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Parametric robust control of power system using delta operator

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Abstract: Changes in real power affect mainly the system frequency, while reactive power is less sensitive to changes in frequency and is mainly dependent on changes in voltage magnitude. Thus, real and reactive powers are controlled separately. The load frequency control (LFC) loop controls the real power and frequency and the automatic voltage regulator (AVR) loop regulates the reactive power and voltage magnitude. Load frequency control has gained in importance with the growth of interconnected systems and has made the operation of interconnected systems possible. This paper deals with the control of active power using delta transformation technique to keep the system in the steady state. Simple models of the essential components used in the control systems in delta domain is studied. The objective of the control strategy is to generate and deliver power in an interconnected system as economically and reliably as possible while maintaining the voltage and frequency within permissible limit.

Keywords: Delta operator, delta transfer function, Load frequency control (LFC), Automatic Generation control

1. INTRODUCTION

Power system operation and control has become a very well discussed and interesting topics among the researchers and scientists for the last few decades. Energy demand by the consumers and supply by the power stations must have to be balanced for continuous operation of power system. This balancing is done by controlling the frequency which is possible by Automatic Generation control (AGC) or Load Frequency Control (LFC) as discussed in [1] and [2]. A new gain scheduler for PI based load frequency control has been proposed by D. Raekpreedapong et.al and a microprocessor based adaptive control strategy in load frequency control has been proposed by Kannaiah, et al. [4]. In [5] a new PID controller for LFC has been presented to show how the damping of the power system has been enhanced while a step change in load occurs. An investigation related to 2-area and 3-area network systems has been proposed in [6] to discuss the LFC with high voltage DC transmission system. Recently various types of LFC schemes have been proposed by the researchers mainly from the field of power system. Internal model control (IMC) based PID LFC controller, LFC for the multi area power system using the fuzzy logic based approach is proposed in [7] and [8]. A Classical Control Design in Delta Domain by Optimal Generalised Moment Matching Using Genetic Algorithm is presented by N.C.Sarcar et.al [9]. A Unified Approach for Load Frequency Control of Isolated Power System using Delta Time Moment is presented by P Sarkar et.al [10].

In the works accumulated over the last six decades, a good volume of literature is available in the area of discrete-time system studies using the shift-operator, and in the complex domain using the associated z transformation. Forward shift operator is a convenient tool to model linear difference equations with constant coefficients and in the complex domain the input-output description or the state space model of the linear discrete-time system can be expressed to a z transfer function or a z transfer function matrix. Despite its wide use, the shift operator and the complex domain z transformed description of the discrete-time systems can not support very high speed digital computation, due cluster of open left half s-plane poles in the z-plane at the point (1,0). These lead to numerical ill conditioning in the formulation of discrete-time model and that the discrete-time model losses consistency with the continuous case.

The above problem can be safely avoided by using delta operator introduced by Middleton *et al*. [11]. The delta operator formulation of the discrete-time systems provides a unified framework to obtain near continuous-time results from the discrete-time systems at very large sampling frequency and further improve the numerical robustness as compared to shift operator description of the discrete-time systems. Middleton and Goodwin have popularized delta operator in [11], the important advantages of the application of this operator in system modeling, identification and control is to improve the numerical properties as compared to forward shift operator. The application of delta operator is now wide spread in system and control and may be seen for fault tolerant control [12], in [13] for the design of adaptive I-PD control. Hongyi Li et al. in their paper [14] applied delta operator for output feedback control of T-S Fuzzy systems with time varying delays. In addition, at high sampling limit the resultant delta operator parameterization converges to its corresponding continuous-time models leading to unified treatment of both discrete and continuous-time systems. The reliable and superior robust numerical properties of delta operator have widened the area of its application in many areas of systems, information and control.

The generator excitation system maintains generator voltage and controls the reactive power flow. The generator excitation of older systems may be provided through slip rings and brushes by means of dc generators mounted on the same shaft as the rotor of the synchronous machine. However, modern excitation systems usually use ac generators with rotating rectifiers, known as brushless excitation. The in the real power demand affects mainly the frequency, whereas a change in the reactive power affects mainly the voltage magnitude. [1]. In section II of this paper a brief introduction of delta-operator representation of discrete-time system is presented. Section III basic generator loop [1] has been discussed. Section IV load frequency control in delta domain and in section V Automatic Generation control in delta domain has been discusses with numerical examples]. Section VI gives the conclusions.

2. Delta Operator Representation of Discrete-time Systems

2.1. State Space Models

Consider a continuous time linear state space system

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) \qquad (1)$$
$$y(t) = Cx(t)$$

Where $x \in R^n$ is the state, $u \in R^m$ is the control input, $y \in R^p$ is the output. Let Δ be the sampling period and q the standard forward shift operator such that qx(t)=x(t+Δ). Now if the input u(t) is sampled by a sampler and hold device then the corresponding discrete-time model in shift form is

$$qx(t) = A_q x(t) + B_q u(t) \qquad (2)$$
$$y(t) = Cx(t)$$

where,

$$A_q = e^{A\Delta} \text{ and } B_q = \int_0^{\Delta} e^{A(\Delta-\tau)} B d\tau \qquad (3)$$

The difficulty with the above representation is that at fast sampling limit i.e. when $\Delta \to 0$

$$\lim_{\Delta\to 0} A_q = I \quad (4) \qquad \& \qquad \lim_{\Delta\to 0} B_q = 0 \quad (5)$$

Therefore the shift operator representation of discrete-time system becomes highly sensitive to round-off errors at fast sampling limit. The delta operator is defined as

$$\delta \triangleq \frac{q-1}{\Delta} \qquad (6)$$

such that

$$\delta x(t) \triangleq \begin{cases} \dfrac{x(t+\Delta)-x(t)}{\Delta} & : \Delta \neq 0 \\ \dfrac{dx(t)}{dt} & : \Delta = 0 \end{cases} \qquad (7)$$

Using the delta operator, the discrete-time representation of the shift operator model is given by

$$\delta x(t) = A_\delta x(t) + B_\delta u(t) \qquad (8)$$
$$y(t) = Cx(t)$$

where

$$A_\delta = \frac{A_q - 1}{\Delta} = \Psi(A,\Delta)A$$
$$B_\delta = \frac{B_q}{\Delta} = \Psi(A,\Delta)B \qquad (9)$$
$$\Psi(A,\Delta) = (I + \frac{A\Delta}{2!} + \frac{A^2\Delta^2}{3!} + \cdots)$$

and

$$\lim_{\Delta\to 0} A_\delta = A \quad (10) \qquad \& \qquad \lim_{\Delta\to 0} B_\delta = B \quad (11)$$

Consequently, in the fast sampling limit the delta operator model in equation (8) tends to the continuous-time state-space model. Thus the use of delta operator ensures better numerical conditioning leading to robust numerical algorithms and further ensures the convergence of discrete-time results to their continuous-time counterpart at the fast sampling limit i.e. when $\Delta \to 0$. This feature of delta operator representation unifies continuous and discrete-time analysis, synthesis, design and control.

2.2 Delta Operator Transfer Function Models

In continuous-time system we have the Laplace transform variable s, which is closely related to the derivative operator d/dt. Similarly in discrete time, the z transform variable z is associated with the shift operator q. The variable γ is the delta operator transformed variable and is defined by the linear relation

$$\gamma = \frac{z-1}{\Delta} \tag{12}$$

and the delta transform is defined as:

$$F_\Delta(\gamma) = S_0^{\propto} f(t)E(\gamma,-t)dt \tag{13}$$

where the generalised integration operator S is defined below:

$$S_{t_1}^{t_2} f(\tau)d\tau \triangleq \begin{cases} \int_{t_1}^{t_2} f(\tau)d\tau & : \Delta = 0 \\ \Delta \sum_{k=\frac{t_1}{\Delta}}^{k=\frac{t_2}{\Delta}-1} f(k\Delta) & : \Delta \neq 0 \end{cases} \tag{14}$$

and

$$E(\gamma,-t) \triangleq \begin{cases} e^{-\gamma t} & : \Delta = 0 \\ (1+\Delta\gamma)^{\frac{-t}{\Delta}} & : \Delta \neq 0 \end{cases} \tag{15}$$

In continuous-time i.e. when $\Delta = 0$ the delta transform defined above converges to the Laplace transform (with s replaced by γ). In discrete time, the delta transform defined above is related to z transform as follows:

$$F_\Delta(\gamma) = F_z(z)\Big|_{z=1+\Delta\gamma} = \Delta\sum_{k=0}^{\propto} f(k\Delta)(1+\Delta\gamma)^{-k} \tag{16}$$

where k is the indexing discrete time parameter and t=kΔ are the independent discrete time instants for $k \in [0,\propto]$. The relationship between delta operator and delta transform is given by

$$T_\Delta \delta f(t) = \gamma T_\Delta f(t) - (1+\Delta\gamma) f(0) \tag{17}$$

Therefore, for zero initial conditions, operating on a function by δ is equivalent to multiplying the function's transform by γ. Therefore operating on the delta operator system transfer function in γ-domain we obtain

$$G_\delta(\gamma) = C(\gamma I - A_\delta)^{-1} B_\delta \tag{18}$$

where as the system transfer function of equation (1)in s- domain and equation (2) in z- domain are as follows

$$G_c(s) = C(sI - A)^{-1}B \tag{19}$$

$$G_q(z) = C(zI - A_q)^{-1}B_q \tag{20}$$

Using equations (4), (5), (10) and (11) we have

$$\lim_{\Delta\to 0} G_q(z) = 0 \quad \text{and} \quad \lim_{\Delta\to 0} G_\delta(\gamma) = G_c(s).$$

Thus we see that as $\Delta \to 0$ the z- domain transfer functions become numerically ill conditioned and uninformative, whereas the delta domain transfer functions converge to the original continuous-time transfer function.

Changes in real power affect mainly thee system frequency, while ractive power is less sensitive to changes in frequency and is mainly dependent on changes in voltage magnitude. Thus, real and reactive powers are controlled separately. The load frequency control (LFC) loop controls the real power and frequency and the automatic voltage regulator (AVR) loop regulates the reactive power and voltage magnitude. Load frequency control has gained in importance with the growth of interconnected systems and has made the operation of interconnected systems possible. Today, it is still the basis of many advanced concepts for the control of large systems. [1]. The method developed for control of individual generators, and eventually control of large interconnections.

This chapter deals with the control of active power using delta transformation technique to keep the system in the steady state. Simple models of the essential components used in the control systems in delta domain is studied. The objective of the control strategy is to generate and deliver power in an interconnected system as economically and reliably as possible while maintaining the voltage and frequency within permissible limit.

3 Basic Generator control loops:

In an interconnected power system, load frequency control (LFC) and automatic voltage regulator (AVR) equipments are installed for each generator. Fig. 1 represents the schematic diagram of the load frequency control (LFC) loop and automatic voltage regulator (AVR) loop. The controllers are set for a particular operating condition and take care of small changes in load demand to maintain the frequency and voltage magnitude within the specified limits. Small changes in real power are mainly dependent on changes in rotor angle δ and, thus, the frequency. The reactive power is mainly dependent on the voltage magnitude i.e on the generator excitation. The excitation system time constant is much smaller than the prime mover time constant and its transient decay much faster and does not affect the LFC dynamic. Thus the cross coupling between the LFC loop and the AVR loop is negligible and the load frequency and excitation voltage control are analyzed independently.

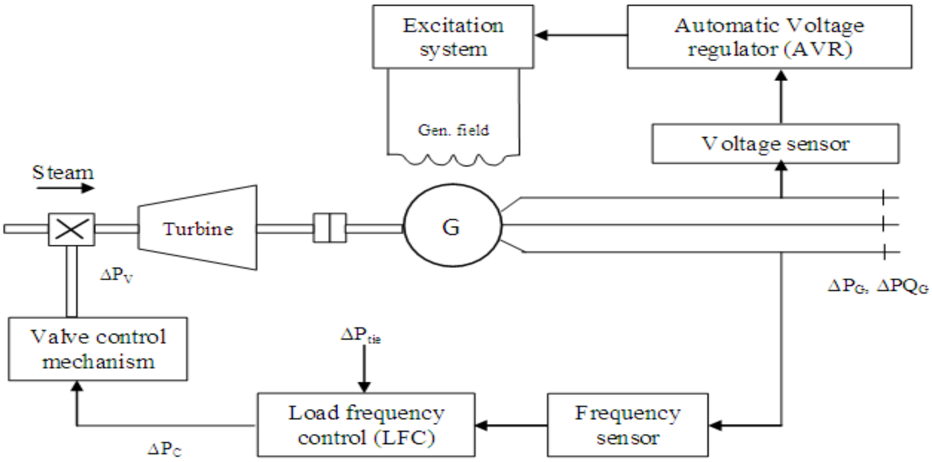

Fig 1 Schematic diagram of Load frequency control (LFC) and Automatic voltage regulator

4 Load Frequency control

The operation objectives of the LFC are to maintain reasonably uniform frequency to divide the load between generators, and to control the tie-line interchange schedules. The change in frequency and tie line real power are sensed, which is a measuer of the change in rotor angle δ, i.e. the error $\Delta\delta$ to be corrected. The erreor signal Δf and ΔP_{tie}, are amplified, mixed, and transformed into a real power command signal ΔP_v, which is sent to the prime mover to call for an increment in the torque. The prime mover, therefore brings change in the generator output by an amount ΔP_g which will change the values of Δf and ΔP_{tie} within the specified tolerance.

The first step in the analysis and design of a control system is mathematical modelling of the system. Two common methods are the transfer function method and state variable method. The state variable approach can be applied for linear as well as nonlinear systems.

The swing equation of synchronous machine to small perturbation is given by

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e \qquad (21)$$

Where H is per unit inertia constant and range is from 1 to 10 seconds, depending on the size and type of machine i.e

$$H = \frac{\text{Kinetic energy in MJ at rated speed}}{\text{machine rating in MVA}} \qquad (22)$$

P_m and P_e are the per unit mechanical and electrical power respectively, ω_s is electrical angular velocity and δ is electrical power angle.

Complete block diagram of the load frequency control of an isolated power station in s domain is shown in Fig. 2

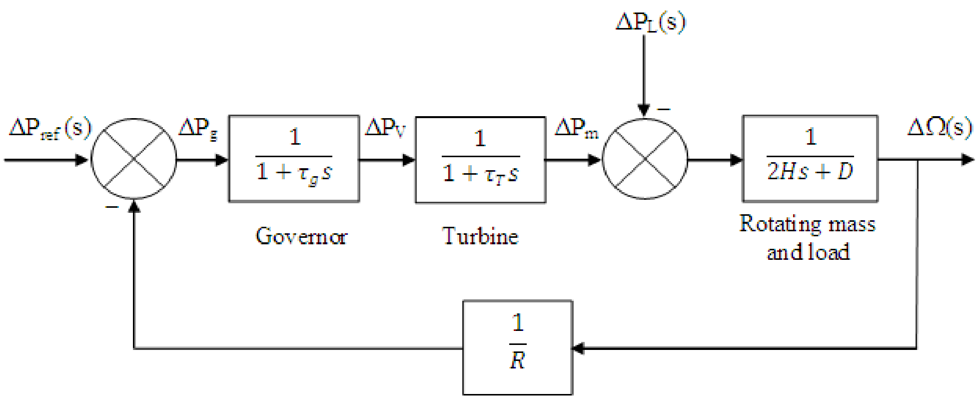

Fig. 2 Load frequency control block diagram of an isolated power system

The closed loop transfer function relating the load change ΔP_L to the frequency deviation $\Delta\Omega$ is in equation number (23) and block diagram is shown in Fig. 3

$$\frac{\Delta\Omega(s)}{-\Delta P_L(s)} = \frac{(1+\tau_g s)(1+\tau_T s)}{(2Hs+D)\,(1+\tau_g s)(1+\tau_T s)+\frac{1}{R}} \tag{23}$$

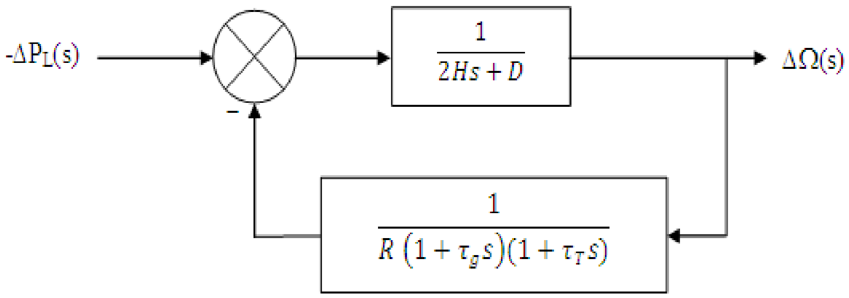

Fig. 3 LFC block diagram with input ΔP_L and output $\Delta\Omega(s)$

Numerical Example:
An isolated power station has the following parameters example 12.1 [1]
Turbine time constant τ_T = 0.5 sec
Governor time constant τ_g = 0.2 sec
Generator inertia constant H = 5 sec
Governor speed regulation R = 0.05 per unit

The load varies 0.8 percent for a 1 percent change in frequency i.e D = 0.8. The turbine rated output is 250 MW at nominal frequency 50 Hz. A sudden load change of 50 MW i.e ΔP_L=0.2 per unit occurs.
Substituting the system parameters in the LFC block diagram of Fig. 3 results in the block diagram shown in Fig 4

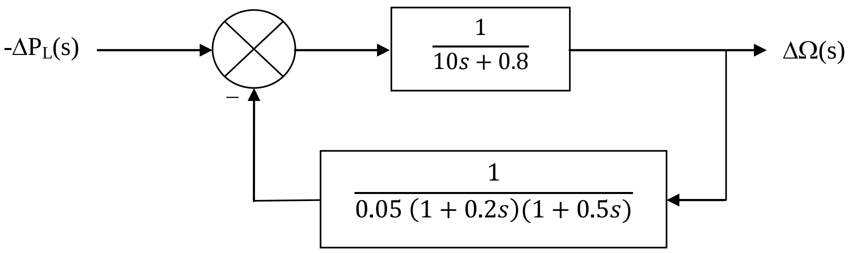

Fig. 4 LFC block diagram for the example

The closed loop transfer function in s domain of the system is given shown in the Fig. 4 is

$$\frac{\Delta\Omega(s)}{-\Delta P_L(s)} = T(s) = \frac{(1+0.2s)(1+0.5s)}{(10s+0.8)\,(1+0.2s)(1+0.5s)+\frac{1}{0.05}} \tag{24}$$

$$= \frac{0.1s^2+0.7s+1}{s^3+7.08s^2+10.56s+20.8} \tag{25}$$

The closed loop transfer function of the system is discritised with zero order hold in delta domain for sampling time 0.01sec, 0.05 sec, 0.001 and 0.0001 sec are given in Eqn. (26), (27), (28) and (29) and the frequency deviation step response and pole zero plot for sampling time 0.01, 0.001 & 0.0001 sec are shown in the Fig. 5 – Fig. 7.

$$\frac{\Delta\Omega(\gamma)}{-\Delta P_L(\gamma)} = \frac{0.0995\gamma^2+0.571\gamma+0.7104}{\gamma^3+5.906\,\gamma^2+9.805\gamma+14.776} \tag{26}$$

$$\frac{\Delta\Omega(\gamma)}{-\Delta P_L(\gamma)} = \frac{0.0999+0.6854\gamma+0.8403}{\gamma^3+6.429\,\gamma^2+10.21\gamma+17.478} \tag{27}$$

$$\frac{\Delta\Omega(\gamma)}{-\Delta P_L(\gamma)} = \frac{0.0999\gamma^2+0.698\gamma+0.9965}{\gamma^3+7.065\,\gamma^2+10.554\gamma+20.727} \tag{28}$$

$$\frac{\Delta\Omega(\gamma)}{-\Delta P_L(\gamma)} = \frac{0.1\gamma^2+0.699\gamma+0.9965}{\gamma^3+7.078\,\gamma^2+10.559\gamma+20.79} \tag{29}$$

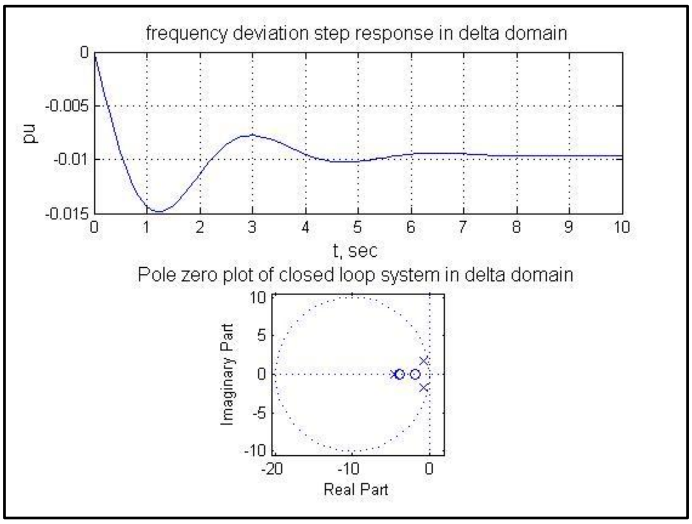

Fig. 5 Frequency deviation step response and pole zero plot in delta domain for sampling time 0.01 sec

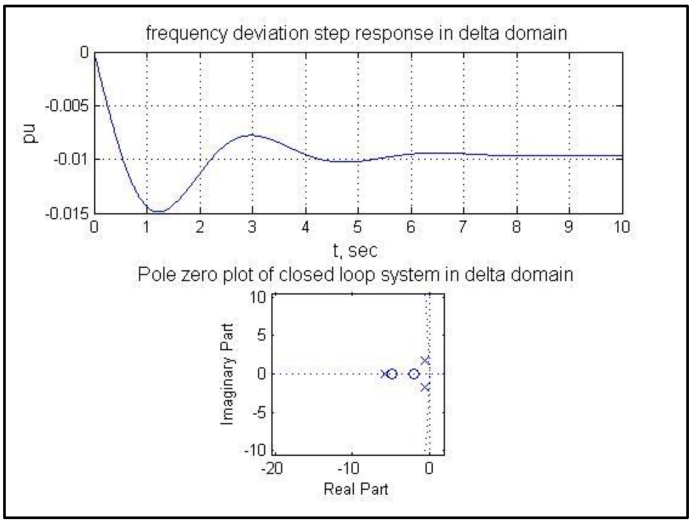

Fig. 6 Frequency deviation step response and pole zero plot in delta domain for sampling time 0.001 sec

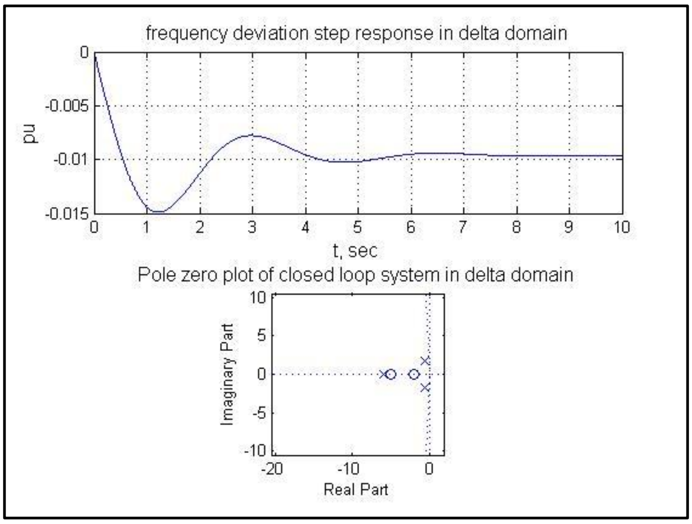

Fig. 7 Frequency deviation step response and pole zero plot in delta domain for sampling time 0.0001 sec

5 Automatic Generation control

If the load on the system is increased, the turbine speed drops before the governor can adjust the input of the steam to the new load. As the change in the value of speed diminishes, error signal becomes smaller and the position of the governor flyballs gets closer to the point required to maintain a constant speed. However, the constant speed will not be the set point, and there will be an offset. One way to restore the speed or frequency to its nominal value is to add an integrator.

The integral unit monitors the average error over a period of time and will overcome the offset. Because of its ability to return a system to its set point, integral action is also known as the rest action. Thus, as the system load changes continuously, the generation is adjusted automatically to restore the frequency to the nominal value. This method is known as automatic generation control (AGC). In the Fig 8 & 9, AGC block diagram of an isolated power system with integral controller and the equivalent block diagram is shown.

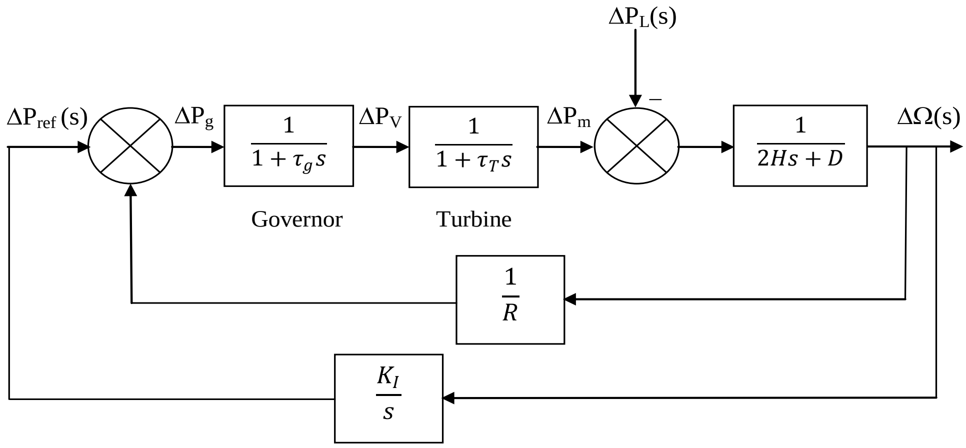

Fig. 8 AGC block diagram of an isolated power system with integral controller

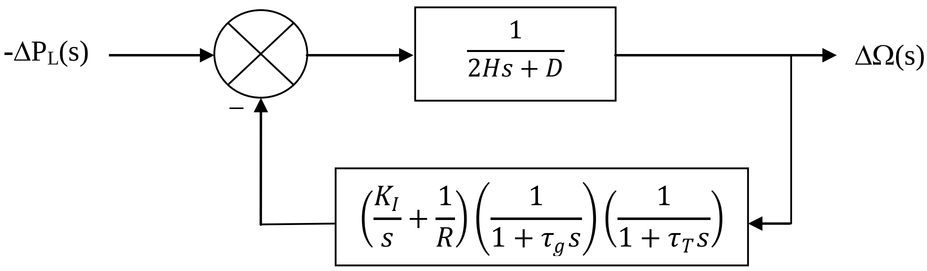

Fig. 9 The equivalent block diagram of AGC for an isolated power system

The above LFC system with integral controller gain K_I = 7, ΔP_L=0.2 and with speed regulation adjusted to R=0.05 per unit results in the following closed loop transfer function in s domain.[1]

$$T(s) = \frac{0.1s^3+0.7s^2+s}{s^4+7.08s^3+10.56s^2+20.8s+7} \quad (30)$$

The closed loop transfer function of the system given in Equn. (30) in delta domain for sampling time 0.01sec, 0.05 sec, 0.001 and 0.0001 sec are given in Eqn. (31),(32), (33) and (34) and the frequency deviation step response and pole zero plot for sampling time 0.01, 0.001 & 0.0001 sec are shown in the Fig 10 – Fig.13.

$$\frac{\Delta\Omega(\gamma)}{-\Delta P_L(\gamma)} = \frac{0.0995\gamma^3+0.5712\gamma^2+0.7099\gamma-3.7963^{-18}}{\gamma^4+5.907\gamma^3+9.867\gamma^2+15.799\gamma+4.972} \quad (31)$$

$$\frac{\Delta\Omega(\gamma)}{-\Delta P_L(\gamma)} = \frac{0.0998\gamma^3+0.631\gamma^2+0.84\gamma+8.227^{-18}}{\gamma^4+6.4295\gamma^3+10.22\gamma^2+18.075\gamma+5.882} \quad (32)$$

$$\frac{\Delta\Omega(\gamma)}{-\Delta P_L(\gamma)} = \frac{0.0999\gamma^3+0.6985\gamma^2+0.9964\gamma+5.859^{-20}}{\gamma^4+7.0655\gamma^3+10.5538\gamma^2+20.7405\gamma+6.9753} \quad (33)$$

$$\frac{\Delta\Omega(\gamma)}{-\Delta P_L(\gamma)} = \frac{0.1\gamma^3+0.6998\gamma^2+0.9995\gamma-8.7347^{-21}}{\gamma^4+7.0786\gamma^3+10.5594\gamma^2+20.794\gamma+6.9975} \quad (34)$$

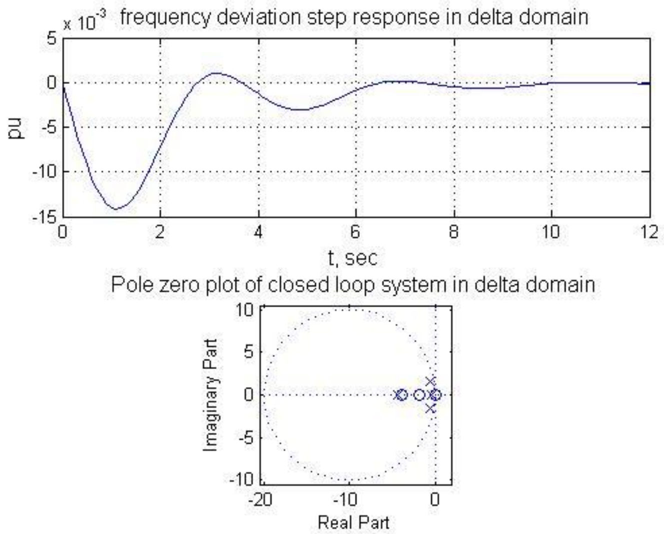

Fig. 10 Frequency deviation step response and pole zero plot in delta domain for sampling time 0.01 sec

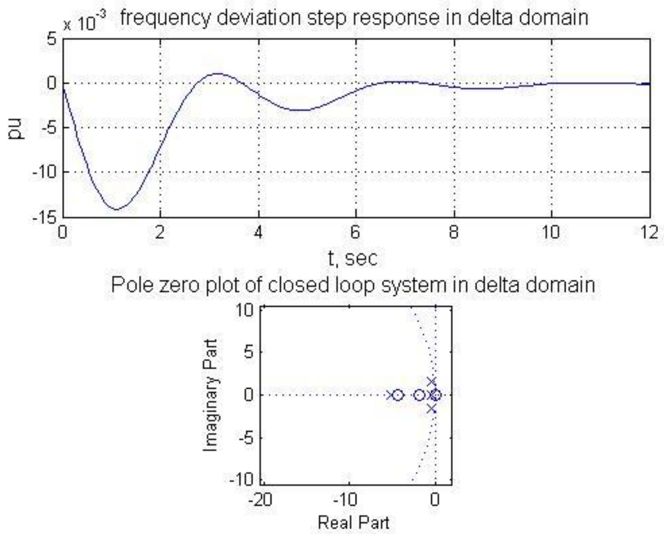

Fig. 11 Frequency deviation step response and pole zero plot in delta domain for sampling time 0.05 sec

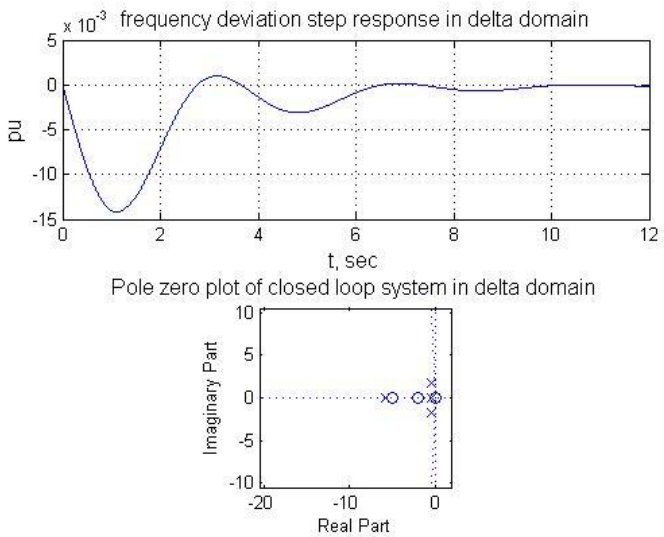

Fig. 12 Frequency deviation step response and pole zero plot in delta domain for sampling time 0.001 sec

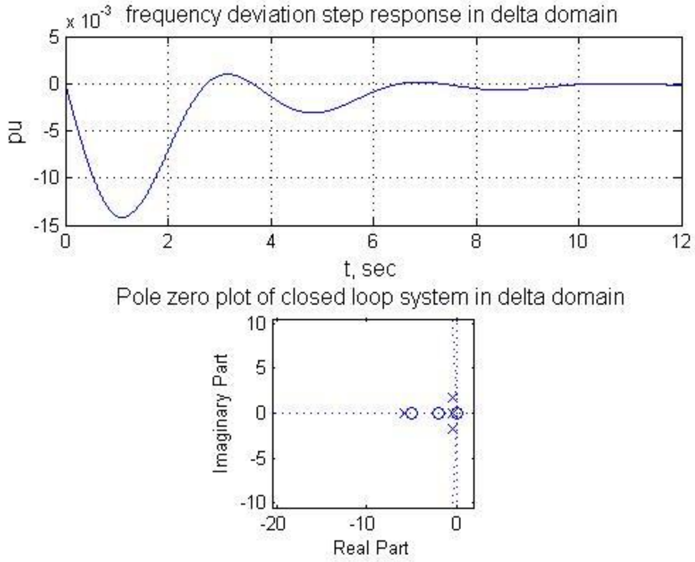

Fig. 13 Frequency deviation step response and pole zero plot in delta domain for sampling time 0.0001 sec

6. CONCLUSIONS

From the frequency deviation step response, it can be observed that the steady state frequency deviation $\Delta\omega_{ss}$ is zero, and the frequency returns to its nominal value in approximately 10 seconds.

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