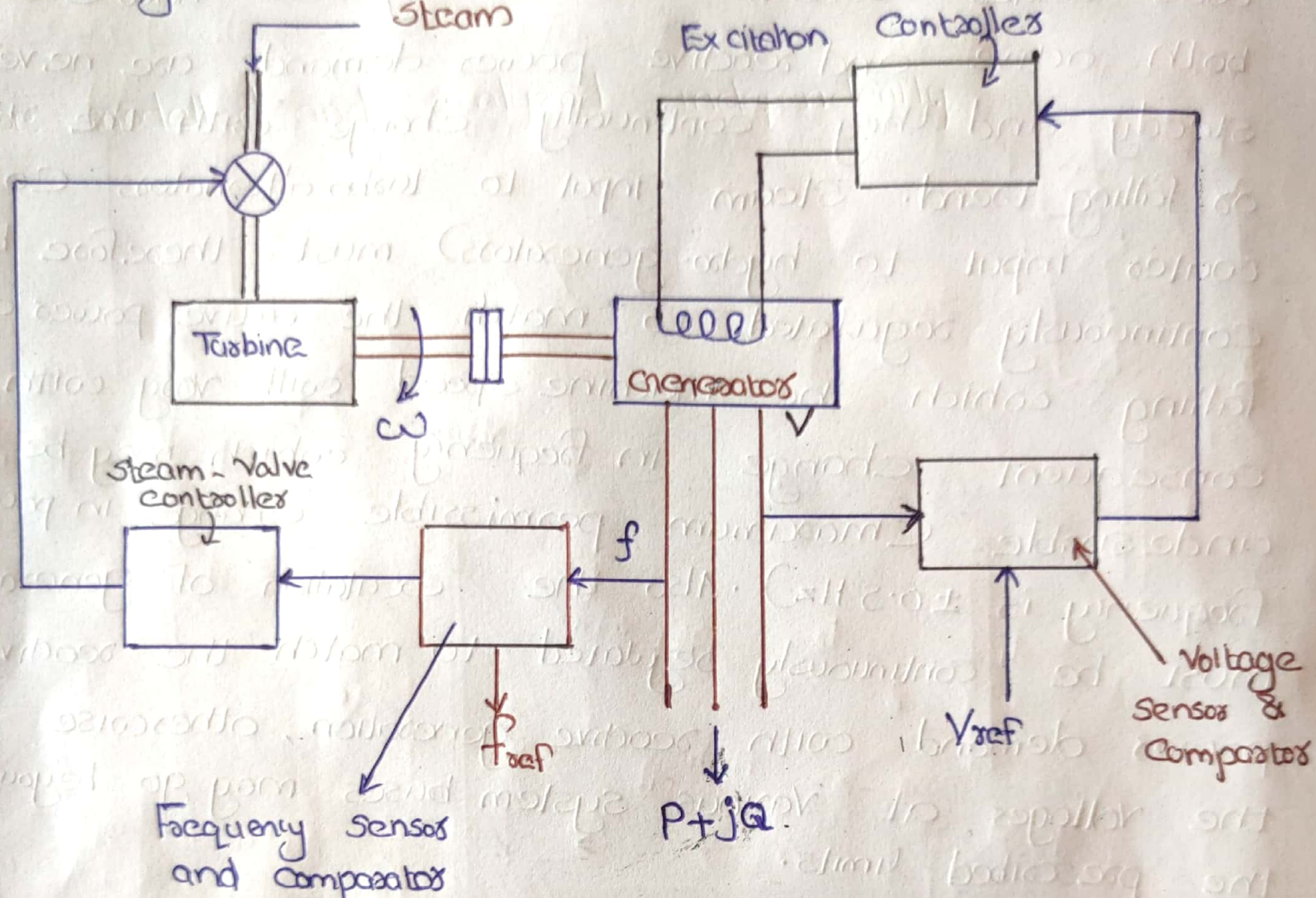
Module-IV

Automatic Generation & Voltage Control:

power system operation considered so far as was under conditions of steady load. However both active and reactive power demands are never steady and they continually change with the rising or falling trend. Steam input to turbo alternators (or water input to hydro-generators) must therefore be continuously regulated to match the active power demand, failing which the machine speed will vary with consequent change in frequency which may be highly undesirable (maximum permissible change in power frequency is ±0.5 Hz). Also the excitation of generators must be continuously regulated to match the reactive power demand with reactive generation, otherwise the voltages at various system buses may go beyond the prescribed limits.

Load-frequency and excitation voltage regulators:

In modern large interconnected systems, manual regulation is not feasible and therefore automatic generation and voltage regulation equipment is installed on each generator. Figure shows the schematic diagram of load frequency and excitation voltage regulators of a turbo generator. The controllers are set for a particular operating conditions and they take care of small changes in load-demand without frequency and voltage exceeding the prescribed limits. With the passage of time, as the change in the load demand becomes large, the controllers must be reset either manually or automatically.



Lay-out of Load-frequency & excitation voltage regulator

For small changes in active power is dependent on internal machine angle 'δ' and is independent of bus voltage, while bus voltage is dependent on machine excitation (therefore on reactive generation Q) and is independent of machin angle 'δ'. change in angle δ is caused by momentary change in generator speed. Therefore, load frequency and excitation voltage controls are non interactive for small changes and can be modelled and analyzed independently. Furthermore, excitation voltage control is fast acting, in which the major time constant encountered is that of the generator field, while the power frequency control is slow acting with major time constant contributed by the turbine and generator moment of inertia. This time constant is much larger than that of generator field. Thus the transients in the excitation voltage control vanish much faster and do not affect the dynamics of power frequency control.

changes in load demand can be identified as-

(i) slow varying changes in mean demand.

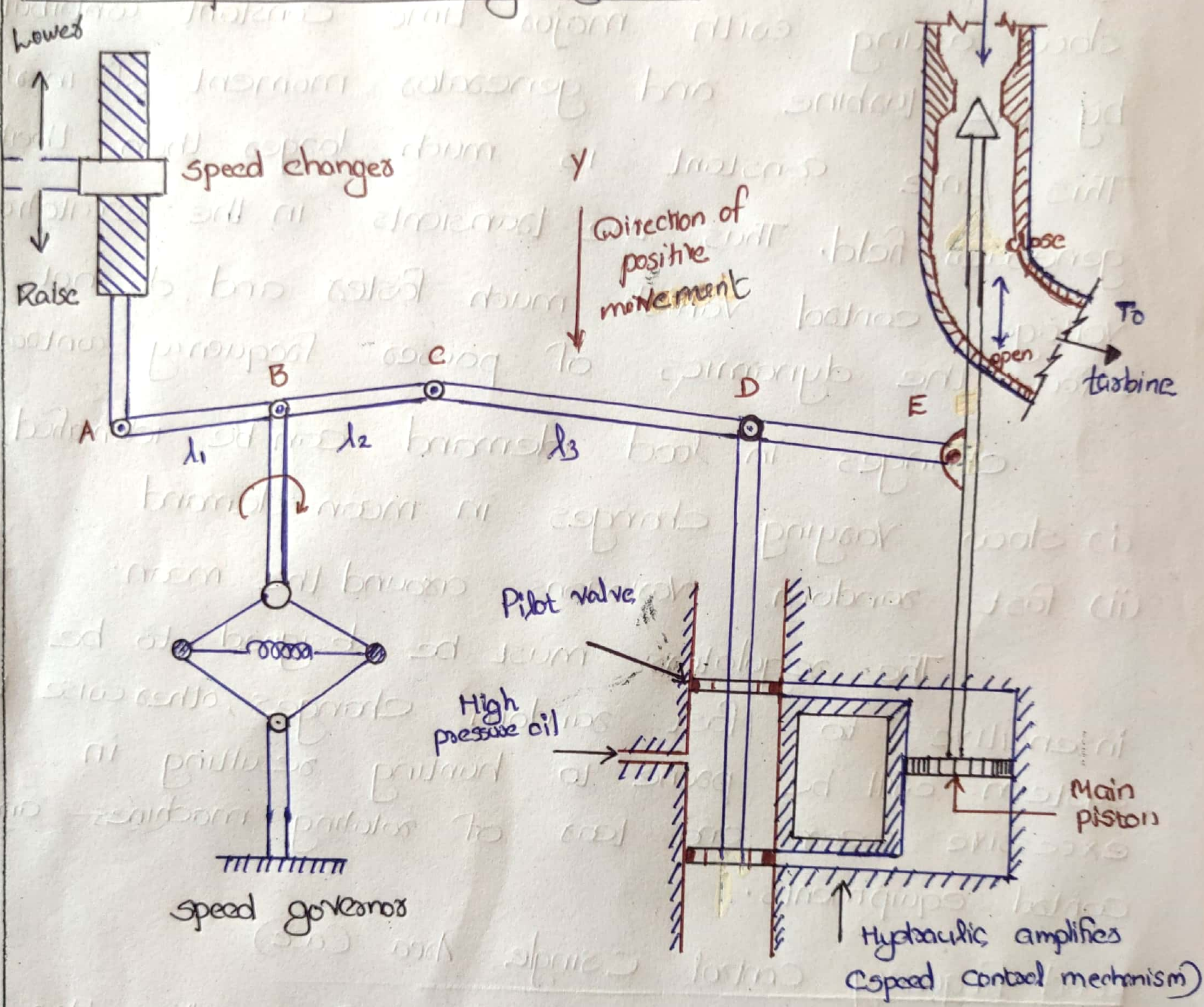
(ii) fast random variations around the mean.

The regulators must be designed to be insensitive to fast random changes, otherwise the system will be prone to hunting resulting in excessive wear and tear of rotating machines and control equipments.

Load frequency control (single Area Case)

Consider the problem of controlling the power output of the generators of a closely knit electric area so as to maintain the scheduled frequency. All the generators in such an area consitute a coherent group so that all the generators speed up and slow down together maintaining their relative power angles. such an area is defined as a control area. The boundaries of a control area will generally coincide with that of an individual Electricity Board.

Turbine Speed Governing System:



Consider a single turbo-generator system supplying an isolated load. The system consists of the following components

(i) fly-ball speed governor:

This is the heart of the system which senses the change in speed (frequency).

As the speed increases the fly balls move outwards and the point B on linkage mechanisam move downwards. The reverse happens when the speed decreases.

(ii) Hydraulic Amplifier :

It comprises a pilot valve and main piston arrangement. Low power level pilot valve movement is converted into high power level piston valve movement. This is necessary in order to open or close the steam valve against high pressure steam.

(iii) Linkage Mechanism:

ABC is a rigid link pivoted at B and CDE is another rigid link pivoted at D. This link mechanism provides a movement to the control valve in proportion to change in speed. It also provides a feedback from the steam valve movement (link 4)

(iv) Speed changer:

It provides a steady state power output setting for the turbine. Its downward movement opens the upper pilot valve so that more steam is admitted to the turbine under steady conditions (hence more steady power output). The reverse happens for upward movement of speed changer.

Model of speed governing system:

Assume that the system is initially operating under steady conditions - the linkage mechanism stationary and pilot valve closed, steam valve opened by a definite magnitude, turbine running at constant speed with turbine power output balancing the generator load. Let the operating conditions be characterized by

f^0 = system frequency (speed)

P_G^0 = Generator output = turbine output (neglecting generator loss)

y_E^0 = steam valve setting

Let the point A on the linkage mechanism be moved downwards by a small amount Δy_A. It is a command which causes the turbine power output to change and can therefore be written as

$$\Delta y_A = K_C \Delta P_C \rightarrow (1)$$ where ΔP_C is the commanded increase in power.

The command signal ΔP_C (ie. Δy_E) sets into motion a sequence of events - the pilot valve moves outwards, high pressure oil flows on to the top of the main piston moving it downwards; the steam valve opening consequently increases, the turbine generator speed increases, ie the frequency goes up. Let us model these events mathematically:

Two factors contribute to the movement of C;

(i) Δy_A contributes $\rightarrow \left(\frac{l_2}{l_1}\right) \Delta y_A$ or $-K_1 \Delta y_A$ (ie upwards) of $-K_1 K_C \Delta P_C$

(ii) Increase in frequency Δf causes the fly balls to move outwards so that B moves downwards by a proportional

amount $k_2' \Delta f$. The consequent movement of C with A remaining fixed with A remaining fixed at Δy_A is $+\left(\frac{l_1+l_2}{l_1}\right) k_2' \Delta f = + k_2 \Delta f$, where $\left(\frac{l_1+l_2}{l_1}\right) k_2' = k_2$
(down wards)

The net movement of C is therefore.

$$\Delta y_C = -k_1 k_C \Delta P_C + k_2 \Delta f \longrightarrow (2)$$

The movement of D, Δy_D is the amount by which the pilot valve opens. It is contributed by Δy_C and Δy_E and can be written as

$$\Delta y_D = \left(\frac{l_4}{l_3+l_4}\right) \Delta y_C + \left(\frac{l_3}{l_3+l_4}\right) \Delta y_E$$

$$\Delta y_D = k_3 \Delta y_C + k_4 \Delta y_E \longrightarrow (3)$$

The movement Δy_D depending upon its sign opens one of the ports of the pilot valve admitting high pressure oil into the cylinder there by moving the main piston opening the steam valve by Δy_E

Assumptions made at this stage.

(i) Inertial reaction forces of main piston and steam valve are neglible compared to the forces exerted on the piston by high pressure oil.

(ii) Because of above reason, the rate of oil admitted to the cylinder is proportional to port opening Δy_D

The volume of oil admitted to the cylinder is thus proportional to the time integral of Δy_D. The movement Δy_E is obtained by dividing the oil volume by the area of cross-section of the piston.

Thus

$$\Delta y_E = K_5 \int_0^K (-\Delta y_D) dt \quad \text{------} \rightarrow (4)$$

It can be verified from the schematic diagram that a positive movement Δy_D causes negative (upward) movement Δy_E accounting for the negative sign used in equation (4).

Taking the laplace transform of eqns (2) to (4)

$$\Delta Y_c(s) = -K_1 K_c \Delta P_c(s) + K_2 \Delta F(s) \quad \text{-----} \rightarrow (5)$$

$$\Delta Y_D(s) = K_3 \Delta Y_c(s) + K_4 \Delta Y_E(s) \quad \text{-----} \rightarrow (6)$$

$$\Delta Y_E(s) = -K_5 \times \frac{1}{s} \Delta Y_D(s) \quad \text{-----} \rightarrow (7)$$

Eliminating $\Delta Y_c(s)$ & $\Delta Y_D(s)$

$$(7) \Rightarrow \quad \Delta Y_E(s) = -K_5 \times \frac{1}{s} \left[K_3 \Delta Y_c(s) + K_4 \Delta Y_E(s) \right]$$

$$= \frac{-K_5 K_3}{s} \Delta Y_c(s) + -\frac{K_5 \cdot K_4}{s} \Delta Y_E(s)$$

$$\Delta Y_E(s) \left[1 + \frac{K_4 K_5}{s} \right] = -\frac{K_5 K_3}{s} \left[-K_1 K_c \Delta P_c(s) + K_2 \Delta F(s) \right]$$

$$= \frac{K_1 K_3 K_5 K_c \Delta P_c(s)}{s} - \frac{K_2 K_3 K_5}{s} \Delta F(s)$$

pre multiplying by $\frac{s}{K_5}$ on both sides:

$$\Delta Y_E(s)\left(\frac{s}{K_5}+K_4\right) = K_1K_3K_c\,\Delta P_c(s) - K_2K_3\,\Delta F(s)$$

$$\Delta Y_E(s) = \frac{K_1K_3K_c\,\Delta P_c(s) - K_2K_3\,\Delta F(s)}{\left(K_4+\frac{s}{K_5}\right)}$$

$$\Delta Y_E(s) = \frac{K_1K_3K_c\left[\Delta P_c(s) - \frac{K_2}{K_1K_c}\Delta F(s)\right]}{K_4\left(1+\frac{s}{K_4K_5}\right)} \quad \text{.....}\to (8)$$

$R = \frac{K_1K_c}{K_2}$ = speed regulation of the governor

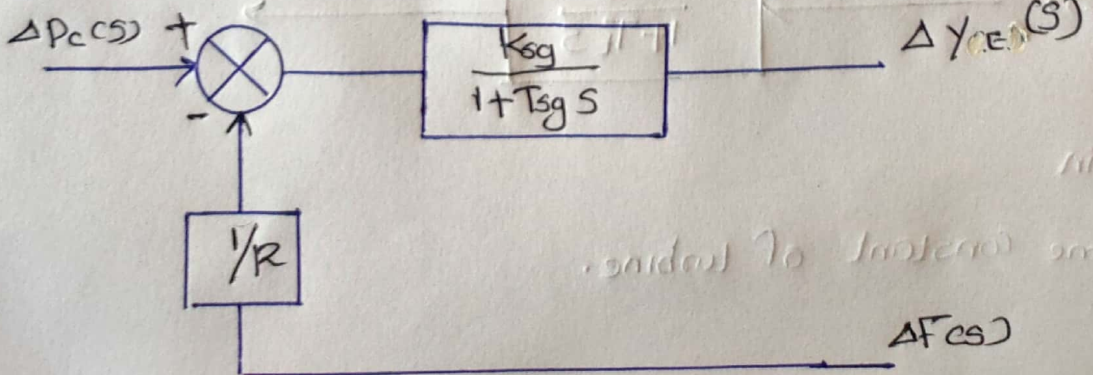
$K_{sg} = \frac{K_1K_3K_c}{K_4}$ = gain of speed governor.

$T_{sg} = \frac{1}{K_4K_5}$ = time constant of speed governor.

$\therefore$ Eqn (8) becomes,

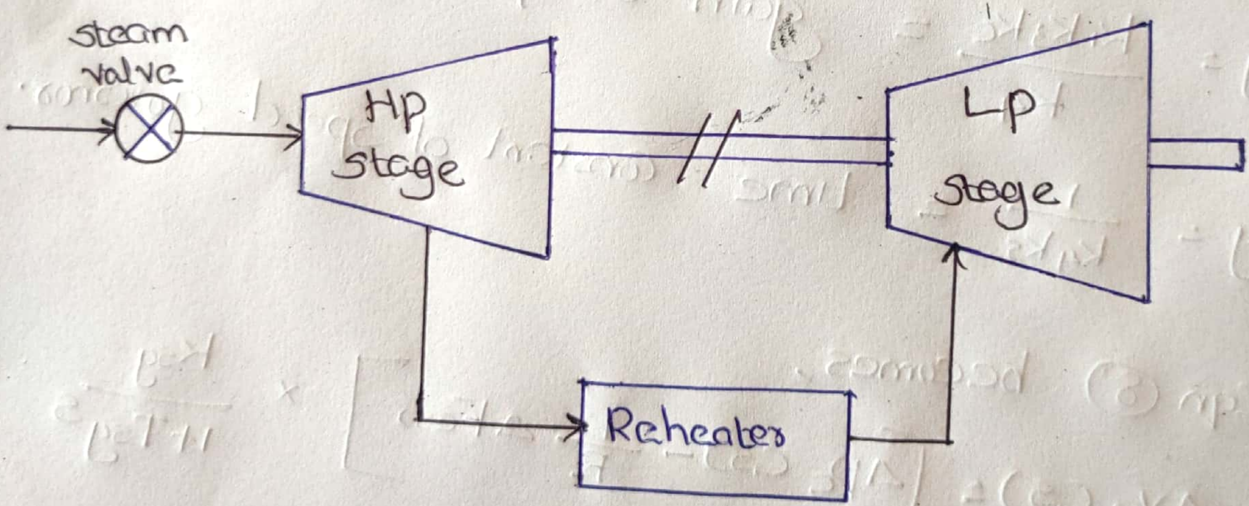
$$\Delta Y_E(s) = \left[\Delta P_c(s) - \frac{1}{R}\Delta F(s)\right] \times \frac{K_{sg}}{1+T_{sg}s} \quad \text{---}\to (9)$$

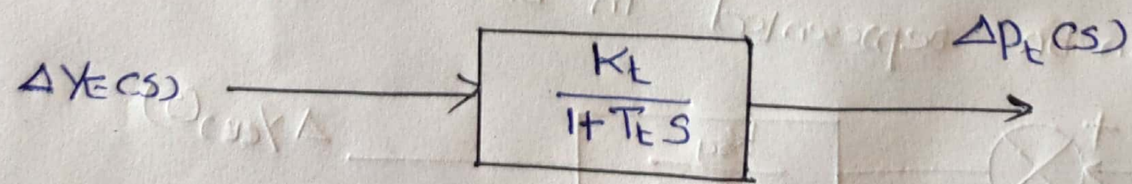
(9) can be represented in block diagram



Turbine Model :

Figure shows a two stage steam turbine with a reheat unit. The dynamic response is largely influenced by two factors (i) entrained steam between the inlet steam valve and first stage of turbine. (ii) The storage action in the reheater which causes the output of the low pressure stage to lag behind that of the high pressure stage. Thus the turbine transfer function is characterized by two time constants. For ease of analysis it will be assumed here that the turbine can be modelled ~~into~~ to have a single equivalent time constant.





$K_t \rightarrow$ gain

$T_t \Rightarrow$ Time constant of turbine.

Generator - Load model:

The increment in power input to the generator - load system is

$\Delta P_G - \Delta P_D$; where $\Delta P_G = \Delta P_t$ incremental turbine power output (assuming generator incremental loss to be neglible) and ΔP_D is the load demand-increment.

The increment in power input to the system is accounted for in two ways,-

(i) Rate of increase of stored K.E in the generator rotor. At scheduled frequency (f°), stored energy is

$$W^\circ_{KE} = H \times P_r \quad \text{kWsec (kilojoules)}$$

where P_r is kW rating of turbo-generator and H is defined as its inertia constant.

The K.E being proportional to square of speed (frequency), the K.E at a frequency of $(f^\circ + \Delta f)$ is given by,

$$W_{KE} = W^\circ_{KE} \left[\frac{f^\circ + \Delta f}{f^\circ}\right]^2 \quad \text{ie} \quad W^\circ_{KE} \propto (f^\circ)^2, \quad W_{KE} \propto (f^\circ + \Delta f)^2$$

$$= W^\circ_{KE} \left[\frac{(f^\circ)^2 + 2f^\circ \Delta f + \Delta f^2}{(f^\circ)^2}\right]$$

Neglecting small terms ie Δf^2

$$= W^\circ_{KE} \left[1 + \frac{2\Delta f}{f^\circ}\right]$$

$$W_{KE} = H P_r \left[1 + \frac{2\Delta f}{f^\circ}\right] \dashrightarrow (1)$$

Rate of change of K.E is therefore,

$$\frac{d}{dt}(W_{ke}) = H P_r \left[0 + \frac{d}{dt}\left(\frac{2\Delta f}{f_0}\right)\right]$$

$$= H P_r \cdot \frac{2}{f_0} \cdot \frac{d}{dt}(\Delta f)$$

$$\frac{d}{dt}(W_{ke}) = \frac{2 H P_r}{f_0} \frac{d}{dt}(\Delta f) \quad \text{------→ (2)}$$

(ii) As the frequency changes, the motor load changes being sensitive to speed, the rate of change of load with respect to frequency, ie $\partial P_D / \partial f$ can be regarded as nearly constant for small changes in frequency Δf and can be expressed as,

$$(\partial P_D / \partial f)\, \Delta f = B \Delta f$$

where constant B can be determined empirically.
B is positive for predominately motor load

writing power balance equations,

$$\Delta P_G - \Delta P_D = \frac{2 H P_r}{f_0} \frac{d}{dt}(\Delta f) + B \Delta f$$

÷ by P_r throughout

$$\Delta P_G(pu) - \Delta P_D(pu) = \frac{2H}{f_0} \frac{d}{dt}(\Delta f) + B(pu)\, \Delta f \quad \text{---→ (3)}$$

Taking laplace trans form,

$$\Delta P_G(s) - \Delta P_D(s) = \frac{2H}{f_0}\, s . \Delta F(s) + B . \Delta F(s)$$

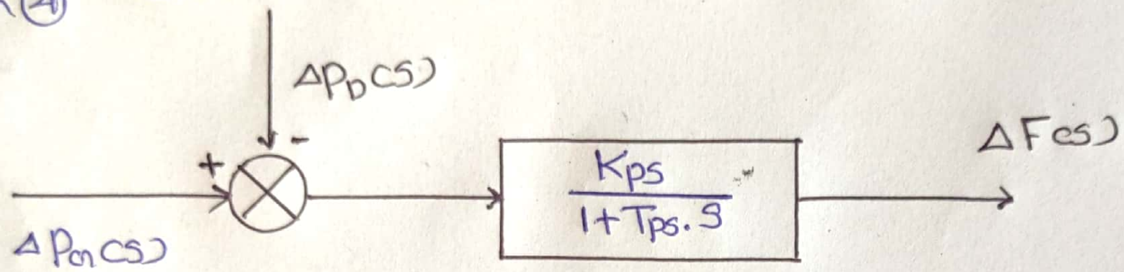
$$\Delta F(s)\left[\frac{2Hs}{f_0} + B\right] = \frac{\Delta P_G(s) - \Delta P_D(s)}{\frac{2Hs}{f_0} + B} = \frac{\Delta P_G(s) - \Delta P_D(s)}{\left[\frac{2Hs}{Bf_0} + 1\right] B}$$

$$\Delta F(s) = \frac{[\Delta P_m(s) - \Delta P_D(s)] \times \frac{1}{B}}{1 + \frac{2H}{Bf_0} s} = [\Delta P_m(s) - \Delta P_D(s)] \times \left[\frac{K_{ps}}{1 + T_{ps} S}\right] \longrightarrow (4)$$

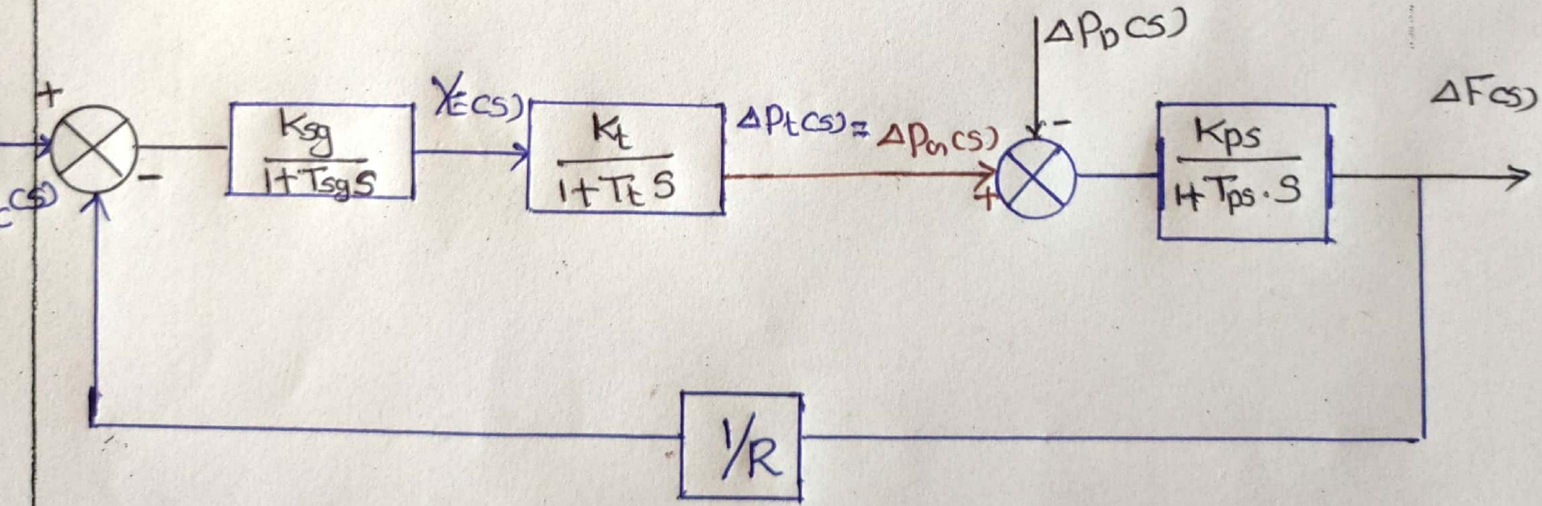
$T_{ps} = \frac{2H}{Bf_0} \rightarrow$ power system time constant

$K_{ps} = 1/B \rightarrow$ power system gain

Eqn (4) can be realized in block diagram representation.



A complete block diagram representation of an isolated power system comprising turbine, generator, governor and load is easily obtained by combining the block diagrams of individual components.



Block diagram model of load-frequency control. (Isolated power system).