}}{1+ST_{PS}+K_{PS}\left(\frac{1}{R}+\frac{K_i}{S}\right)} \cdot \Delta P_D$$

$$= \frac{-K_{PS}}{T_{PS}} \left[\frac{1}{\frac{1}{T_{PS}}+S+\frac{K_{PS}}{T_{PS}}\left(\frac{1}{R}+\frac{K_i}{S}\right)}\right] \cdot \Delta P_D$$

$$= -\frac{K_{PS}}{T_{PS}} \left[\frac{1}{S^2+\left(1+\frac{K_{PS}}{R}\right)\frac{S}{T_{PS}}+\frac{K_{PS}K_i}{T_{PS}}}\right] \cdot \Delta P_D$$

The nature of $\Delta F(t)$ depends on roots of above characteristic equation

i.e $S^2+\left(1+\frac{K_{PS}}{R}\right)\frac{S}{T_{PS}}+\frac{K_{PS}K_i}{T_{PS}} = 0$

$\frac{\left(1+\frac{K_{PS}}{R}\right)^2}{(2T_{PS})^2}$ adding and subtracting to above equation, we get

$$\Rightarrow s^2 + \left(1+\frac{K_{ps}}{R}\right)\frac{s}{T_{ps}} + \frac{K_{ps}K_i}{T_{ps}} + \left(\frac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2 - \left(\frac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2 = 0$$

$$\Rightarrow s^2 + \left(\frac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2 + \left(1+\frac{K_{ps}}{R}\right)\frac{s}{T_{ps}} + \frac{K_{ps}K_i}{T_{ps}} - \left(\frac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2 = 0$$

$$\Rightarrow \left(s + \frac{\left(1+\frac{K_{ps}}{R}\right)}{2T_{ps}}\right)^2 + \frac{K_{ps}K_i}{T_{ps}} - \left(\frac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2 = 0$$

The above equation is in the form of

$(s+\alpha)^2 + \omega^2 = 0$

where $\alpha = \dfrac{1+\frac{K_{ps}}{R}}{2T_{ps}}$ is a positive real number.

$$\omega = \left[\frac{K_{ps}K_i}{T_{ps}} - \left(\frac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2\right]^{\frac{1}{2}}$$

The nature of roots of equation depends on (i) $\omega^2 = 0$ (ii) $\omega^2 > 0$ (iii) $\omega^2 < 0$

case I: $\omega^2 = 0$:

The characteristic equation has a repeated root (α). Hence expression for ΔP contains the terms of the type $e^{-\alpha t}$ (or) $te^{-\alpha t}$

∴ The response is critically damped one

i.e $\dfrac{K_{ps}K_i}{T_{ps}} - \left(\dfrac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2 = 0$

$$\Rightarrow \frac{K_{ps}K_i}{T_{ps}} = \left(\frac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2$$

$$\Rightarrow K_i = \frac{T_{ps}}{K_{ps}}\left(\frac{1+\frac{K_{ps}}{R}}{2T_{ps}}\right)^2$$

$$K_{i\,critical} = \frac{1}{4T_{ps}K_{ps}}\left(1+\frac{K_{ps}}{R}\right)^2$$

Case II: $\omega^2 > 0$:

Now $(s+\alpha)^2 = -\omega^2$

Where "ω^2" is a positive real number.

$s+\alpha = \pm j\omega$ or $s = -\alpha \pm j\omega$

The time response $\Delta F(t)$ will becomes of the type $e^{-\alpha t}\sin\omega t$ damped oscillatory terms is called a and $e^{-\alpha t}\cos\omega t$, this case super critical case.

In this case, $K_i > K_{i\,critical}$

Case III: $\omega^2 < 0$:

Then ω^2 is a negative real number. So $-\omega^2$ is a positive real number

$(s+\alpha)^2 = -\omega^2$ which

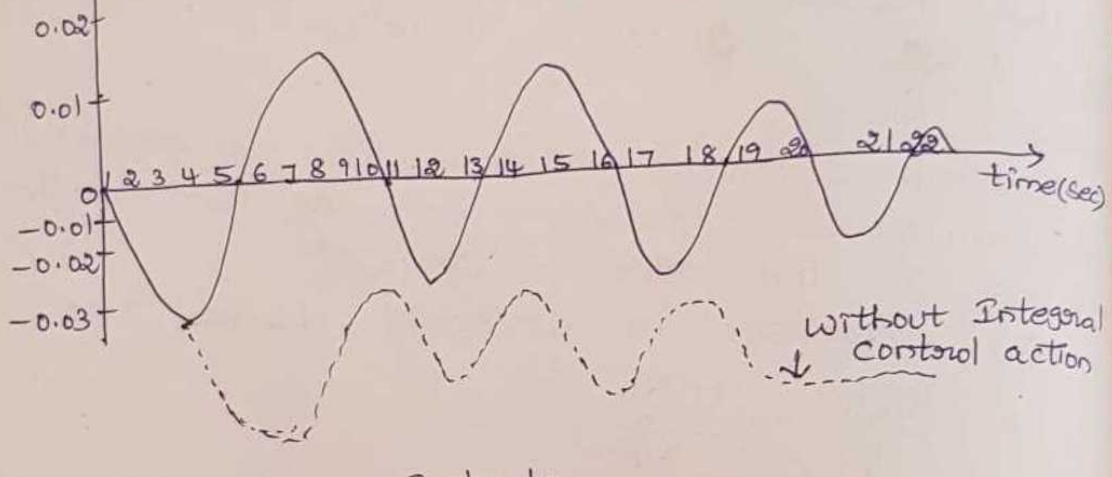
$\omega^2 = \gamma^2$ (say)

$s+\alpha = +\gamma \ (\gamma < \alpha)$ (or) $s = -\alpha - \gamma \ (\gamma > \alpha)$

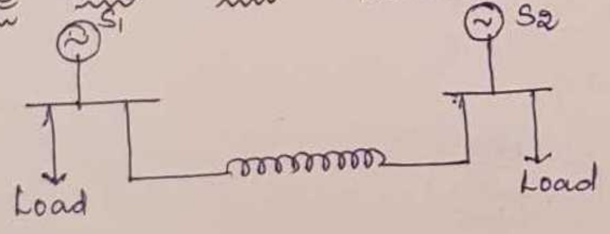
$s = -\alpha + \gamma$

$s = -\beta_1$ (or) $-\beta_2$ (say)

In this case the time response $\Delta f(t)$ will comprise terms of type $e^{-\beta_1 t}$ (or) $e^{-\beta_2 t}$



Tie Line Bias Control:



If a system consist of more than one machine or single machine connected to a group of loads then it is necessary to maintain constant speed and frequency.

If a change in load is taken by two machines running in parallel as shown in above figure, the complexity of system is increased. The Possibility of sharing the load by two machines is as follows.

1. Flat frequency Regulation.
2. Parallel frequency Regulation.
3. Flat tie line loading Control.

1. Flat Frequency Regulation:

Let us Consider S_1 and S_2 are two stations interconnected through a tie line. If change in load is either S_1 or S_2 and if generation of S_1 alone is regulated to adjust this change in order to maintain constant frequency, then this method of regulation is known as flat frequency regulation. under this condition S_2 is operating as base load.

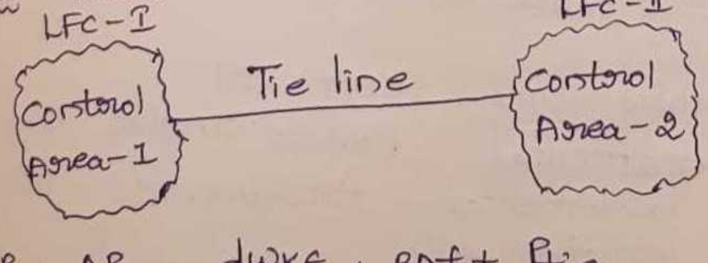
2. Parallel Frequency Regulation:

The other Possibility of change in load is that both S_1 and S_2 would regulate their generation to maintain constant frequency. This method of regulation is known as Parallel frequency Regulation.

3. Flat tie line loading control:

The third Possibility is that change in a particular area is taken care of by the generator in that area, thereby the tieline loading remains Constant. This method of regulating the generators for keeping the constant frequency is known as flat tie line loading control.

Two Area Load Frequency Control:



$$\Delta P_G - \Delta P_D = \frac{dW_{KE}}{dt} + B\Delta f + P_{tie}$$

Step I:

An extended Power system can be divided into a no. of load frequency control areas interconnected by means of tie lines.

The main control objective is to regulate frequency of each area and simultaneously regulate the tie line power.

It is assumed that each control area can be represented by an equivalent speed governor, turbine and generator.

In an isolated control area, the incremental power $\Delta P_G - \Delta P_D$ was accounted by $\frac{dW_{KE}}{dt} + B\Delta f$

In an interconnected system,

Since a tieline transports power in (or) out of an area, this must be taken into account in incremental power balance equation of two area i.e.,

$$\Delta P_G - \Delta P_D = \frac{dW_{KE}}{dt} + B\Delta f + \Delta P_{tie}$$

$\therefore$ Power transported out of control area 1 is given by

$$P_{tie1} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1^\circ - \delta_2^\circ) \rightarrow ①$$

where $\delta_1^\circ, \delta_2^\circ$ = Power angles of equivalent machines of the two areas.

<u>step II</u>:

For incremental changes in δ_1 and δ_2, the incremental tieline power can be expressed as (differentiating eq ① w.r.to Δ)

$$\Delta P_{tie1}(p.u) = T_{12}(\Delta\delta_1 - \Delta\delta_2) \rightarrow ②$$

$$\because T_{12} = \frac{|V_1||V_2|}{X_{12} \cdot P_{r1}} \cos(\delta_1 - \delta_2) \rightarrow ③$$

where T_{12} = synchronizing coefficient

Since the incremental power angles are integrals of incremental frequencies then eq ② can be written as

$$\Delta P_{tie1,\,p.u} = 2\pi T_{12}\left(\int \Delta f_1 dt - \int \Delta f_2 dt\right) \rightarrow ④$$

$$\because V = \frac{d}{t}$$

$$\Delta w = \frac{\Delta f}{\Delta t}$$

$\Delta\delta = \Delta\omega \Delta t$
$= 2\pi \Delta f \Delta t$
$= 2\pi \Delta f\, dt$

where Δf_1 and Δf_2 are incremental frequency changes of area 1 and area 2 respectively.

step III:
the incremental tie line power out of area 2 is given by

$$\Delta P_{tie2}\,(p.u) = 2\pi T_{21}\left[\int \Delta f_2\, dt - \int \Delta f_1\, dt\right] \rightarrow (5)$$

where $T_{21} = \left(\frac{P_{r1}}{P_{r2}}\right) a_{12} =$ synchronizing co efficient. $\rightarrow (6)$

step IV:
Incremental power balance equation can be written as

$$\Delta P_G - \Delta P_D = \frac{dW_{KE}}{dt} + B\Delta f + \Delta P_{tie}$$

For area 1,

$$\Delta P_{G1} - \Delta P_{D1} = \frac{2H_1}{f^0} \cdot \frac{d}{dt} \Delta f_1 + B_1 \Delta f_1 + \Delta P_{tie1} \rightarrow (7)$$

Taking laplace transformation on both sides of eq (7), we get

$$\Delta P_{G1}(s) - \Delta P_{D1}(s) = \frac{2H_1}{f^0} s \cdot \Delta f_1(s) + B_1 \Delta f_1(s) + \Delta P_{tie1}(s)$$

$$= \Delta f_1(s)\left[\frac{2H_1}{f^0} s + B_1\right] + \Delta P_{tie1}(s)$$

$$\left[\frac{2H_1}{f^0} s + B_1\right] \Delta f_1(s) = \Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie1}(s)$$

$$\Delta f_1(s) = \frac{\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie1}(s)}{\frac{2H_1}{f^0} s + B_1}$$

$$= \frac{\left[\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie1}(s)\right]\left(\frac{1}{B_1}\right)}{\frac{2H_1}{f^0 B_1} s + 1}$$

But we know that,

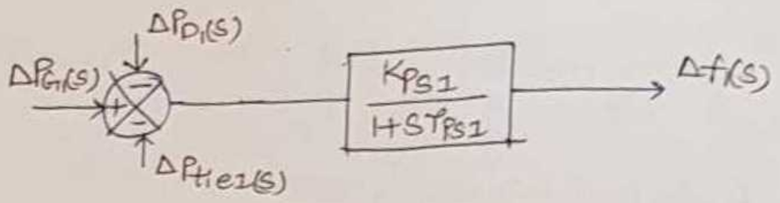
$$\frac{1}{B_1} = K_{PS1} \quad \text{and} \quad T_{PS1} = \frac{2H_1}{B_1 f_0},$$

By substituting K_{PS1} and T_{PS1} in above equation, we get

$$\Delta f_1(s) = \frac{\left[\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie1}(s)\right] K_{PS1}}{T_{PS1} \cdot s + 1}$$

$$\Delta f_1(s) = \left(\Delta P_{G_1}(s) - \Delta P_{D_1}(s) - \Delta P_{tie1}(s)\right)\left[\frac{K_{PS1}}{1+sT_{PS1}}\right] \rightarrow ⑧$$

The above equation can be represented in a block diagram as



Step V:

Taking laplace transformation for eq④, the signal $\Delta P_{tie1}(s)$ is obtained as

$$\Delta P_{tie1}(s) = \frac{2\pi T_{12}}{s}\left[\Delta f_1(s) - \Delta f_2(s)\right] \rightarrow ⑨$$

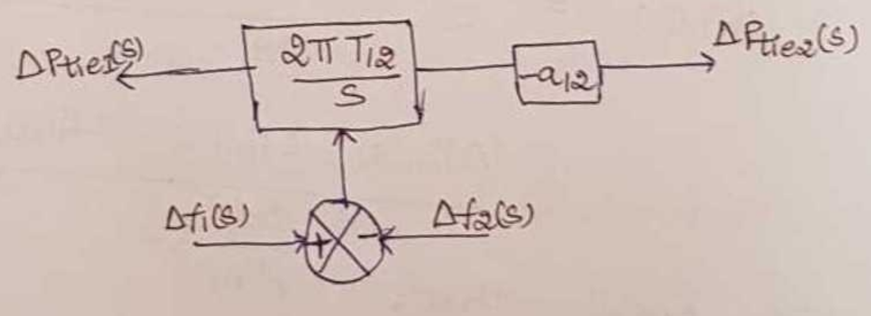
Similarly laplace transformation for eq⑤ can be obtained as

$$\Delta P_{tie2}(s) = \frac{2\pi T_{21}}{s}\left[\Delta f_2(s) - \Delta f_1(s)\right] \qquad \left[\because T_{21} = a_{12}T_{12}\right]$$

$$= \frac{2\pi a_{12} T_{12}}{s}\left[\Delta f_2(s) - \Delta f_1(s)\right]$$

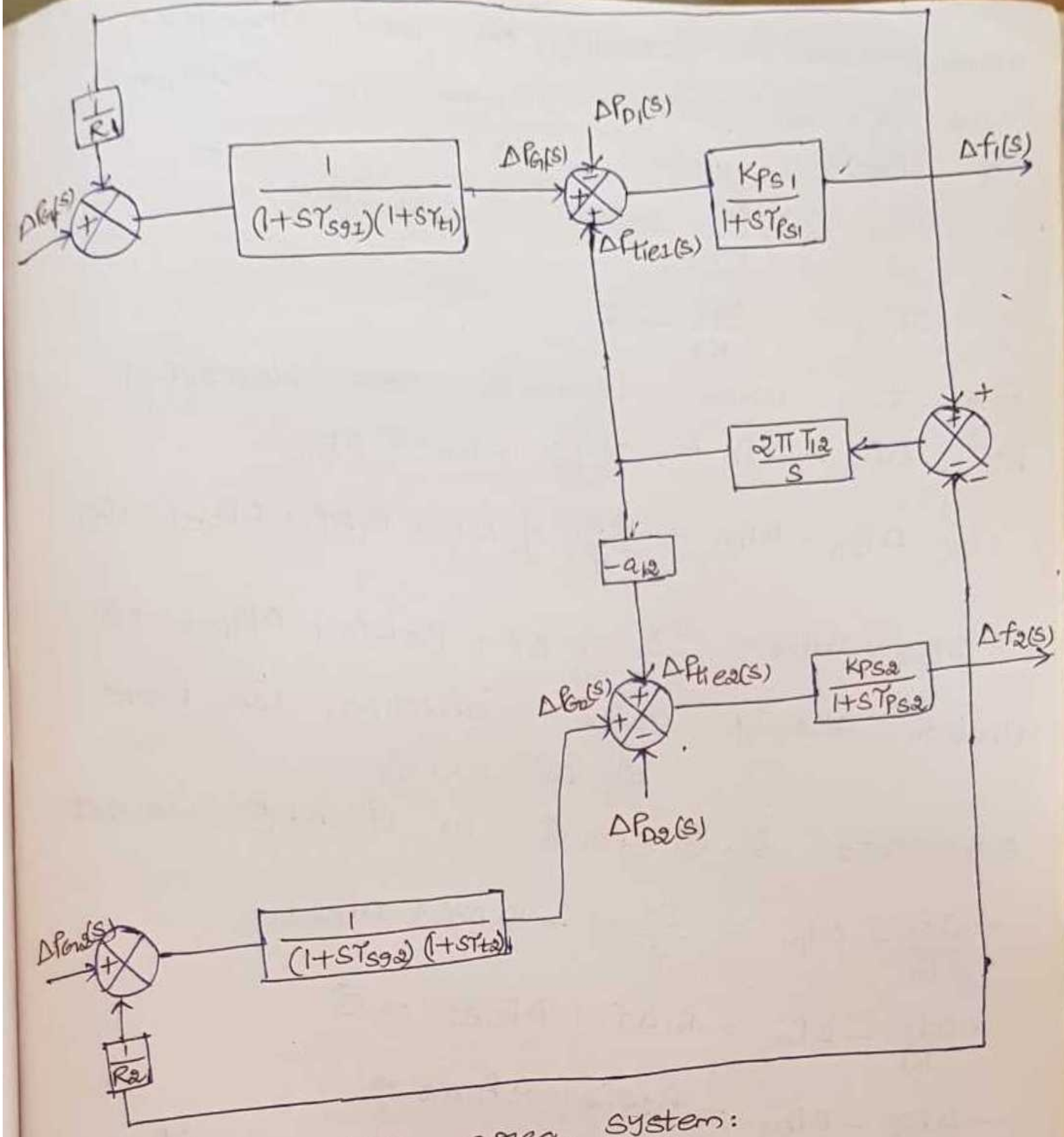
$$= -\frac{2\pi a_{12} T_{12}}{s}\left[\Delta f_1(s) - \Delta f_2(s)\right] \rightarrow ⑩$$

Eq⑨ and eq⑩ can be represented in a block diagram as



Step VI:

composite block diagram of two area load frequency control is



Response of two area system:

1. uncontrolled Case — Steady state / Dynamic state
2. Controller Case — Steady state / Dynamic State

1. uncontrolled Case:

For an uncontrolled Case $\Delta P_{C_1} = \Delta P_{C_2} = 0$ (1), speed changer positions are fixed i.e., $P_{C_1} \neq P_{C_2} \neq 0$

(1) static (or) steady state Response:

Let ΔP_{D1}, ΔP_{D2} be sudden incremental step change in the loads of control area 1 and control area 2 respectively.

ΔP_{G1}, ΔP_{G2} be incremental changes in generation in control area 1 and control area 2 as a result of load changes.

Δf is a static change in frequency, we have

$$\Delta P_{G11} = \frac{-\Delta f_1}{R_1} \rightarrow (2);$$

$$\Delta P_{G2} = -\frac{\Delta f_2}{R_2} \rightarrow (3)$$

For two area, dynamics are described by

$$\Delta P_G - \Delta P_D = \frac{dW_{KE}}{dt} + B\Delta f + \Delta P_{tie}$$

$$\Delta P_{G1} - \Delta P_{D1} = \frac{2H_1}{f^0}\frac{d}{dt}\Delta f + B_1\Delta f_1 + \Delta P_{tie1} \rightarrow (4)$$

$$\Delta P_{G2} - \Delta P_{D2} = \frac{2H_2}{f^0}\cdot\frac{d}{dt}\Delta f + B_2\Delta f_2 + \Delta P_{tie2} \rightarrow (5)$$

Under steady state condition, we have

$$\frac{d}{dt}\Delta f = 0 \rightarrow (6)$$

Substitute (2), (3) and (6) in (4) and (5), we get

$$-\frac{\Delta f_1}{R_1} - \Delta P_{D1} = \frac{2H_1}{f^0}(0) + B_1\Delta f_1 + \Delta P_{tie1}$$

$$-\frac{\Delta f_1}{R_1} - \Delta P_{D1} = B_1\Delta f_1 + \Delta P_{tie1} \rightarrow (7)$$

$$-\frac{\Delta f_2}{R_2} - \Delta P_{D2} = B_2\Delta f_2 + \Delta P_{tie2}$$

$$\because \Delta P_{tie2} = -a_{12}\Delta P_{tie1}$$

$$\therefore -\frac{\Delta f_2}{R_2} - \Delta P_{D2} = B_2\Delta f_2 - a_{12}\Delta P_{tie1} \rightarrow (8)$$

Since $\Delta P_{tie2} = -a_{12}\Delta P_{tie1}$ and $\Delta f_1 = \Delta f_2 = \Delta f$

From eq (7),

$$-\frac{\Delta f}{R_1} - \Delta P_{D1} = B_1\Delta f + \Delta P_{tie1}$$

$$\Delta P_{tie1} = \frac{-\Delta f}{R_1} - \Delta P_{D1} - B_1\Delta f$$

$$= -\left[\frac{1}{R_1} + B_1\right]\Delta f - \Delta P_{D1} \rightarrow (9)$$

Substitute (9) in (8), we get

$$-\frac{\Delta f_2}{R_2} - \Delta P_{D2} = B_2\Delta f_2 - a_{12}\left[-\left(\frac{1}{R_1} + B_1\right)\Delta f - \Delta P_{D1}\right]$$

$$\frac{\Delta f_2}{R_2} - \Delta P_{D2} = B_2 \Delta f_2 + a_{12}\left[\left(\frac{1}{R_1}+B_1\right)\Delta f + \Delta P_{D1}\right]$$

$$\Delta f_2 = \Delta f$$

$$\frac{\Delta f}{R_2} - \Delta P_{D2} = B_2 \Delta f + a_{12}\left[\Delta f\left(\frac{1}{R}+B_1\right) + \Delta P_{D1}\right]$$

$$\frac{\Delta f}{R_2} + B_2 \Delta f + a_{12}\Delta f\left(\frac{1}{R_1}+B_1\right) = -\Delta P_{D2} - a_{12}\Delta P_{D1}$$

$$\Delta f\left[\frac{1}{R_2} + B_2 + a_{12}\left(\frac{1}{R_1}+B_1\right)\right] = -\Delta P_{D2} - a_{12}\Delta P_{D1}$$

$$\Delta f = -\frac{\left[\Delta P_{D2} + a_{12}\Delta P_{D1}\right]}{\left(\frac{1}{R_2}+B_2\right) + a_{12}\left(\frac{1}{R_1}+B_1\right)}$$

$$\Delta f = -\left[\frac{\Delta P_{D2} + a_{12}\Delta P_{D1}}{\left(\frac{1}{R_2}+B_2\right) + a_{12}\left(\frac{1}{R_1}+B_1\right)}\right] \rightarrow (10)$$

Substitute Δf in (9), we get

$$(9) \Rightarrow \Delta P_{tie1} = \left(\frac{1}{R_1}+B_1\right)\left[\frac{\Delta P_{D2} + a_{12}\Delta P_{D1}}{\left(\frac{1}{R_2}+B_2\right) + a_{12}\left(\frac{1}{R_1}+B_1\right)}\right] - \Delta P_{D1}$$

$$\Delta P_{tie1} = \frac{(\Delta P_{D2} + a_{12}\Delta P_{D1})\left(\frac{1}{R_1}+B_1\right) - \Delta P_{D1}\left[\left(\frac{1}{R_2}+B_2\right) + a_{12}\left(\frac{1}{R_1}+B_1\right)\right]}{\left[\frac{1}{R_2}+B_2\right] + a_{12}\left(\frac{1}{R_1}+B_1\right)}$$

$$= \frac{\Delta P_{D2}\left(\frac{1}{R_1}+B_1\right) + a_{12}\Delta P_{D1}\left(\frac{1}{R_1}+B_1\right) - \Delta P_{D1}\left(\frac{1}{R_2}+B_2\right) - \Delta P_{D1} a_{12}\left(\frac{1}{R_1}+B_1\right)]}{\left[\frac{1}{R_2}+B_2\right] + a_{12}\left[\frac{1}{R_1}+B_1\right]}$$

$$= \frac{\Delta P_{D2}\left(\frac{1}{R_1}+B_1\right) - \Delta P_{D1}\left(\frac{1}{R_2}+B_2\right)}{\frac{1}{R_2} + B_2 + a_{12}\left(\frac{1}{R_1}+B_1\right)} \rightarrow (11)$$

eq (10) and (11) are modified as

the line frequency $\Delta f = -\dfrac{\Delta P_{D2} + a_{12}\Delta P_{D1}}{\left(\frac{1}{R_2}+B_2\right) + a_{12}\left(\frac{1}{R_1}+B_1\right)}$

But we know that, $\beta_1 = B_1 + \frac{1}{R_1}$ and

$$\beta_2 = \frac{1}{R_2} + B_2$$

then the above equations becomes

$$\Delta f = \left[\frac{\Delta P_{D2} + a_{12}\Delta P_{D1}}{\beta_2 + a_{12}\beta_1}\right] \rightarrow (12)$$

Tie line Power, $\Delta P_{T21} = \dfrac{\Delta P_{D2}\left(\frac{1}{R_1}+B_1\right) - \Delta P_{D1}\left(\frac{1}{R_2}+B_2\right)}{\left(\frac{1}{R_2}+B_2\right) + a_{12}\left(\frac{1}{R_1}+B_1\right)}$

$$= \frac{\beta_1 \Delta P_{D2} - \Delta P_{D1}\beta_2}{\beta_2 + a_{12}\beta_1} \rightarrow (13)$$

eq (12) and (13) gives value of static changes in frequency and tie line Power respectively as a result of sudden change load in two areas, it can be observed the frequency and tie line Power variation do not reduced to zero in an equation uncontrolled case.

consider two identical (same) areas

$P_1 = P_2 = P$, $\beta_1 = \beta_2 = \beta$, $a_{12} = 1$.

substitute above terms in (12) and (13), we get

$$\Delta f = -\left(\frac{\Delta P_{D2} + \Delta P_{D1}}{\beta + \beta}\right)$$

$$= -\left[\frac{\Delta P_{D1} + \Delta P_{D2}}{2\beta}\right] Hz \rightarrow (14)$$

Similarly $\Delta P_{TL1} = \dfrac{\beta(\Delta P_{D2} - \Delta P_{D1})}{2\beta}$.

$$= \frac{\Delta P_{D2} - \Delta P_{D1}}{2} \text{ mw} \rightarrow (15)$$

If sudden load change occurs only in area 2 then $\Delta P_{D1} = 0$

then (14) => $\Delta f = -\dfrac{\Delta P_{D2}}{2\beta}$ Hz $\rightarrow (16)$

$$\Delta P_{Tie1} = \frac{\Delta P_{D2}}{2} \text{ mw} \rightarrow (17)$$

(ii) Dynamic Response:

To describe dynamic response of two area system, 7th order differential equations are required, the solutions to this equations be very complex.

Some important characteristics can be brought out by analysis which makes by following assumptions.

1. $\tau_{sg} - \tau_t = 0$
2. The damping constants of two areas are neglected i.e $B_1 = B_2 = 0$.
3. For two areas dynamics are described by

$$\Delta P_{G1} - \Delta P_{D1} = \frac{2H_1}{f^0} \cdot \frac{d}{dt} \Delta f_1 + B_1 \Delta f_1 + \Delta P_{tie1} \rightarrow ①$$

$$\Delta P_{G2} - \Delta P_{D2} = \frac{2H_2}{f^0} \cdot \frac{d}{dt} \Delta f_2 + B_2 \Delta f_2 + \Delta P_{tie2} \rightarrow ②$$

Taking Laplace transform for ① & ②, we get

$$\Delta P_{G1}(S) - \Delta P_{D1}(S) = \frac{2H_1}{f^0} s\Delta f_1(S) + B_1 \Delta f_1(S) + \Delta P_{tie1}(S)$$

$$\Delta P_{G2}(S) - \Delta P_{D2}(S) = \frac{2H_2}{f^0} s\Delta f_2(S) + B_2 \Delta f_2(S) + \Delta P_{tie2}(S)$$

$$\Delta P_{G1}(S) - \Delta P_{D1}(S) = \frac{2H_1}{f^0} s\Delta f_1(S) + \Delta P_{tie1}(S)$$

$$\Delta P_{G2}(S) - \Delta P_{D2}(S) = \frac{2H_2}{f^0} s\Delta f_2(S) + \Delta P_{tie2}(S)$$

$$\Rightarrow \Delta f_1(S) = \left[\Delta P_{G1}(S) - \Delta P_{D1}(S) - \Delta P_{tie1}(S)\right] \times \frac{f_0}{2H_1 s} \rightarrow ③$$

$$\Delta f_2(S) = \left[\Delta P_{G2}(S) - \Delta P_{D2}(S) - \Delta P_{tie2}(S)\right] \times \frac{f_0}{2H_2 s} \rightarrow ④$$

From the composite block diagram, the following equations can be obtained.

$$\Delta P_{G1}(S) = \frac{-\Delta F_1(S)}{R_1} \rightarrow ⑤$$

$$\Delta P_{G2}(S) = -\frac{\Delta F_2(S)}{R_2} \rightarrow ⑥$$

The two control areas are identical.

Therefore $H_1 = H_2 = H$ and $a_{12} = -\frac{P_1}{P_2} = -1$.

Substituting the above terms in eq ⑤, ⑥

in eq ③ and ④, we get

$$③ \Rightarrow \Delta f_1(S) = \left[-\frac{\Delta F_1(S)}{R_1} - \Delta P_{D_1}(S) - \Delta P_{tie1}(S)\right] \times \frac{f^\circ}{2HS}$$

$$= -\frac{\Delta F_1(S)}{R} \cdot \frac{f^\circ}{2HS} + \left[-\Delta P_{D_1}(S) - \Delta P_{Tie1}(S)\right]\frac{f^\circ}{2HS}$$

$$\left(1 + \frac{f^\circ}{2HSR}\right)\Delta F_1(S) = \left[-\Delta P_{D_1}(S) - \Delta P_{Tie1}(S)\right]\frac{f^\circ}{2HS}$$

$$\Delta f_1(S) = \frac{\left[-\Delta P_{D_1}(S) - \Delta P_{Tie1}(S)\right] \cdot \frac{f^\circ}{2HS}}{1 + \frac{f^\circ}{2HSR}} \rightarrow ⑦$$

$$④ \Rightarrow \Delta F_2(S) = \left[-\frac{\Delta F_2(S)}{R} - \Delta P_{D2}(S) - \Delta P_{tie2}(S)\right]\frac{f^\circ}{2HS}$$

$$= -\frac{\Delta F_2(S)}{R} \cdot \frac{f^\circ}{2HS} + \left[-\Delta P_{D2}(S) - \Delta P_{Tie2}(S)\right]\frac{f^\circ}{2HS}$$

$$\left(1 + \frac{f^\circ}{2HSR}\right)\Delta F_2(S) = \left[-\Delta P_{D2}(S) - \Delta P_{Tie2}(S)\right]\frac{f^\circ}{2HS}$$

$$\Delta f_2(S) = \frac{\left[-\Delta P_{D2}(S) - \Delta P_{Tie2}(S)\right]\frac{f^\circ}{2HS}}{1 + \frac{f^\circ}{2HSR}} \rightarrow ⑧$$

we know that $\Delta P_{tie1}(S) = \frac{2\pi T_{12}}{S}\left[\Delta f_1(S) - \Delta f_2(S)\right]$ → ⑨

and $\Delta P_{tie2}(S) = +\Delta P_{tie1}(S) \rightarrow ⑩$

substituting ⑦, ⑧ and ⑩ in ⑨, we get

$$\Delta P_{tie1}(S) = \frac{2\pi T_{12}}{S}\left[\frac{\left[\Delta P_{D_1}(S) - \Delta P_{Tie1}(S)\right]\frac{f^\circ}{2HS}}{1 + \frac{f^\circ}{2HSR}} - \frac{\left[-\Delta P_{D2}(S) - \Delta P_{Tie1}(S)\right]\frac{f^\circ}{2HS}}{1 + \frac{f^\circ}{2HSR}}\right]$$

$$\Delta P_{tie1}(S)\left[1 + \frac{\frac{2\pi T_{12}}{S}\frac{f^\circ}{2HS}}{1 + \frac{f^\circ}{2HSR}} + \frac{\frac{2\pi T_{12}}{S}\frac{f^\circ}{2HS}}{1 + \frac{f^\circ}{2HSR}}\right] =$$

$$= \frac{2\pi T_{12}}{S}\left[\frac{\Delta P_{D2}(S)\frac{f^\circ}{2HS}}{1+\frac{f^\circ}{2HSR}} - \frac{\Delta P_{D}(S)\frac{f^\circ}{2HS}}{1+\frac{f^\circ}{2HSR}}\right]$$

$$\Delta P_{Tie1}(S)\left[1+\frac{\frac{4\pi T_{12}}{S}\frac{f^\circ}{2HS}}{1+\frac{f^\circ}{2HSR}}\right] = \frac{2\pi T_{12}}{S}\frac{\frac{f^\circ}{2HS}}{1+\frac{f^\circ}{2HSR}}\left[\Delta P_{D2}(S)-\Delta P_{D1}(S)\right]$$

$$\Delta P_{Tie1}(S)\left[\frac{1+\frac{f^\circ}{2HSR}+\frac{4\pi T_{12}}{S}\frac{f^\circ}{\cancel{2}HS}}{1+\cancel{\frac{f^\circ}{2HSR}}}\right] = \frac{\cancel{2}\pi T_{12}}{S}\frac{\frac{f^\circ}{\cancel{2}HS}}{1+\cancel{\frac{f^\circ}{2HSR}}}\left[\Delta P_{D2}(S)-\Delta P_{D}(S)\right]$$

$$\Delta P_{Tie1}(S)\left[1+\frac{f^\circ}{2HSR}+\frac{2\pi T_{12}}{S}\cdot\frac{f^\circ}{HS}\right] = \frac{\pi T_{12}f^\circ}{HS^2}\left[\Delta P_{D2}(S)-\Delta P_{D}(S)\right]$$

$$\therefore \Delta P_{Tie1}(S) = \frac{\frac{\pi T_{12}f^\circ}{HS^2}\left[\Delta P_{D2}(S)-\Delta P_{D1}(S)\right]}{1+\frac{f^\circ}{2HSR}+\frac{2\pi T_{12}}{S}\cdot\frac{f^\circ}{HS}}$$

$$\Delta P_{Tie1}(S) = \frac{\left[\Delta P_{D2}(S)-\Delta P_{D1}(S)\right]\frac{\pi f^\circ T_{12}}{H}}{\left[S^2+\left(\frac{f^\circ}{2RH}\right)S+\frac{2\pi T_{12}f^\circ}{H}\right]}$$

From the above equations, the following observations can be made

The denominator is of the form of

$$S^2+2\alpha S+\omega^2 = (S+\alpha)^2+(\omega^2-\alpha^2)$$

where $\alpha = \frac{f^\circ}{4RH}$ and $\omega = \sqrt{\frac{2\pi T_{12}f^\circ}{H}}$

'α' and 'ω^2' are both real and positive

$\therefore$ The three conditions are

If $\alpha=\omega_n$, system is critically damped.

If $\alpha>\omega_n$, system becomes over damped.

If $\alpha<\omega_n$, then $S_{12} = -\alpha \pm j\sqrt{\omega_n^2-\alpha^2}$

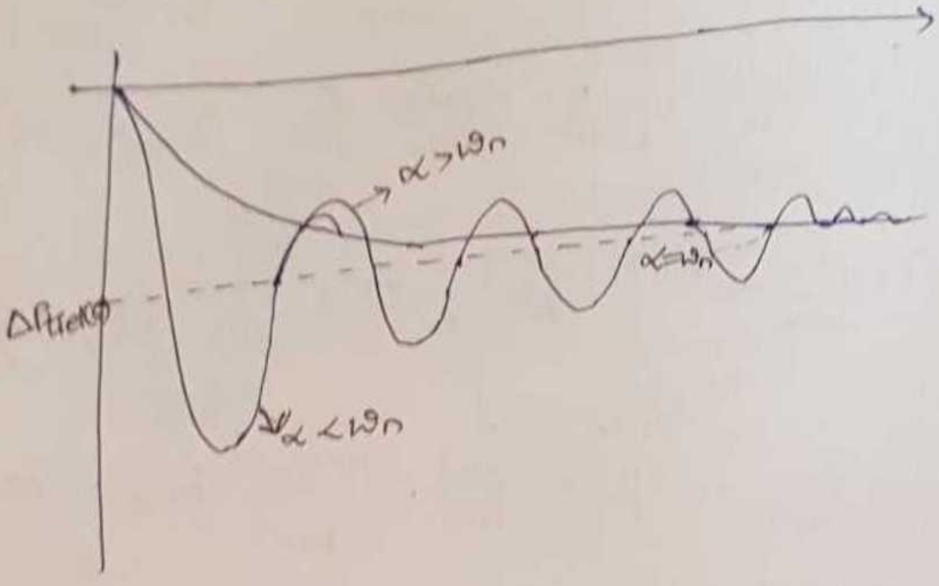
$$= -\alpha \pm j\omega_n\sqrt{1-\left(\frac{\alpha}{\omega_n}\right)^2}$$

$$= -\alpha \pm j\omega_0$$

where α = damping factor or decrement of attenuation

ω_0 – Damped angular frequency.

$$\omega_0 = \sqrt{\frac{2\pi f^{\circ} T_{12}}{H} - \left(B + \frac{1}{R}\right)^2 \frac{f^{\circ 2}}{16H^2}}$$

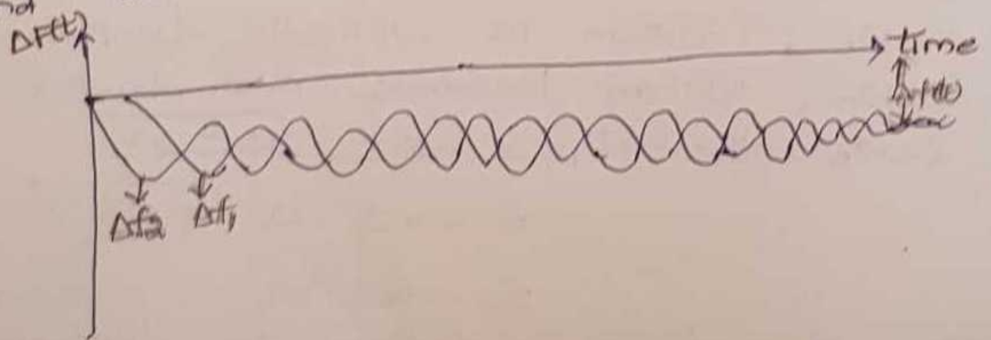


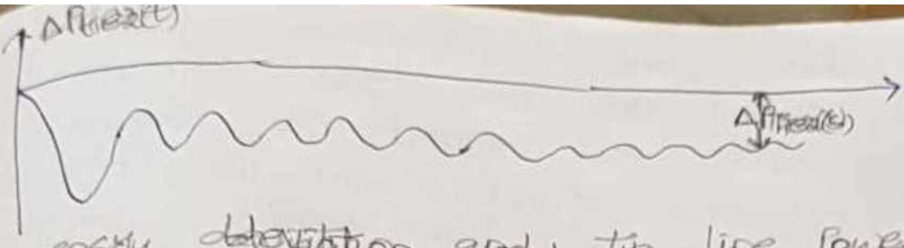
Case I:
Since parameter 'α' also depends on 'B', bu
$B << \frac{1}{R}$.
$\therefore$ The effect of coefficient B is neglecte

Case II:
After a disturbance, change in tie line power oscillates at damped angular frequency

Case III:
The damping of tie line variation is strongly dependant upon parameter 'α' = $\frac{f^{\circ}}{HRH}$

The damping is function of 'R' parameter. if 'R' value is low, damping is strong and vice versa





Frequency deviation and tie line power change following a step load change in area ②.

Load Frequency and economic Dispatch Controls:

Economic load dispatch and LFC play a vital role in modern power system. In LFC, zero steady-state frequency error and a fast, dynamic response were achieved by integral controller action. But this control is independant of economic dispatch i.e., there is no control over economic loading of various generating units of the control area.

Some control over loading of individual units can be exercised by adjusting the gain factors (K_I) of integral signal of ACE as fed to individual units. But this is not a satisfactory solution.

A suitable and satisfactory solution is obtained by using independent controls of load frequency and economic dispatch. The load frequency controller provides a fast-acting frequency control and regulates the system around an operating point, whereas the economic dispatch controller provides a slow-acting control, which adjusts the speed-changer settings every minute in accordance with a command signal generated by central economic dispatch ~~control centre~~ computer.

EDC - economic Dispatch controller

CEDC - Central economic dispatch computer

The speed changer setting is changed in accordance with economic dispatch error signal, (i.e., $P_G(desired) - P_G(actual)$) conveniently modified by signal $\int ACE\, dt$ at that instant of time. The Central economic dispatch computer (CEDC) provides the signal P_G(desired) and the signal is transmitted to local economic dispatch controller (EDC). The system they operate with economic dispatch error is only for very short periods of time before it is readily used.

The tertiary control can be implemented by using EDC and EDC works on the cost characteristics of various generating units in the area. The speed-changer settings are once again operated in accordance with an economic dispatch computer program.

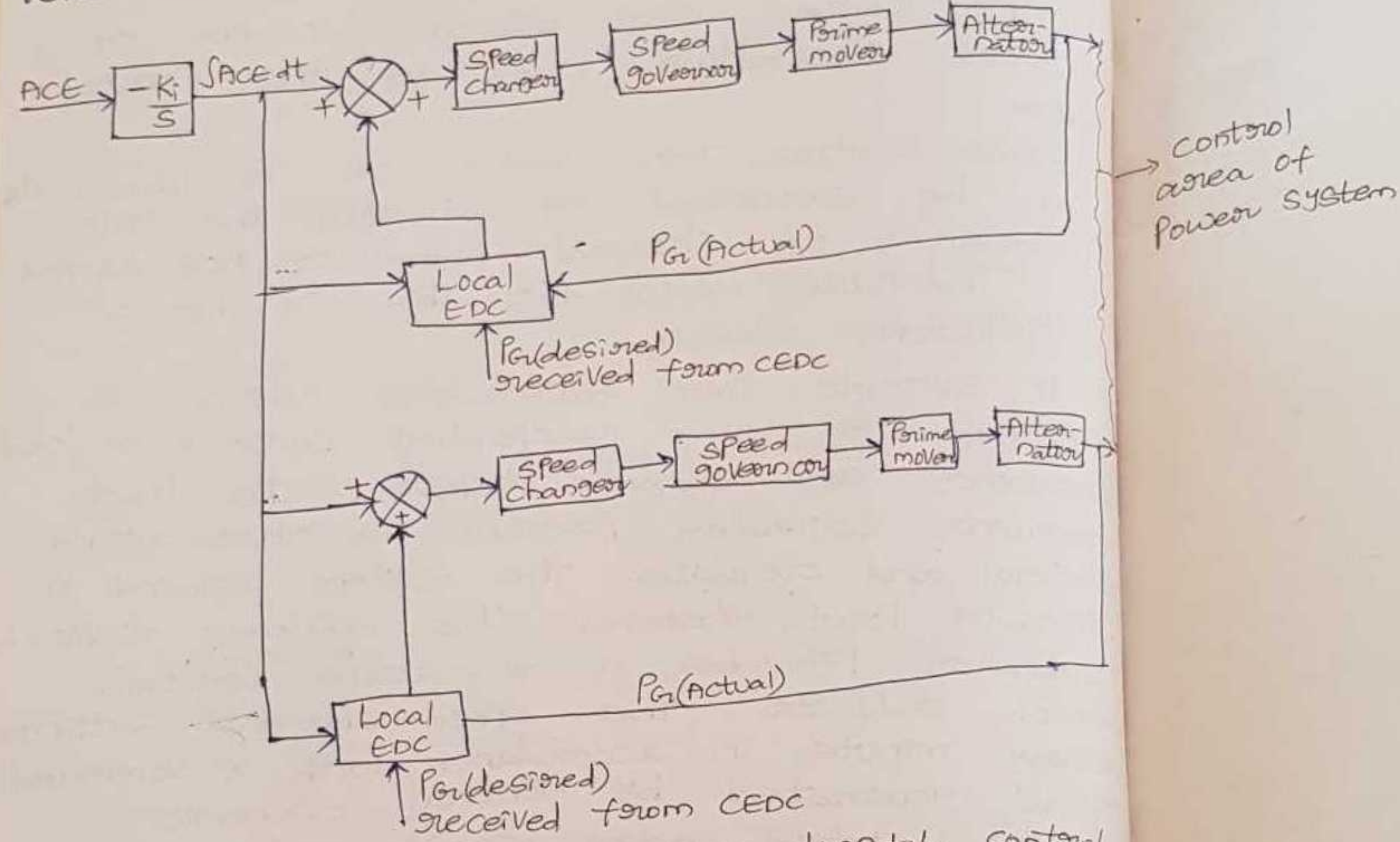


Fig. Load frequency and economic dispatch control of control area of a Power system

The CEDC's are provided at a central control center. The variable part of load is carried by units that are controlled from central control center. medium-sized fossil fuel units and hydro units are used for control. During peak load hours, lesser efficient units, such as gas-turbine units or diesel units, are employed in addition; generators operating at partial output (with spinning reserve) and standby generators provide a reserve margin.

The central control center monitors information including area frequency, outputs of generating units, and tie-line power flows to interconnected areas. This information is used by ALFC in order to maintain area frequency at its scheduled value and net tie-line power flow out of the area at its schedding value. Raise and lower reference power signals are dispatched to the turbine governors of controlled units.

Economic dispatch is co-ordinated with LFC such that the reference power signals dispatched to controlled units move the units toward their economic loading and satisfy LFC objectives.

Controlled case:

steady state Response:

Let step changes in load ΔP_{D1} and ΔP_{D2} simultaneously occur in control area 1 and control area 2 respectively or in either area.

A new static equilibrium state i.e., steady state condition is reached output signals of all integrated blocks will become constant.

In this case the speed changer command signal ΔP_{C1} and ΔP_{C2} have reached constant values.

This requires that both integrate signals has to be zero.

The input signals are

$$\Delta P_{C_1} = -K_1 \int (\Delta P_{tie1} + b_1 \Delta f_1)\, dt \rightarrow ①$$

$$\Delta P_{C2} = -K_2 \int (\Delta P_{tie2} + b_2 \Delta f_2)\, dt \rightarrow ②$$

Input of integrating block $-\frac{K_{I_1}}{s}$ is

$$\Delta P_{tie1}(s) + b_1 \Delta f_1(s) = 0 \rightarrow ③$$

Input of integrating block $-\frac{K_{I_2}}{s}$ is,

$$\Delta P_{tie2}(s) + b_2 \Delta f_2(s) = 0 \rightarrow ④$$

Input of integrating block $\frac{-2\pi T_{12}}{s}$ is

$$\Delta f_1 - \Delta f_2 = 0 \rightarrow ⑤$$

Eq③ and eq④ are simultaneously satisfied

$$\Delta P_{tie1}(ss) = 0 \quad \text{and} \quad \Delta P_{tie2}(ss) = 0$$

Also $\Delta f_1(ss) = 0$; $\Delta f_2(ss) = 0$

The requirements for integral control action are

1. ACE (Area control error) must be equal to zero atleast in all 10 minute periods.
2. Average deviation of ACE from zero must be within specified minute based on percentage of system generation for all 10 min period.

The performance criteria is also applied to disturbance condition and is required that

1. ACE must return to zero within 10 min period.
2. Corrective control action must be take within one minute at a disturbance

Dynamic Response:

The determination of dynamic response of two area model is more difficult this is due to fact that the system of equations to be solved is at the order 'q'.

∴ Actual solution was not attempted.

But, the results obtain from an approximate analysis of two identical area power system for three different values of b are represented in fig(a), (b) and (c)

The below graph fig(a) corresponds to case of b=0. It can be seen that the tie line power deviation reduces to zero while the frequency does not.

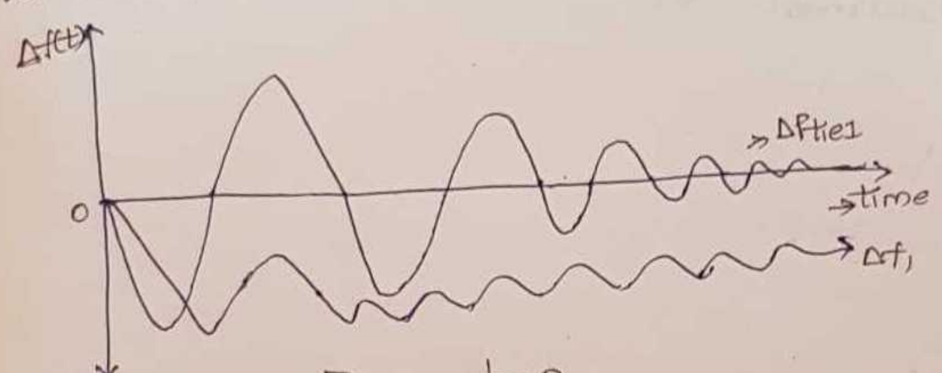


Fig a. b=0

The graph at fig b corresponds to other extreme case b=∞, no the frequency error vanishes but tie line power does not vanish.

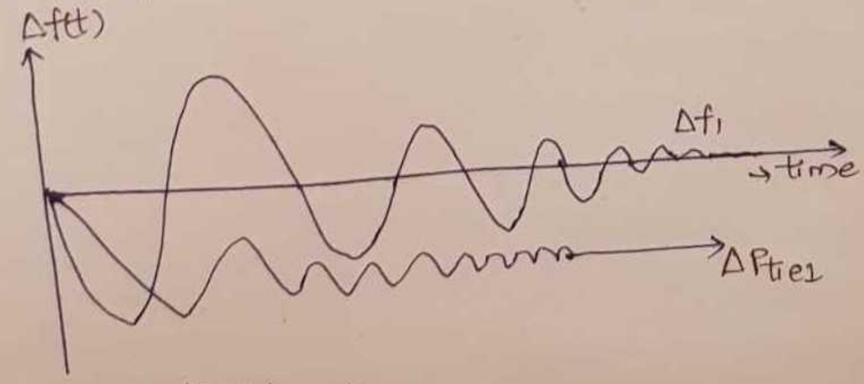


Fig b. b = ∞

The graph of fig c. corresponds to the intermediate case when in both the frequency and tieline Power errors decrease to zero.

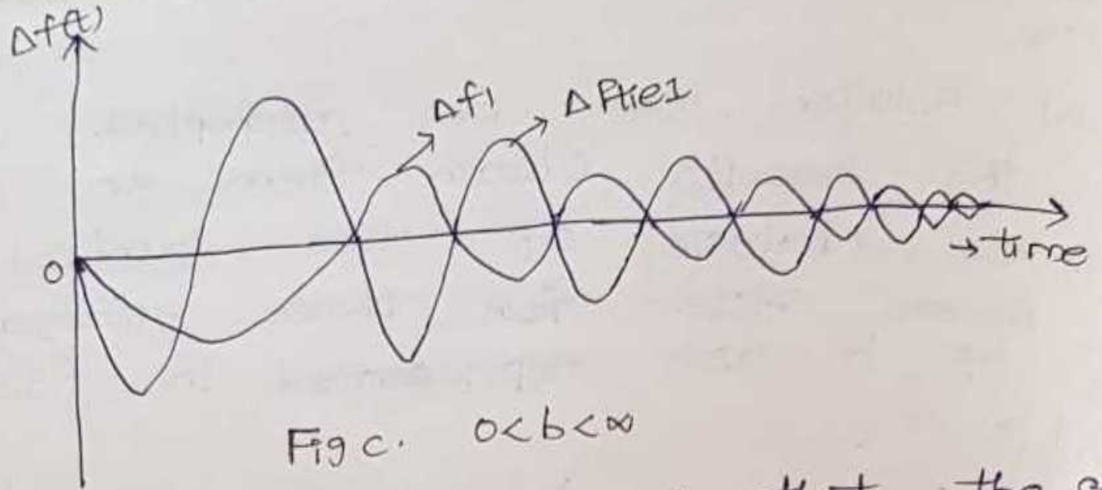


Fig c. $0 < b < \infty$

It can be concluded that the stability is not always guaranteed. Hence there is a need for proper Parameter selection and adjustment of their Values.