Problem analysis in MW frequency control of an Interconnected Power system using sampled data technique

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Abstract- This work proposes problem analysis of two – area thermal – thermal interconnected power systems using conventional PI – controller technique and a scheme for improvement of responses in discrete data fashion with step load perturbation of 1% in both the areas. This paper focused on modeling of interconnected system in Z-transform form and we obtained pulse transfer function for same without any approximations. Simulations have been performed in MATLAB/SIMULINK.

Keywords – Automatic Generation Control (AGC), mathematical modeling of thermal-thermal system, SIMULINK model in discrete time domain, sampled data theory, pulse transfer function, SIMULINK results.

I. INTRODUCTION

Power system engineers were & still paid more attention on controlling of real or MW power, since it is the basic governing elements of revenue. Dated back to three or four decades when power system network, transmission system, utilities were not so complicated, and engineers paid less attention on controlling of these system. But due to the advent of modern engineering & technology, today's network becomes more and more extensive, uses long transmission system, frequent load fluctuation, high load demands etc. therefore, we must enhance the modern control strategy which not only satisfies the above requirements even maintained the system security, reliability & ability.

Sudden changes of load in the system causes turbine speed drops before the governor takes action. As the change in the value of speed decreases, the error signal gets smaller & position of governor valves get close to actual position. However, this is not the actual set point, there is an offset. To overcome this problem integration action is applied; this scheme is called ***automatic generation control (AGC)***. The main purpose of AGC is to restore the system frequency to its nominal value & economic sharing of power between different areas.

MW frequency control or AGC control problem is that of sudden small load perturbation continuously disturb the operation of electrical energy system. AGC have two important control action loops, primary loop employed to minimize the system frequency error irrespective to load perturbation, while supplementary loop adjust frequency to its nominal setting.

The primary objective of AGC is to control the scheduled value of power by adjusting output of selected generator irrespective of location; this function is commonly known as load frequency control. A secondary objective is to adjust the required change in generation to match loads among the units.

Modern power system network consist of interconnection of thermal, nuclear, hydro & gas power plants. Nuclear power plant working at base load close to maximum load, therefore AGC does not play an important action in this system. On the other hand gas power plant provides a small amount of power compare to actual requirement; hence there is no significance role of AGC in gas power plant. Thus the natural choice of AGC employed for thermal & hydro system only.

During large transient disturbance & emergencies AGC is bypassed & other emergency control takes place. The synchronization of different units depends upon (1) voltage magnitudes (2) system frequency & (3) phase sequences. Any wide variation from the nominal values of frequency or voltage causes system to be collapse. Here AGC guide the system from any undesirable situation.

There are lots of researches were made in past six decades with different control strategies. Elegerd's were study the interconnected system in continuous time domain, while in actual field this had been done at a fixed interval of time or in z – transform form. Indulkar's were study the same system but discrete in nature, but he assumed that governor & steam turbine have unity gain system for simplicity of mathematical calculation. Based on the knowledge of literature this paper focused on study of interconnected system in pulse transfer function from keeping the actual transfer function of governor & turbine systems. This paper also studies the dynamic responses in discrete time domain by deriving the actual transfer function of two area system both in Laplace domain & Z-transfer domain. We consider simple conventional PI control strategy with 1% load perturbation in both the units.

II. SYSTEM INVESTIGATED

Here we consider two area interconnected thermal power system for analysis of their dynamic responses due to small perturbation of load in one and/or both the control area. Since in actual field, measurement of frequency & tie-line power error is done at a fixed interval of time therefore we model the system in discrete form. The actual discrete model of thermal – thermal (2 – area system with non-reheat thermal) unit is shown in fig (1). The nominal values of all parameters are given in appendix – 2.

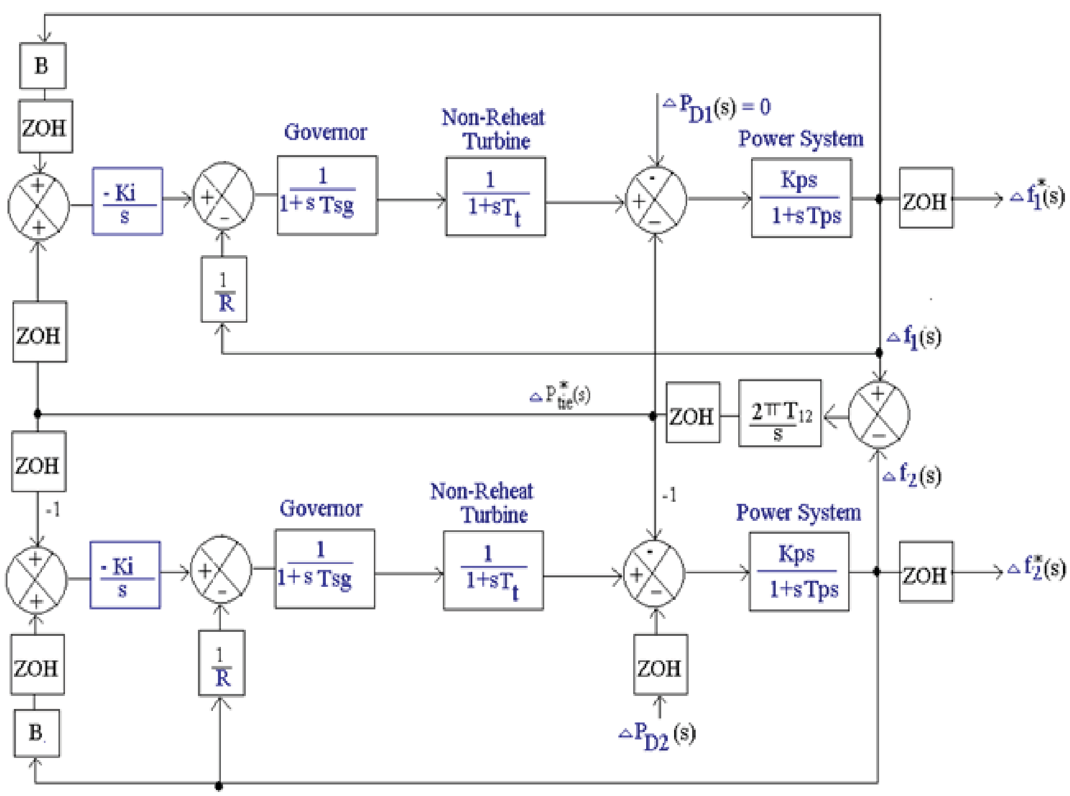

Fig: (1) Block Diagram representation of interconnected power system in discrete domain

III. MODELING OF DISCRETE POWER SYSTEM

This paper model the concerned interconnected power system in state space from.

State variables are the minimal set of variables such that the knowledge of the variable at $t = t_0$ with the knowledge of input for $t > t_0$ completely determined the future behavior of the system for all $t > t_0$.

The continuous time dynamics behavior of the AGC system is described by the linear vector differential equation, as

$$\dot{X} = Ax + Bu + Gw - - - - - (1)$$

Where, A, B & G are the system matrix, input matrix & disturbance matrices, respectively, depending upon system parameters & other operating conditions and x = [Δf_1 Δf_2 ΔP_{t1} ΔP_{t2} ΔP_{C1} ΔP_{c2} ΔX_{G1} ΔX_{G2} ΔP_{tie}], u = [Δu_1 Δu_2]^T & G = [ΔP_{D1} ΔP_{D2}]^T are the state variables, input vectors & disturbance vectors.

State space model of interconnected power system is defined as

$$A = \begin{bmatrix} -0.05 & 6 & 0 & 0 & 0 & 0 & -6 & 0 & 0 \\ 0 & 3.33 & -3.33 & 0 & 0 & 0 & 0 & 0 & 0 \\ -5.208 & 0 & -125 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.05 & 6 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & -3.33 & 3.33 & 0 & 0 & 0 \\ 0 & 0 & 0 & -5.208 & 0 & -125 & 0 & 0 & 0 \\ 0.545 & 0 & 0 & -0.545 & 0 & 0 & 0 & 0 & 0 \\ 0.425 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0.425 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 12.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 12.5 & 0 & 0 & 0 \end{bmatrix}^T$$

$$G = \begin{bmatrix} -6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -6 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$T_1(s) = -\frac{\Delta f_1(s)}{\Delta P_{D2}(s)} =$$

$$\frac{-19.62s^6 - 621.3s^5 - 6554s^4 - 2.621e004s^3 - 39240s^2 - 1.363e004s}{s^9 + 31.77s^8 + 343.7s^7 + 1769s^6 + 7458s^5 + 1.99e004s^4 + 3.948e004s^3 + 4.701e004s^2 + 2.497e004s + 4633}$$

------------------ (2)

Therefore, characteristic equations of the concerned system is

$$s^9 + 31.77s^8 + 343.7s^7 + 1769s^6 + 7458s^5 + 1.99e004s^4 + 3.948e004s^3 + 4.701e004s^2 + 2.497e004s + 4633 = 0 - - - - - - - - - - - (3)$$

Since, in actual practice measurement is done in discrete domain, therefore equation (1) can be rewritten by linear vector difference equation in discrete domain as

$$x(k+1) = A_d\, x(k) + B_d\, u(k) + G_d\, w(k) \quad \text{---------} \ (4)$$

Where, x(k), u(k) & w(k) are specified at t = kT; k = 0, 1, …… etc, & T be the sampling time period & matrices are defined as

$$A_d \approx [I - A * T], \qquad B_d \approx B * T, \qquad G_d \approx G * T \qquad \text{----------------} \ (5)$$

$$A_d = \begin{bmatrix} 1.005 & -0.6 & 0 & 0 & 0 & 0 & 0.6 & 0 & 0 \\ 0 & 0.667 & 0.333 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.5208 & 0 & 2.25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.005 & -0.6 & 0 & -0.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.333 & -0.333 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5208 & 0 & 2.25 & 0 & 0 & 0 \\ -0.0545 & 0 & 0 & 0.0545 & 0 & 0 & 1 & 0 & 0 \\ -0.0425 & 0 & 0 & 0 & 0 & 0 & -0.1 & 1 & 0 \\ 0 & 0 & 0 & -0.0425 & 0 & 0 & 0.1 & 0 & 1 \end{bmatrix} \quad B_d = \begin{bmatrix} 0 & 0 & 1.25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.25 & 0 & 0 & 0 \end{bmatrix}^T$$

$$G_d = \begin{bmatrix} -0.6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.6 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$T_1(z) = -\frac{\Delta f_1(z)}{\Delta P_{D2}(z)}$$

$$\frac{-3.269\text{x}10^{-6}\, z^8 + 5.559\text{x}10^{-6} z^7 + 2.702\text{x}10^{-5} z^6 - 0.0001023\, z^5 + 0.0001397\, z^4 - 8.812\text{x}10^{-5}\, z^3 + 1.817\text{x}10^{-5} z^2 + 5.554\text{x}10^{-6} z - 2.381\text{x}10^{-6}}{z^9 - 8.698\, z^8 + 33.61\, z^7 - 75.76\, z^6 + 109.7\, z^5 - 105.9\, z^4 + 68.15\, z^3 - 28.18\, z^2 + 6.794\, z - 0.7278}$$

----------------------(6)

IV. PULSE TRANSFER FUNCTION

In this work we study frequency & tie – line power error in sampled data fashion, hence pulse transfer function model or z – domain model is designed, for this purpose sampling operation is done between controller & system. Considering a simple sample data system, fig: (2), consisting of sampler & plant with Transfer function G(s).

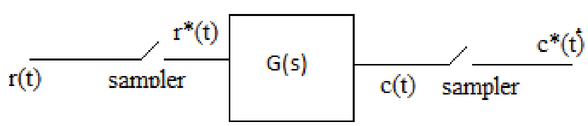

Fig: (2) A simple sample – data system

r(t) & r*(t) are the input & output of sampler respectively, similarly c(t) & c*(t) are the continuous & starred output of the system, respectively. Thus,

c(t) = r*(t) * g(t) ------------(7)

If the output c(t) is now sampled,

$$\text{c(kT)} = \sum_{m=0} y(kT)g((k-m)T),$$

Where T be the sampling period, then

$$\text{C*(t)} = \sum c(kT)\delta(t-kT)$$
$$= \sum\left[\sum r(mT)g(k-m)T\right]\delta(t-kT) \qquad \text{-----------(8)}$$

Taking Laplace Transform of above equation, we have

$$\text{C*(s)} = \sum r(mT)\sum g(kT)\ e^{-(k+m)sT}$$
$$= \sum r(mT)e^{-msT}\sum g(kT)\ e^{-ksT}$$
$$= \text{R*(s) G*(s)} \qquad \text{-------------------(9)}$$

Since, $z = e^{sT}$, therefore, C(z) = R(z) G(z)

Since hold circuit is also used along with sampler, the output of sample & hold circuit is C*(s) = $\frac{1-e^{-sT}}{s}$

Detail calculation of pulse transfer function is shown in appendix – 1.

V. SIMULINK RESULTS

Two area interconnected thermal-thermal power system were studied in MATLAB-SIMULINK environment. Fig: (2) to fig: (7) depict $\Delta f_1(t)$, $\Delta P_{tie,12}(t)$ & $\Delta f_1(z)$ responses both in continuous time domain and discrete time domain using SIMULINK. In the present study, we divided our result into four cases:

Case1: Continuous time domain analysis of interconnected power system without any controller & frequency bias setting.

Case2: Continuous time domain analysis of interconnected power system with PI-controller of K_i = 0.4 & frequency bias setting, B_i = 0.

Case3: Continuous time domain analysis of interconnected power system with PI-controller of K_i = 0.4 & frequency bias setting, B_i = 0.425.

Case4: Discrete time domain frequency analysis of control area – 1 with two different sampling period of T = 0.1 sec & 0.2 sec.

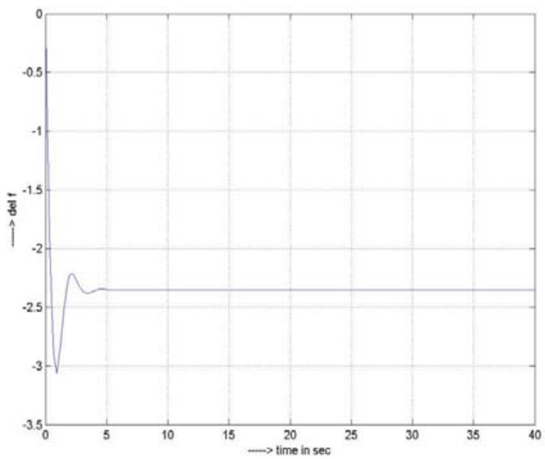

Fig (2) frequency error without any controller action and bias setting

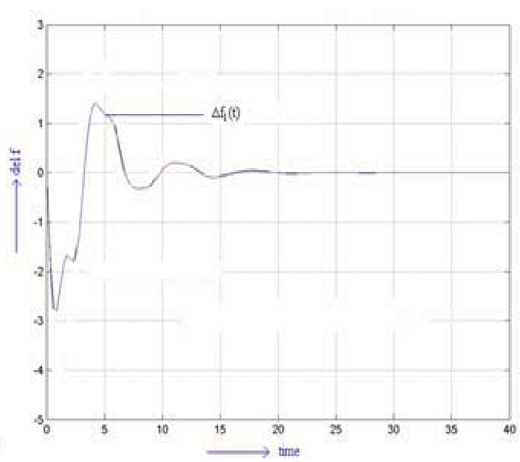

Fig (3) frequency error with PI – controller action and bias setting, B_i=0

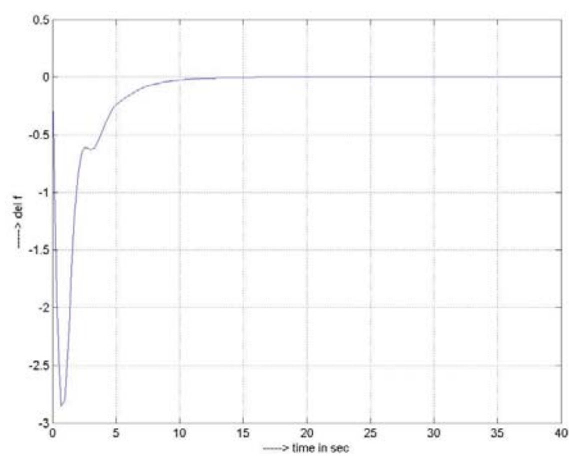

Fig (4) frequency error with PI – controller action and bias setting, B_i = 0.425

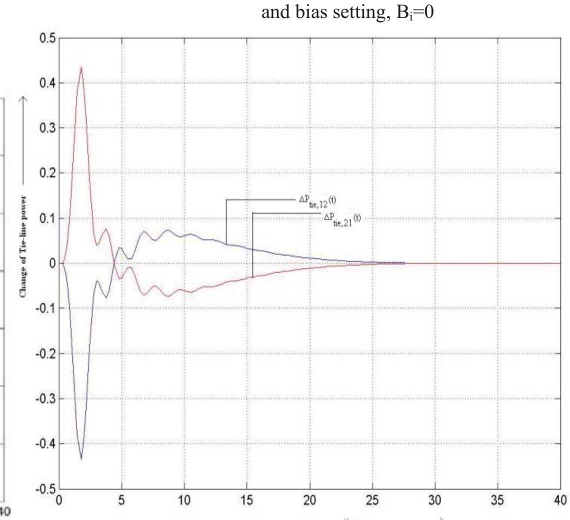

Fig (5) Tie-line power error with PI – controller action and bias setting, B_i = 0.425

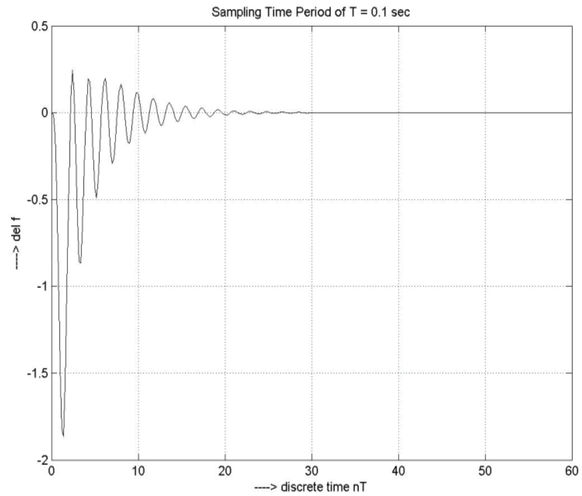

Fig (6) Discrete time frequency error with PI – controller action and bias setting, $B_i = 0.425$ having sampling time T = 0.1 sec

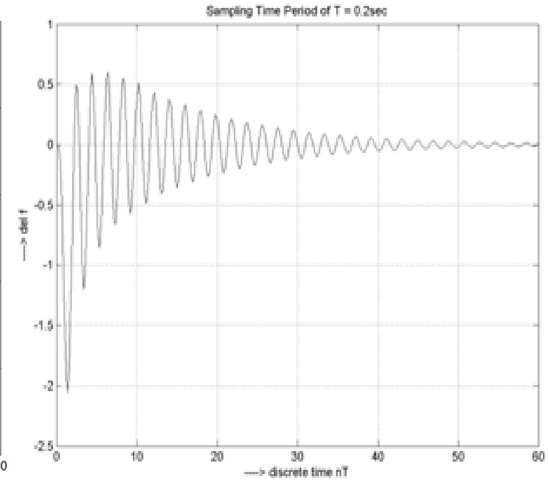

Fig (7) Discrete time frequency error with PI – controller action and bias setting, $B_i = 0.425$ having sampling time T = 0.2 sec

VI. CONCLUSION

In this paper sampled data theory with the help of z – transform technique including all system parameters, specially governor and steam turbine transfer functions, of system for first time is presented. It is realistic to apply this technique because both frequency and tie – line power were measured at a fixed interval of time. Tie line power and frequency deviation were observed from simulation results with step load changes in both system areas. It has been shown from results that both $\Delta f_1(t)$ & ΔP_{tie} are different from the results obtained in continuous time domain, i.e.; using Laplace transform method.

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I. Appendix – 1

Calculation of pulse transfer function:

From fig: (1), we have (for area – 1)

$$[\{\left[\frac{2\Pi T_{12}(1-e^{-sT})}{s^2}\Delta f_D{}^*(s)\right]\left(\frac{1-e^{-sT}}{s}\right)+B\left(\frac{1-e^{-sT}}{s}\right)\Delta f_1{}^*(s)\}(-\frac{K_i}{s})-(\frac{1}{R})\Delta f_1{}^*(s)]\left(\frac{1}{(1+sT_{sg})(1+sT_t)}\right)$$

$$-\frac{2\Pi T_{12}(1-e^{-sT})}{s^2}\Delta f_D{}^*(s)\}\left(\frac{K_P}{1+sT_P}\right)=\Delta f_1{}^*(s)------------(10)$$

$$[\{\left[\frac{2\Pi T_{12}(1-e^{-sT})}{s^2}\Delta f_D^*(s)\right]\left(\frac{1-e^{-sT}}{s}\right)+B\left(\frac{1-e^{-sT}}{s}\right)\Delta f_2^*(s)\}(-\frac{K_i}{s})-(\frac{1}{R})\Delta f_2^*(s)]\left(\frac{1}{(1+sT_{sg})(1+sT_t)}\right)$$

$$-\frac{2\Pi T_{12}(1-e^{-sT})}{s^2}\Delta f_D^*(s)\}\left(\frac{K_P}{1+sT_P}\right)=\Delta f_2^*(s)-----------(11)$$

Adding equation (10) & (11), we get

$$\Rightarrow \left[\frac{-BK_i(1-e^{-sT})}{s^2}\Delta f_1^*(s)-\frac{1}{R}\Delta f_1^*(s)\right]\left(\frac{K_P}{(1+sT_{sg})(1+sT_t)(1+sT_P)}\right)+\left[\frac{-BK_i(1-e^{-sT})}{s^2}\Delta f_2^*(s)-\frac{1}{R}\Delta f_2^*(s)\right]$$

$$\left(\frac{K_P}{(1+sT_{sg})(1+sT_t)(1+sT_P)}\right)-\left(\frac{K_P(1-e^{-sT})}{s(1+sT_P)}\right)\Delta P_{D2}^*(s)=\Delta f_1^*(s)+\Delta f_2^*(s)=\Delta f_A^*(s)$$

$$\frac{-K(1-e^{-sT})}{s(1+K_1s+s^2K_2+s^3K_3)}\Delta P_{D2}^*(s)=\Delta f_A^*(s)\left[1+\frac{BKK_i(1-e^{-sT})}{s^2(1+K_1s+s^2K_2+s^3K_3)}\right]-----(12)$$

(After some mathematical manipulation)
From equation (10) we get,

$$[\{\left[\frac{2\Pi T_{12}(1-e^{-sT})}{s^2}\Delta f_D^*(s)\right]\left(\frac{1-e^{-sT}}{s}\right)+B\left(\frac{1-e^{-sT}}{s}\right)\Delta f_1^*(s)\}(-\frac{K_i}{s})-(\frac{1}{R})\Delta f_1^*(s)]\left(\frac{1}{(1+sT_{sg})(1+sT_t)}\right)$$

$$-\frac{2\Pi T_{12}(1-e^{-sT})}{s^2}\Delta f_D^*(s)\}\left(\frac{K_P}{1+sT_P}\right)=\Delta f_1^*(s)$$

$$\Rightarrow \left[-\frac{2\Pi T_{12}K_iK_P(1-e^{-sT})^2}{s^4(1+sT_{sg})(1+sT_t)(1+sT_P)}\Delta f_D^*(s)\right]-\left[\frac{BK_iK_P(1-e^{-sT})}{s^2(1+sT_{sg})(1+sT_t)(1+sT_P)}\Delta f_1^*(s)\right]-$$

$$\left[\frac{2\Pi T_{12}K_P(1-e^{-sT})}{s^2(1+sT_P)}\Delta f_D^*(s)\right]-\frac{K_P}{R(1+sT_{sg})(1+sT_t)(1+sT_P)}\Delta f_1^*(s)=\Delta f_1^*(s)$$

$$\Rightarrow -\frac{X_0(1-e^{-sT})(1+sT_{sg})(1+sT_t)}{s^2(1+sK_1+s^2K_2+s^3K_3)}\left[1+\frac{K_i(1-e^{-sT})}{s^2(1+sT_{sg})(1+sT_t)}\right]\Delta f_D^*(s)=\Delta f_1^*(s)\left[1+\frac{BKK_i(1-e^{-sT})}{s^2(1+sK_1+s^2K_2+s^3K_3)}\right]$$

------------ (13)

Now, $$2\Delta f_1^*(s)=\Delta f_A^*(s)+\Delta f_D^*(s)-----(14)$$

Substituting value of $\Delta f_A^*(s)$ & $\Delta f_D^*(s)$ from equation (12) & (13) to equation (14), we get

$$\frac{\Delta f_1^*(s)}{\Delta P_{D2}^*(s)}=\frac{N(s)}{D(s)}$$

Where,

$$N(s)=-\left(\frac{K(1-e^{-sT})}{s(1+sK_1+s^2K_2+s^3K_3)}\right)\left(\frac{X_0(1-e^{-sT})(1+sT_{sg})(1+sT_t)}{s^2(1+sK_1+s^2K_2+s^3K_3)}\right)\left(1+\frac{K_i(1-e^{-sT})}{s^2(1+sT_{sg})(1+sT_t)}\right)$$

Taking z-transform of above equation, we get
N(z) =

$$\frac{K(z-1)}{z}x_1(z)\frac{X_0(z-1)}{z}x_2(z)\left[1+\frac{K_i(z-1)}{z}x_3(z)\right]$$

$$D(s)=\frac{2X_0(1-e^{-sT})(1+sT_{sg})(1+sT_t)}{s^2(1+sK_1+s^2K_2+s^3K_3)}\left(1+\frac{K_i(1-e^{-sT})}{s^2(1+sT_{sg})(1+sT_t)}\right)+\left(1+\frac{BK_iK(1-e^{-sT})}{s^2(1+sK_1+s^2K_2+s^3K_3)}\right)$$

Therefore, D(z) = Z[D(s)]

$$D(z)=\frac{2X_0z}{(z-1)}x_2(z)\left[1+\frac{K_i(z-1)}{z}x_3(z)\right]+\left[1+\frac{BK_iK(z-1)}{z}x_4(z)\right]$$

Where,

$$x_1(z)=\left[\frac{z}{z-1}+\frac{P_1z}{z-e^{-m_1T}}+\frac{P_2z}{z-e^{-m_2T}}+\frac{P_3z}{z-e^{-m_3T}}\right] \qquad P_1=\left[-\frac{1}{(1-a)(1-b)}\right]$$

$$x_2(z)=\left[\frac{P_4z}{z-e^{-m_1T}}+\frac{P_5z}{z-e^{-m_2T}}+\frac{P_6z}{z-e^{-m_3T}}+\frac{Tz}{(z-1)^2}+\frac{P_7z}{z-1}\right] \qquad P_2=\left[-\frac{1}{(1-\frac{1}{a})(1-c)}\right]$$

$$x_3(z)=\left[\frac{Tz}{(z-1)^2}+\frac{P_8z}{(z-1)}+\frac{P_9}{T_{sg}}\frac{z}{z-e^{-\frac{T}{T_{sg}}}}+\frac{P_{10}}{T_t}\frac{z}{z-e^{-\frac{T}{T_t}}}\right] \qquad P_3=\left[-\frac{1}{(1-\frac{1}{b})(1-\frac{1}{c})}\right]$$

$$x_4(z)=\left[\frac{Tz}{(z-1)^2}+\frac{P_{11}z}{(z-1)}+\frac{P_{12}z}{z-e^{-m_1T}}+\frac{P_{13}z}{z-e^{-m_2T}}+\frac{P_{14}z}{z-e^{-m_3T}}\right]$$

$$P_4=\left[\frac{(1-m_1T_{sg})(1-m_1T_t)}{m_1(1-\frac{m_1}{m_2})(1-\frac{m_1}{m_3})}\right]$$

$$P_5=\left[\frac{(1-m_2T_{sg})(1-m_2T_t)}{m_2(1-\frac{m_2}{m_1})(1-\frac{m_2}{m_3})}\right] \qquad P_6=\left[\frac{(1-m_3T_{sg})(1-m_3T_t)}{m_3(1-\frac{m_3}{m_1})(1-\frac{m_3}{m_2})}\right]$$

$$P_7=\frac{(m_1m_2m_3)(T_{sg}+T_t)-(m_1m_2+m_3m_2+m_1m_3)}{m_1m_2m_3} \qquad P_8=-(T_{sg}+T_t) \qquad P_9=\frac{T_{sg}^{\ 2}}{(1-\frac{T_t}{T_{sg}})}$$

$$P_{10}=\frac{T_t^2}{(1-\frac{T_{sg}}{T_t})} \qquad P_{11}=\left[\frac{(m_1m_2+m_3m_2+m_1m_3)}{m_1m_2m_3}\right]$$

$$P_{12} = \left[\frac{1}{m_1 (1 - \frac{m_1}{m_2})(1 - \frac{m_1}{m_3})} \right] \qquad P_{13} = \left[\frac{1}{m_2 (1 - \frac{m_2}{m_1})(1 - \frac{m_2}{m_3})} \right]$$

$$P_{14} = \left[\frac{1}{m_3 (1 - \frac{m_3}{m_1})(1 - \frac{m_3}{m_2})} \right]$$

II. Appendix – 2

Rating of generators (Pr_i) = 2000MW, turbine time constant (T_r) = 0.3 sec, speed governor time constant (T_r) = 0.3 sec, gain (K_{ps}) & time constant (T_{ps}) of power system 120 & 20 sec, respectively, synchronizing time constant (T_{12}) = $\frac{0.545}{2\pi}$ sec, Governor speed regulation parameter in Hz per p.u. MW (R_i) = $\frac{1}{2.4}$, Frequency bias constant (B_i) = 0.425, Integration time constant (K_i) = 0.4 sec.