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Optimal Design of Load Frequency Control of Single Area System

P. Praveena[1], H. S. Shubhanka[2], V. Neha[3], P. Prasath[4] and G. S. Veda[5]
[1,2,3,4&5]Department of Electrical and Electronics Engineering
MVJ College of Engineering, Bangalore, Karnataka, India
E-Mail: puvada.praveena@mvjce.edu.in, prasathkavitha1997@gmail.com
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***Abstract* - In a single-area power system, if a load demand changes randomly, the frequency varies. The main aim of load frequency control (LFC) is to minimize the transient variations and to make sure that the steady state error is zero. Many modern and robust control techniques are used to implement an authentic controller. The objective of these control techniques is to produce and deliver power reliably by maintaining both frequency and voltage within the threshold range. As real power changes, system frequency gets affected and reactive power is dependent on variation in voltage level. Hence real power and reactive power are controlled separately. The role of automatic generation control (AGC) in power system operations under normal operating conditions is analysed. To study the reliability of various control techniques of LFC of the proposed system through simulation in MATLAB-Simulink.**
***Keywords:* Load Frequency Control (LFC), Automatic Generation Control (AGC)**

I. INTRODUCTION

Power system is used for the conversion of available natural energy to electrical energy. Electrical power quality is the main objective for the optimization of electrical instruments. Three phase AC is used for the transportation of electricity. During the transportation, both active and reactive power balance must be maintained between generation and utilization of power. As frequency or voltage change, even equilibrium point change. Good quality of electrical power means both the frequency and voltage are to be fixed at desired values irrespective of all the changes in loads that occur randomly. It is not possible to maintain both active and reactive power without any control. This would result in variation of voltage and frequency levels. The active power and frequency control which is also referred as unknown external disturbance is called load frequency control (LFC).

As consumer load and industrial load continuously varies, both active and reactive power requirements vary. Consequently, the steam input to turbo-generators must be regulated properly, else there can be variation in machine speed and hence change in frequency which is highly undesirable in the power system operation. Theoretically, frequency can be made to zero, but in practice, it is not possible. Thus, there is a certain permissible limit for the variation in frequency. Larger deviations in frequency will have hazardous effect on the consumer end and may lead to damage of the costly equipment’s in the industry. Today all the systems are interconnected in nature. Thus, it is highly challenging task to maintain frequency constant. Here manual regulation is not effective, leading to the need for automatic control.

The deviations in frequency call for the need to design a controller which should be robust and simpler in nature. Till date, more than 90% of industries still employ PID controllers owing to their simplicity, clear functionality and ease of use. The widespread use of PID controller and the drawbacks of optimal control techniques gave birth to the combination of simplicity of PID controller with optimal tuning approaches.

II. MOTIVATION

Due to the increasing number of power grid blackouts observed in the recent years, which can be illustrated with few examples like in 1999, there was a blackout in Brazil, in August 2003, in Northeast USA-Canada and in 2005, in Russia. Recently in July 2012, India suffered the largest ever power outage in the history affecting over 620 million people, equivalent to 9% of the world population, in the regions of north, east and north-east regions of India. In order to avoid these issues, there is need for the load frequency to be constant. The frequency deviation can directly impact the power system operation.

A. Effect of Frequency

1. Various electrical equipment operations depend on the frequency of the electric supply.
   a. *Induction Motors:* speed depends on frequency.
   b. *Transformers:* Induced voltage depends on frequency.
   c. *Generators:* speed is directly proportional to frequency.
   d. *Turbines:* blade rotation is contingent upon frequency.
2. Stability of the power system depends on the frequency. If there is lot of deviation between sending and receiving end frequency, there are chances of generators falling out of synchronism.
3. A huge increase in frequency causes harmonic currents which in turn will cause the heating of the system with insulation failure.
4. Frequency affects the inductive and capacitive reactance and has less effect on purely resistive loads. It affects the power factor of the delivered voltage.

To overcome the issues related to frequency deviation, robust control strategies are required which can improvise the system performance and system security. The simplest and important controller to manage these issues is PID type controller.

B. LFC and Its Need

The modern power systems with industrial and commercial loads need to operate at constant frequency with reliable power. Load Frequency Control (LFC) is an important issue in power system control and operation for supplying power with good quality. Due to the statistical nature of load fluctuation, we cannot avoid continuous load changes, but we can hope to keep the system frequency within sufficiently small tolerance levels by adjusting the generation continuously. The main goal of LFC is to maintain zero steady state error for frequency deviation, tracking the load disturbances and demands and maintaining an acceptable overshoot and settling time.

III. PRIMARY AND SECONDARY CONTROL

Active power is balanced in the primary control action.However, maintaining the frequency at scheduled value (50Hz) cannot be provided. Therefore, steady state frequency error can occur forever, and control action is not enough for single area system. The second level of generation control is also called as secondary or supplementary control. In modern large inter-connected systems, manual regulation is not feasible, so automatic generation and voltage regulation equipment is installed in each generator. The proportional integral (PI) controllers regulate by checking for small changes in load demand without frequency and voltage exceeding the prescribed limit.

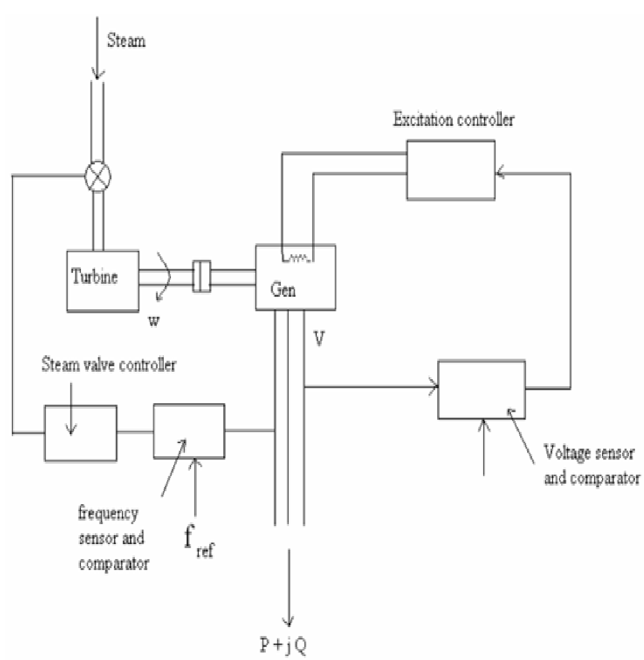

Fig. 1 Schematic diagram of load frequency and excitation voltage regulator of a turbo-generator

IV. TURBINE SPEED GOVERNING SYSTEM

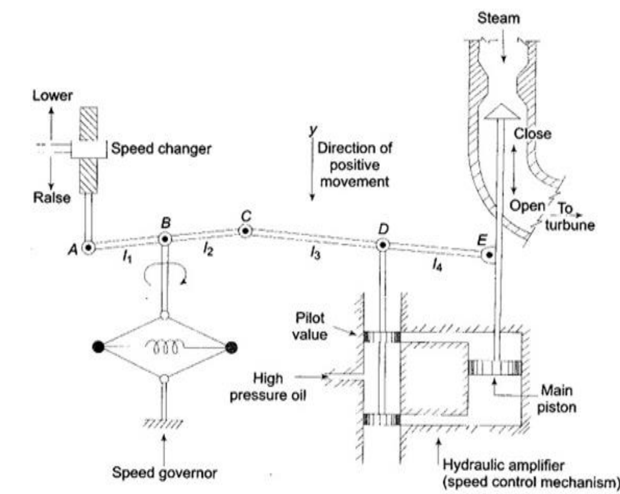

Fig. 2 Turbine speed governing system

1. *Fly Ball Speed Governor:* This is the heart of the system which senses the change in speed (frequency). When the speed increases, the fly balls move outwards and the point B on linkage mechanism moves downwards. The reverse happens when the speed decreases.
2. *Hydraulic Amplifier:* It consists of a pilot valve. The main piston low power level pilot valve movement is converted into a high-power level piston valve movement. This is essential for opening or closing of the steam valve against high pressure steam.
3. *Linkage Mechanism:* ABC is a rigid link pivoted at B and CDE is another rigid link pivoted at this link mechanism provides a movement to the control valve in proportion to change in speed. It provides a feedback from the steam valve movement as well.
4. *Speed Changer:* It provides a steady state power output value for the turbine. Its downward movement leads to the opening of the upper pilot valve such that more steam is let inside the turbine under steady conditions (hence more steady power output). The reverse action takes place for the upward movement of speed changer.

V. MODEL OF SPEED GOVERNING SYSTEM

A. Generator Model: Applying swing equation of a synchronous machine to small perturbation, we have:

$$\Delta P_m - \Delta P_e = \frac{2H\, d^2\Delta\delta}{\omega_s\, dt^2} \qquad (1)$$

Or in terms of small deviation in speed:

$$\frac{d\,\Delta\frac{\omega}{\omega_s}}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e) \qquad (2)$$

Where,

$\Delta P_m - \Delta P_e$ = increment in power input to generator

H = inertia constant

ΔP_m = mechanical power output in terms of small deviation in speed with speed expressed in p.u., without explicit p.u notation, we have:

$$\frac{d\,\Delta\omega}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e) \qquad (3)$$

Taking Laplace transform of the above equation

$$\Delta\Omega\,(s) = \frac{1}{2Hs}\,[\Delta P_m(s) - \Delta P_e\,(s)] \qquad (4)$$

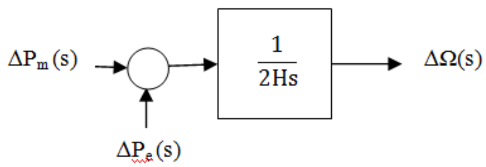

Fig. 3 Block diagram of generator

B. Load Model: The load consists of mixture of electrical devices. Lighting and heating loads are independent of frequency but motor loads vary for the changes in frequency. The speed-load characteristic of a load can be approximated by

$$\Delta P_E = \Delta P_L + D\,\Delta\Omega \qquad (5)$$

The load model and generator model is combined as shown in figure 4

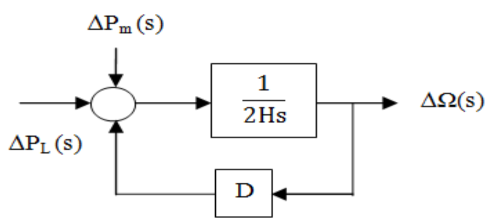

Fig. 4 Block diagram of generator and load

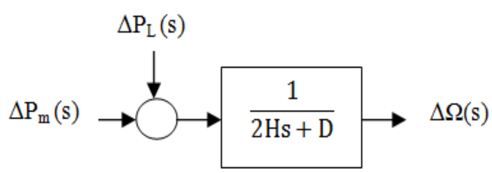

Fig. 5 Block diagram of generator and load

*C. Prime Mover Model:*The model for the turbine associates the changes in the mechanical power output ΔP_m to changes in the steam valve position. The prime mover model for the non-reheat steam turbine can be approximated with a single time constant which results in the following transfer function

$$G_T\,(s) = \frac{\Delta P_m(s)}{\Delta P_v\,(s)} = \frac{1}{1+Tts} \qquad (6)$$

The block diagram of steam turbine is as follows:

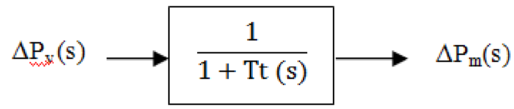

Fig. 6 Block diagram of simple steam turbine

D. Governor Model: When the load on the generator is increased, the electrical power exceeds the mechanical power input. This power deficiency is supplied by the kinetic energy stored in the rotating system. The reduction in the kinetic energy causes the turbine speed to reduce and generator frequency to fall. The change in speed is sensed by the turbine governor which in turn adjusts the turbine input valve to change the mechanical power output to bring the speed to a new a value.

*E. Speed Changer:*The speed changer consists of a servomotor which can be operated either manually or automatically for scheduling load at nominal frequency. Upon the adjustment of this set point, a desired load dispatch is scheduled at nominal frequency. For stable operation, the governors are designed to permit the speed to drop as the load is increased. The speed governor mechanism acts as a comparator whose output is ΔP_g the difference between the reference set power and the power 1/R

$$\Delta P_g(s) = \Delta P_{ref}\,(s) - \frac{1}{R}\,\Delta\Omega(s) \qquad (7)$$

The command $\Delta P_g$is transformed through the hydraulic amplifier to steam valve position command $\Delta P_{v.}$ A linear relationship is assumed and simple time constant τ_g is considered as follows:

$$\Delta\,P_v(s) = \frac{1}{1+\tau_g s}\,\Delta P_g\,(s) \qquad (8)$$

The above equations are represented as speed governing system block diagram in the below diagram

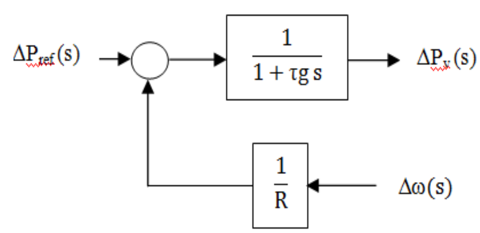

Fig. 7 Block diagram of speed governor system for steam turbine

The complete block diagram of the load frequency control of a power station is as follows:

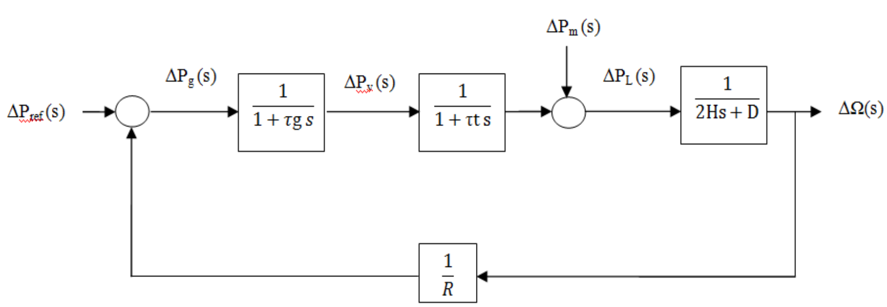

Fig. 8 Complete block diagram of LFC

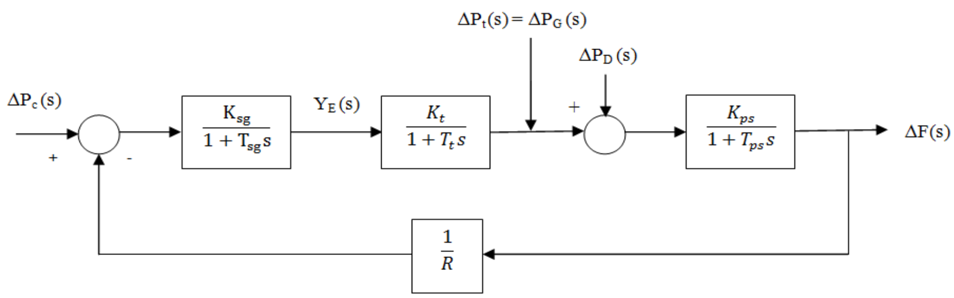

Fig. 9 Block diagram model of load LFC

VI. SYSTEM UNDER CONSIDERATION

Load frequency control of a single area system has been modeled and is subjected to various control strategies.

A. LFCwithout Controller

Fig. 9 is the reference block diagram.

The above system is taken into consideration with the following values:

T_{sg}= 0.4

T_t= 0.5

T_{ps}= 20

K_{ps}= 100

R=3

K_{sg}andK_t= 1

Substituting the above values, the transfer function of the above system is derived as

$$\Delta F(s)\Big|_{\Delta Pc(s)=0} = \frac{-K_{ps}}{s(1+T_{ps})+\frac{(K_{sg}K_tK_{ps})/R}{(1+T_{sg}s)\,(1+T_ts)}} * \frac{\Delta P_D}{s} \qquad (9)$$

$$\frac{\Delta F(s)}{\Delta P_D(S)} = \frac{-K_{ps}}{s(1+T_{ps})+\frac{K_{sg}K_tK_{ps}/R}{(1+T_{sg}s)\,(1+T_ts)}} \qquad (10)$$

$$\frac{\Delta F(s)}{\Delta P_D(S)} = \frac{-100}{12s^4+54.6s^3+62.7s^2+3s} \qquad (11)$$

B. LFC with Proportional Plus Integral Control

System frequency specifications are rather stringent and therefore, a large deviation in the frequency cannot be tolerated. It is expected for the steady change in frequency to be nullified. Asthe steady state frequency is brought back to the nominal value by the modification of speed changer settings, the system may undergo undesired changes in dynamic frequency with changes in load. So, it can said that speed changer settings be adjusted automatically by monitoring the frequency changes. For this reason, a signal from ΔF is fed through an integrator to the speed changer resulting in the below block diagram.The system now modifies to a proportional plus integral controller gives zero steady state error, i.e., $\Delta f|_{\text{steady state}} = 0$

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

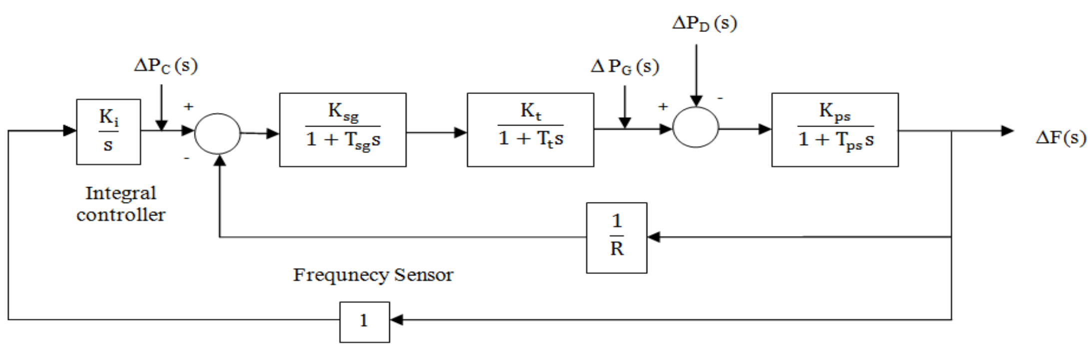

Fig. 10 Block diagram of proportional plus integral load frequency control

$$\Delta F(s) = \frac{-K_{ps}}{(1+T_{ps})+\left(\frac{1}{R}+\frac{K_i}{s}\right)*\frac{K_{ps}}{(1+T_{sg}s)(1+T_ts)}} * \frac{\Delta P_D}{s} \qquad (12)$$

$$\frac{\Delta F(s)}{\Delta P_D} = \frac{s\,R\,K_{ps}(1+T_{sg}s)(1+T_ts)}{s^2(1+T_{sg}s)(1+T_ts)(1+T_{ps}s)R+K_{ps}(K_i\,R+s)} \qquad (13)$$

Substituting the values for the above equation,

$$\frac{\Delta F(s)}{\Delta P_D} = \frac{20s^2+90s+100}{4s^5+18.2s^4+20.9s^3+s^2+33.33s+9} \qquad (14)$$

C. LFC using PID controller

The Proportional-Integral-Derivativecontroller (PID controller) consists of a control loop feedback mechanism which is often used in industrial control systems and many other applications which demandsa continuously modulated control. A PID controller will continuously evaluate an error value e(t) considering it as the difference between the desired set points (SP) and the measured process variable (PV). It then applies a correction based on PID terms. The

PID algorithm is responsible for restoring from current speed to the desired speed in an optimal way, without any delay or overshoot and by controlling the power output. In simple words, the PID controller improves the dynamic response and reduces or eliminates the steady-state error. In a proportional controller the output, also called as actuating signal, is directly proportional to the error signal. The proportionality constant is K_p. Proportional controllers help in reducing the steady state error, thus it makes the system more stable. Slow response of the over damped systems can be made faster with the help of proportional controllers. In a derivative controller the output is directly proportional to the derivative of the error signal. The proportionality constant is K_d. The derivative term adds a finite zero to the open loop plant transfer function and improves the transient response. In integral controllers, the output is directly proportional to the integral of the error signal. The proportionality constant is K_i. Due to this unique ability they can return the controlled variable to the exact set point followed by a disturbance. The integral term adds a pole at origin resulting in the increase of the system type consequently reducing the steady-state error.

This controller is usually regarded as a nearly robust controller. Therefore,PID controllers are easier to implement as it uses lower resources. It is easier to tune by simple trial and error. It gives better response to unmeasured disturbances as proportional and derivative actions immediately act on an unknown disturbance. The PID controller transfer function is as follows:

$$U(t) = K_p e(t) + K_i \int_0^t e(t)dT + K_d \frac{d}{dt} e(t) \qquad (15)$$

Where u(t) is the controller output and e(t) is the error signal. The gains of the PID controller are K_p, K_i and K_d. The Laplace transform of the above equation is

$$L(s) = K_p + \frac{K_i}{s} + K_d\, s \qquad (16)$$

In this paper, the performance of PID controller is designed using the integral of squared error (ISE), the performance criterion for ISE is as follow:

$$ISE = \int_0^{\infty} e^2(t)dt \qquad (17)$$

The block diagram of the LFC with PID controller has been shown in the next page. The transfer function of this block is derived.

$$\Delta F(s) = \frac{-K_{ps}}{(1+T_{ps})+\left(\frac{RsK_p+K_iR+K_ds^2R+s}{Rs}\right)*\frac{K_{ps}}{(1+T_{sg}s)(1+T_ts)}} * \frac{\Delta P_D}{s} \qquad (18)$$

$$\frac{\Delta F(s)}{\Delta P_D} = \frac{RK_{ps}(1+T_{sg}s)(1+T_ts)}{Rs+s^2RT_{ps}+K_{ps}(RsK_p+K_iR+K_ds^2R+s)} \qquad (19)$$

Upon substituting the values of all the variables, the transfer function obtained is

$$\frac{\Delta F(s)}{\Delta P_D} = \frac{20s^3+90s^2+100s}{4s^4+18.2s^3+s^2(20.9+100K_d)+s(1+100K_p)+100K_i} \qquad (20)$$

The above three systems under consideration have been simulated in the MATLAB-SIMULIMK environment and the simulation study is reported in the next section.

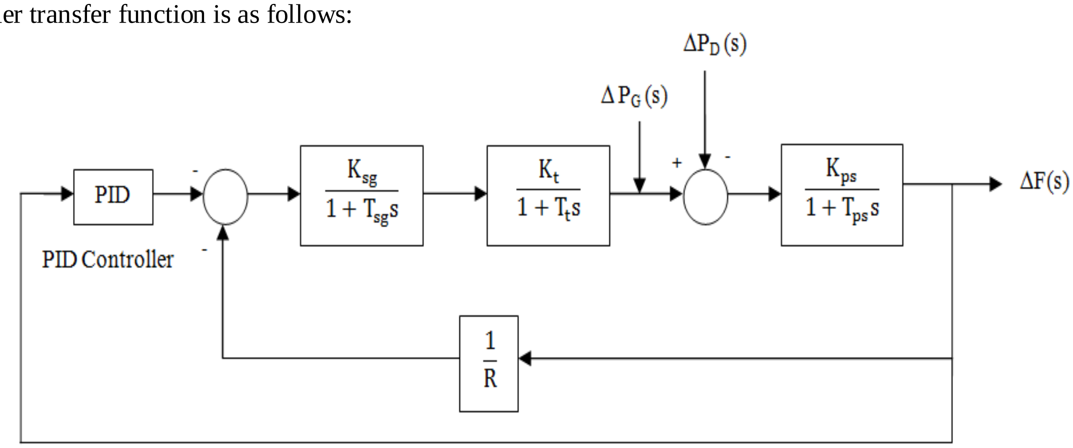

Fig. 11 Block diagram LFC with PID controller

VII. SIMULATION STUDY

The simulation has been conducted in MATLAB Simulink package for single area power system for load frequency control without controller, load frequency control with PI controller and PID controller.

A. Load Frequency Control Without Controller: The Simulink model is as follows

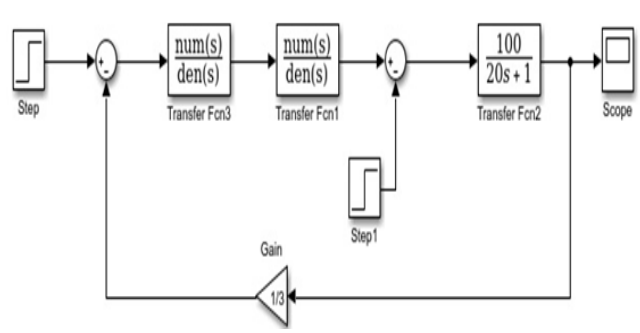

Fig. 12 Block diagram of Simulink model of LFC without controller

The waveform is as follows:

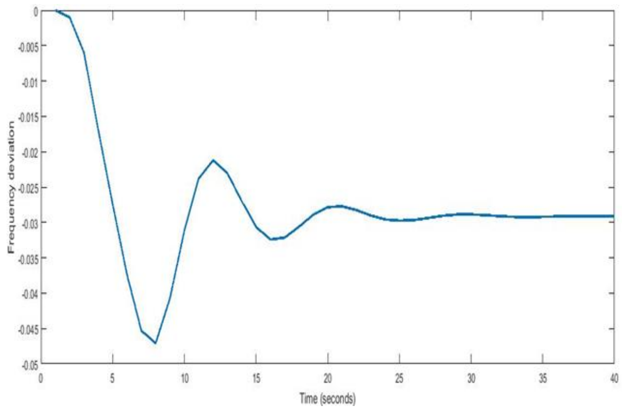

Fig. 13 Waveform of LFC without controller

From the simulation, it is observed that the above system has an overshoot of 48.088%.

B. Load Frequency Control with Pi Controller: The Simulink model is as follows

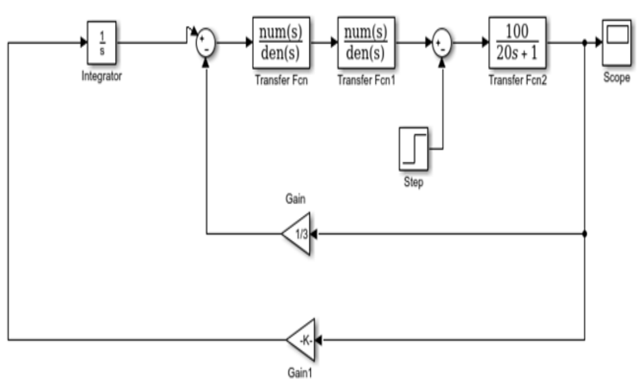

Fig. 14 Block diagram of Simulink model of proportional plus integral LFC

The waveform is as follows:

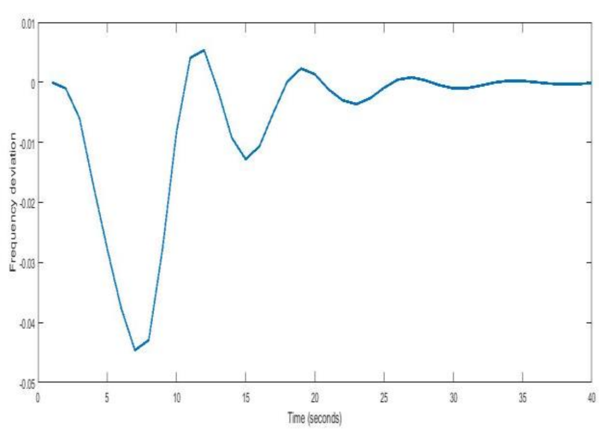

Fig. 15 Waveform of LFC with proportional plus integral control

From the simulation, it is observed that the above system has an overshoot of 20.909%.

C. Load frequency control with PID controller: The Simulink model is as follows

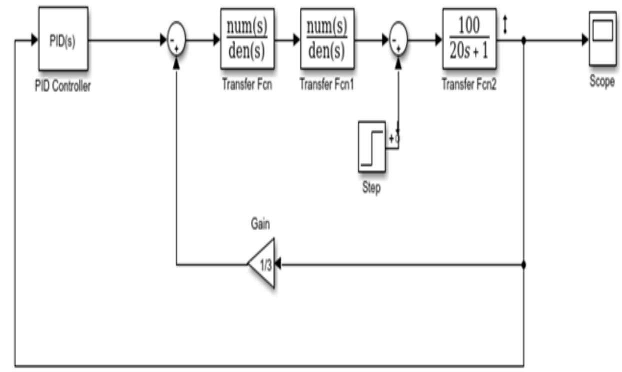

Fig. 16 Block diagram of Simulink model of LFC with PID controller

TABLE I PID TUNING TABLE

S. No.	P	I	D	Rise time (sec)	Overshoot (%)
1.	0.27	0.05	0	0.843	13.22
2.	0.20	0.138	0	1.427	83.86
3.	0.02	0.195	0	0.480	114.61
4.	0.06	0.19	0	0.398	126.90
5.	0.13	0.175	0	0.895	46.32
6.	0.19	0.1	0	0.624	35.53
7.	0.05	0.23	0	0.118	178.04
8.	0.13	0.19	0	0.753	60.48
9.	0.15	0.17	0	0.879	46.32
10.	0.178	0.13	0	0.511	53.80
11.	1.74	1.51	0.49	0.180	123.31
12.	0.62	0.15	0.60	-	-
13.	0.06	0.011	0.622	-	-

The above values are obtained by trial and error method of the PID tuning. From the table it is evident that the best suited P, I and D values for the load frequency control system are P=0.27, I=0.05 and D=0. These values of P,I and D give the least peak overshoot that is 13.22%.

The waveform is as follows:

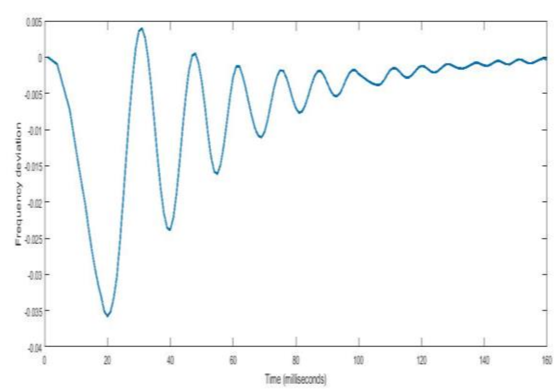

Fig. 17 Waveform of LFC with PID controller

VIII. COMPARITIVE STUDY

TABLE II COMPARATIVE STUDY OF THREE METHODS OF LFC

	Without Controller	With Proportional plus Integral Control	With PID controller
% Peak overshoot	48.088	20.909	13.22

IX. CONCLUSION

In this paper, a detailed comparative study of the frequency deviation of a single area power system has been put forth. Three methods of load frequency control have been implemented on an isolated power system. Load frequency control with and without controller was investigated in MATLAB SIMULINK environment and their respective graphs were analyzed to check the efficient way to handle the frequency divergence. Load frequency control when tuned with PID controller gave more optimal result. The trial and error method of tuning of PID controller gave best suited values of P, I and D.

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