FUZZY LOGIC ASSISTED LOAD FREQUENCY CONTROL OF A TWO AREA POWER SYSTEM

[1]Ajinkya Ashok Wankhede, [2]Vijay Harne

[1]PG Scholar, [2]Assistant Professor
[1]Department of Electrical Engineering,
[1]Govt. College of Engineering, Amravati, India

Abstract : Load frequency control (LFC) is a very important component in power system operation and control for supplying sufficient and reliable electric power with high quality. This paper addresses fuzzy logic controller for load frequency control of a two area power system. A deviation of frequency value from the standard (±0.5Hz) arises when real power generation fails to supply demand along with network losses. Various LFC studies have been done exploiting control strategies ranging from classical control schemes to soft analysis techniques. Conventional PI controller is designed and tuned with two techniques: using Ziegler Nichols (ZN) tuning and PID tuner app from MATLAB control system toolbox. Intelligent analysis tool, fuzzy logic, is used for performance improvement of the developed controller. Incorporation of advanced tools and optimization techniques improves control response time allowing fast recovery of the system during disturbances and reducing system down time. The system simulation is realized using MATLAB/ Simulink software. The comparison is done based on various performance indices like settling times and peak overshoots for 1 percent step load perturbation.

***IndexTerms* - Load frequency control, Fuzzy logic controller, single area control, Ziegler Nichols, Proportional, Integral, derivative**

I. INTRODUCTION

In recent years, power systems have more complicated and nonlinear configurations. Many industrial establishments are affected by operating point variations [1]. Electricity sector and end user are concerned about power quality reliability, efficiency and energy future. There are many reasons about increasing concerns on power quality. The microprocessor based equipment and power electronic devices are more sensitive to power quality. On the other hand, an electric network consists of many interconnected subsystems. If a fault occurs in a subsystem, disturbances and interruptions adversely affecting power quality take place in the power system. Any disharmonies between energy generation and demand cause frequency deviations. Thus, significant frequency deviations leads to system blackout [2]. Power system loads are usually variable so that controller system must be designed to provide power system quality. Interconnected power systems regulate power flows and frequency by means of an automatic generation control (AGC). AGC is a feedback control system adjusting a generator output power to remain defined frequency [3]. AGC comprises a load frequency control (LFC) loop and an automatic voltage regulator (AVR) loop. LFC system provides generator load control via frequency [3]. Zero steady-state errors of frequency deviations and optimal transient behavior are objectives of the LFC in a multi-area interconnected power system [4].

So far there are many studies about load frequency control of interconnected power systems. The aim is a design of feedback controller to realize desired power flow and frequency in multi-area power system. In literature, control strategies based on conventional, fuzzy and neural network controller are proposed [5]. Several authors suggest variable-structure systems, various adaptive control techniques and Riccati equation approach for load a frequency controller design [6, 7]. There are many studies about different control strategies having advantages and disadvantages [1, 2, 5, 8-10]. In Reference [9], a load frequency control using a conventional PID controller is applied and it is emphasized that the controller performance is better that others. However, if a power system structure has nonlinear dynamics and parts, the system operating point varies and conventional controllers needing system model must not be used. In Reference [5], a modified dynamic neural networks controller is proposed. It is determined that the proposed controller offers better performance than conventional neural network controller. In Reference [2], for a single area system and two area interconnected power systems, artificial intelligence techniques are purposed for the automatic generation control and the comparison is performed between intelligent controllers and the conventional PI and PID controllers. In Reference [10], a robust decentralized control strategy is used for Load frequency control for four area power systems to obtain robust stability and better performances. In References [1, 8], power system load frequency control is realized by fuzzy gain scheduling of PI controller.

II. MATHEMATICAL MODELLING

2.1 MODELING OF SINGLE-AREA SYSTEM

Nomenclatures

R_1, R_2 represents the speed regulation.
D_1, D_2 represents the frequency-sensitive load coefficient.
H_1, H_2 represents inertia constant.
T_{g1}, T_{g2} represents the governor time constant.
T_{t1}, T_{t2} represents the turbine time constant.
B_1, B_2 represents the frequency bias factors.

Governor model: The command ΔPg is transformed by hydraulic amplifier to the steam valve position ΔP_v. The T_g is governor time constant, the transfer function of governor is given in Eqn. 2.1.1

$$\frac{\Delta Pv(s)}{\Delta Pg(s)} = \frac{1}{1+Tg_s} \quad (2.1.1)$$

Prime mover model: The prime mover is used for producing mechanical power; it may be steam for steam turbine, water wall for hydraulic turbine. The model of prime mover ΔP_m relates the mechanical power output to change in steam valve ΔP_v value. The transfer function is given in Eqn. 2.1.2

$$\frac{\Delta Pm(s)}{\Delta Pv(s)} = \frac{1}{1+Tt_s} \quad (2.1.2)$$

Load and inertia model: The motor load is sensitive to the frequency change and can be analysed by speed load characteristic as given in Eqn. 2.1.3

$$\frac{\Delta w(s)}{\Delta P_m - \Delta P_l} = \frac{1}{2H+D} \quad (2.1.3)$$

frequency bias factor: The frequency biased factor is sum of frequency sensitive load change (*D*) and speed regulation as given in Eqn. 2.1.4

$$B = \frac{1}{R} + D \quad (2.1.4)$$

The block diagram of the system can be presented using Eqn. 2.1 to Eqn. 2.4 and is shown in Fig. 1.

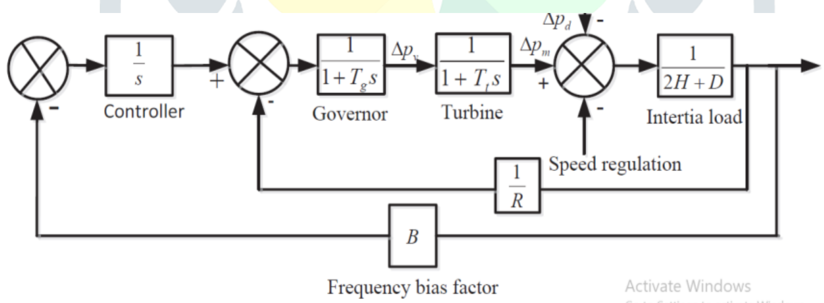

Fig. 1. Block diagram of load frequency control for single area system

2.2 MODELING OF TWO-AREA SYSTEM

A two-area system is represented by an equivalent generating unit interconnected by a lossless tie line with reactance of X_{tie} in Fig. 2.

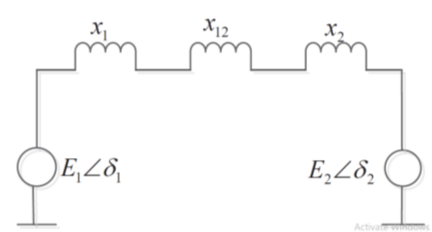

Fig. 2. Representation of two-area system

The real power transferred over the tie-line during normal operating conditions is given by Eqn. 2.2.1

$$P_{12} = \frac{|E1||E2|}{X_{12}} \sin\Delta\delta_{12} \quad (2.2.1)$$

Consider a small deviation of rotor angle δ_0 the resulting tie line power ΔP_{12} is given by Eqn. 2.2.2.

$$\Delta P_{12} = \frac{\delta P_{12}}{\delta \delta_{12}} \qquad (2.2.2)$$

The synchronous power coefficient is given by Eqn. 2.7.

$$P_S = \frac{|E1||E2|}{X_{12}} \cos\Delta\delta_{12} \qquad (2.2.3)$$

Considering a load change ΔP_{L1} in area-1 at the time of steady state in frequency. It results as $\Delta\varpi = \Delta\varpi_1 = \Delta\varpi_2$

$$\Delta P_{m1} - \Delta P_{m2} - \Delta P_{l1} = \Delta\varpi D_1$$
$$\Delta P_{m2} + \Delta P_{12} = \Delta\varpi D_2 \qquad (2.2.4)$$

The change in mechanical power is determined by using the governor speed characteristic and is given as

$$\Delta\varpi = \frac{-\Delta Pl1}{B1+B2} \qquad (2.2.5)$$

$$\Delta P_{12} = \frac{B2}{B1+B2}(-\Delta P_{l1}) \qquad (2.2.6)$$

2.3 TIE-LINE BIAS CONTROL

The tie-line bias control is used to maintain frequency and power at a pre-specified value where in each area manages its own load. The conventional LFC is based on the tie line bias control; in which each area is trying to reduce error to zero. The area control error (ACE) is given by –

$$ACE_1 = \Delta P_{12} + B_1\Delta\varpi_1$$
$$ACE_2 = \Delta P_{21} + B_2\Delta\varpi_2 \qquad (2.3.1)$$

By using the above Eqn. 2.11, the block diagram can be made as given below of a two area interconnected power system is shown in Fig. 3.

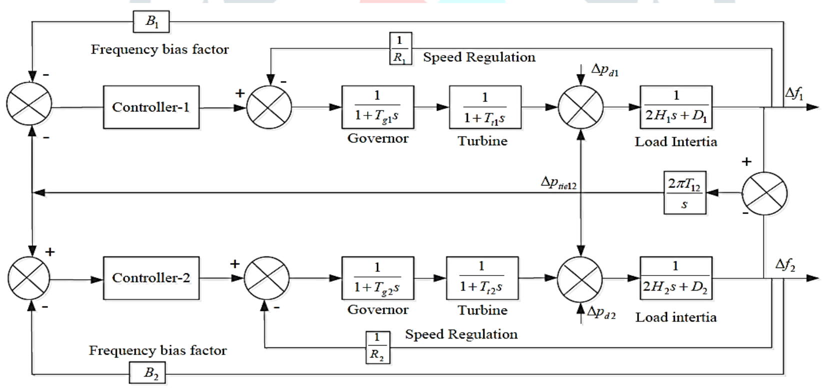

Fig. 3. Block diagram of two-area interconnected system

The incremental power is relatd to kinetic energy and frequency dependent loads,

$$\Delta P_m(t) - \Delta P_L(t) = \frac{2H}{f}\frac{d}{dt}\Delta f + D\Delta f \qquad (2.3.2)$$

Taking Laplace transform of above equation

$$\Delta P_m(s) - \Delta P_L(s) = \frac{2H}{f}\Delta F + D\Delta F \qquad (2.3.3)$$

$$\Delta F = \frac{\Delta P_m(s) - \Delta P_L(s)}{\frac{2Hs}{f} + D}$$

$$\Delta F = [\Delta P_m(t) - \Delta P_L(t)]\frac{K_P}{1 + T_{ps}} \qquad (2.3.4)$$

A. PI Controller Design

Proportional and Integral (PI) controller is widely use in industries due to its simplicity, easy implementation and less number of parameters to tune. The dynamics of the system under consideration is modeled on MATLAB using each component transfer function and PI controller model is also integrated. Two approaches were followed to tune the proportional and integral gains of the controller: Ziegler and Nichols (ZN) method and using automatic tuning using PID tuner tool from MATLAB control systems toolbox.

The transfer function model of the thermal power plant consists of main parts: the speed governor and turbine obtained from the mathematical model of the components and the generator-load model obtained using the swing equation of the machine. In most cases system block diagram is used with transfer function representation. The block diagram representation is used in visualizing the dynamics of the model. Unlike schematic representations, block diagrams show the cause and effect relation in the system as well as how the components in the system interact with each other. The overall composition of the system under configuration is given in Figure 4.

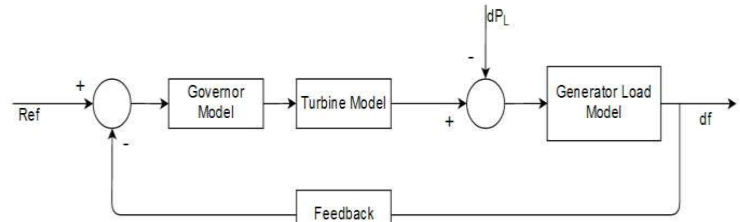

Figure4: Power System Configuration of Without Controller

The two area representation for the test system using MATLAB Simulink model is shown Figure 5. As can be seen in the figure two units are made to share 50% of the load each. Hence, a gain of 0.5 is used to divide the control signal ΔP_c for each unit. The parameters of components are given in Table 1

Table I: Parameters of components of thermal system used

R=2.4Hz/pu MW		
Governor	K_{gov}	1
	T_{gov}	0.2
Turbine	K_{tur}	1
	T_{tur}	0.6
Generator	$K_p = \frac{1}{D}$	138.7
	$T_p = \frac{2H}{fD}$	23.73

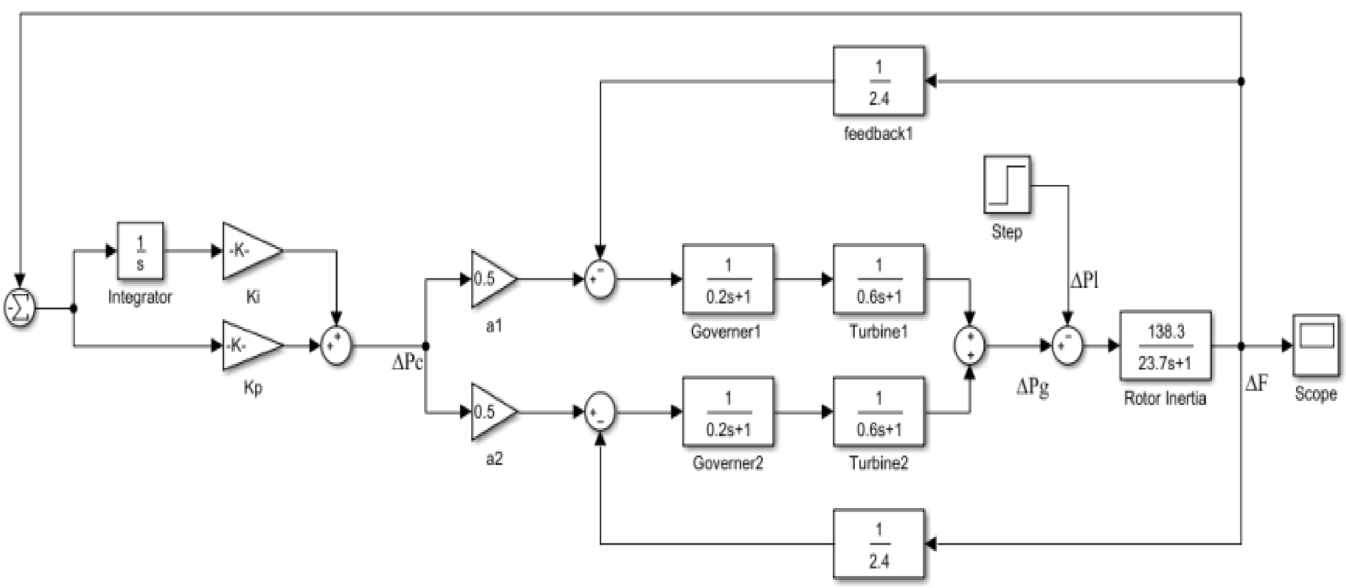

Figure 5: Two Area Control with Two Generating Units

1. PI Tuning Using ZN Tuning Method

This method differs from method 2 discussed in the following section. In that it uses analytical approach to calculate the critical gain and critical period of the proportional controller and refers ZN table to obtain the respective proportional and integral gain. To determine the parameters of the controller the system characteristic equation of the closed loop transfer function is used. Closed loop transfer function characteristic equation is a means to determine the stability of a system by looking at its coefficients. Mathematically characteristic equation is the denominator of the closed loop transfer function of the system. The procedures followed to calculate the gains of the controller are:

- Obtain the closed loop system transfer function and characteristic equation.
- Calculating the proportional gain that makes the system marginally stable using Routh stability criteria (by obtaining Routh array)
- Obtaining the frequency and period of sustained oscillation
- Using Ziegler-Nichols (critical gain and period based) obtain integral and proportional gain

The closed loop transfer function of the system is calculated by taking the input of controller signal (ΔP_C) and output, frequency deviation (ΔP_{out}) is given as:

$$\frac{\Delta P_{out}}{\Delta P_c} = \frac{138.7}{2.844\, s^3 + 19.08 s^2 + 24.5 s + 49.16} \quad (2.3.5)$$

When connected with a proportional controller of gain K, the characteristic equation (D(S)) which is the denominator of the closed loop transfer function is given as:

$$D(s) = 2.844\, s^3 + 19.08 s^2 + 24.5 s + (58.8 + 138.7K) \quad (2.3.6)$$

The critical gain and critical period obtained are 0.76 and 2.14sec respectively. Proportional and integral gains of the PI controller obtained from this method are: $K_i = 0.1766$ and $K_p = 0.3753$.

For the gain obtained, the step response of the controller is shown in Figure 8. The parameters of the controller are given in Table II

TABLE II: PARAMETERS OF PI CONTROLLER ZN TUNED

Rise time (sec)	0.8022
Settling time (sec)	8.0795
Overshoot (sec)	3.78
Peak (sec)	3.88

2. PI Automatic Tuning Using PID Tuner App

PID tuner tool in MATLAB control system toolbox is used to determine the gains of the controller. The PID tuner tool from control systems toolbox automatically tunes the controller gains for different controller types (P, PI and PID) to achieve balance between performance and robustness.

Procedures followed to use this app are:

- Obtaining the transfer function of the plant
- Use function in MATLAB: pidtool (name of the plant) to obtain the tuned gain

The following mathwork algorithm was used to use the PID tuner app.

```
S = tf('s');
Plant = 138.7 / [2.844*(s)^3 + 19.08(s)^2 + 24.5(s) + 49.16]
pidtool (plant)
```

The controller gains obtained from this approach is given as Ki= 0.1537and Kp = 3.349x10-5. The step response for this controller is shown in Figure 9. The values of the parameters in this approach are highlighted in Table III:

TABLE III: PARAMETERS OF PI CONTROLLER TUNED BY PID TUNER APP

Rise time (sec)	1.91
Settling time (sec)	9.84
Overshoot (sec)	2.72
Peak (sec)	1.03

The performance of a controller is measured with its response when subject to different inputs such as step response and ramp response. Inputs are quantified by quantities that characterize the response curve. These quantities are rise time, percent overshoot expressed as percentage, settling time and steady state error.

Table IV shows the comparison of settling time of PI controller when the gains are tuned on the two methods specified. ZN tuned PI controller showed better performance as can be observed from its settling time.

TABLE IV: PARAMETERS OF PI CONTROLLER COMPARISON

Tuning method	Settling time (sec)
Ziegler Nichols	8.0795
PID tuner app	9.84

B. Fuzzy Logic for Tuning PI Controller Gain

The gain of the conventional PI controller remains the same as the system parameters, more importantly the frequency changes. These characteristics of the controller have impacted its overall response. In this study, the method of fuzzy logic is used to improve the performance of the conventional PI controller designed for the test system. Fuzzy method is used to vary the gain of the controller based on different values of frequency deviation.

As an input to the fuzzy system the frequency deviation and the rate of change of frequency deviation is used. This is based on the standard mathematical model of the control output of PI controller

The schematic diagram integration of fuzzy system integrated with the conventional system is shown Figure 6.

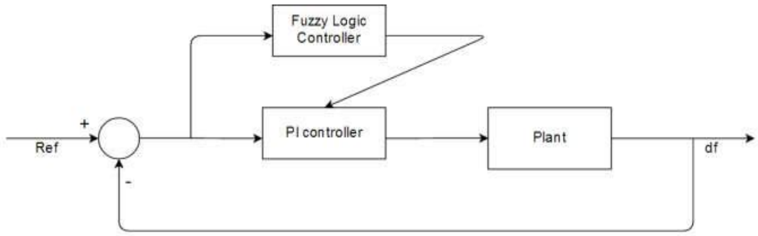

Figure 6: Integrating Fuzzy Logic Controller to PI Controller Based LFC

For the fuzzy inference system, the range of the inputs frequency deviation (df) is taken to be [-1, 1] which is above the tolerable range [-0.6, 0.6] of the 60 Hz system and the range for the rate of change of frequency deviation (ddf) is taken as [-0.01, 0.01]. For the output of the fuzzy system, the rate of change of the command signal change (ddP) is taken as [-1, 1]. The input variables ranges are taken to be able to include wide changes in the system.

The Load frequency controller is a supplementary control whose action depends on frequency deviation such that for a negative frequency deviation it should put a command to raise the speed of the rotating mass in generation. The fuzzy rule is constructed following three basic principles:

1. If frequency deviation and the rate of change of frequency deviation are both zero then the current control should be maintained (i.e. no change in control signal is required)
2. If frequency deviation is non-zero and the rate of change in deviation is relatively small the control output is mostly affected by frequency deviation and is adjusted to push the deviation to zero.
3. If frequency deviation is non-zero and deviation is varying significant rate then the control output is modified depending on the sign of both frequency deviation and the rate of change of deviation to force the deviation to zero.

The rule base for the fuzzy system is given in Table V.
Where, N and P stands for negative and positive, La (large), Mo (moderate) and Sm (small).

TABLE V: RULE BASE FOR FUZZY CONTROLLER

	Δf							
dΔf		NLa	NMo	NSm	Z	PSm	PMo	PLa
	NLa	PLa	PLa	PLa	PMo	PMo	PSm	Z
	NMo	PLa	PLa	PMo	PMo	PSm	Z	NSm
	NSm	PMo	PMo	PMo	PSm	PSm	Z	NSm
	Z	PMo	PSm	PSm	Z	Z	NSm	NMo
	PSm	PMo	PSm	PSm	NSm	NSm	NMo	NMo
	PMo	PSm	Z	NSm	NSm	NMo	NMo	NLa
	PLa	Z	NSm	NSm	NSm	NMo	NLa	NLa

The overall system dynamic model consisting fuzzy logic controller block from control systems toolbox is shown in Figure 7. When the proportional gain of the PI controller is tuned by fuzzy rule base system and a step input is applied to study the performance of the controller, the step response is shown in Figure 10. From the fuzzy tuned PI controller, the parameters obtained are settling time of 15.82 sec and overshoot percent of 5.7.

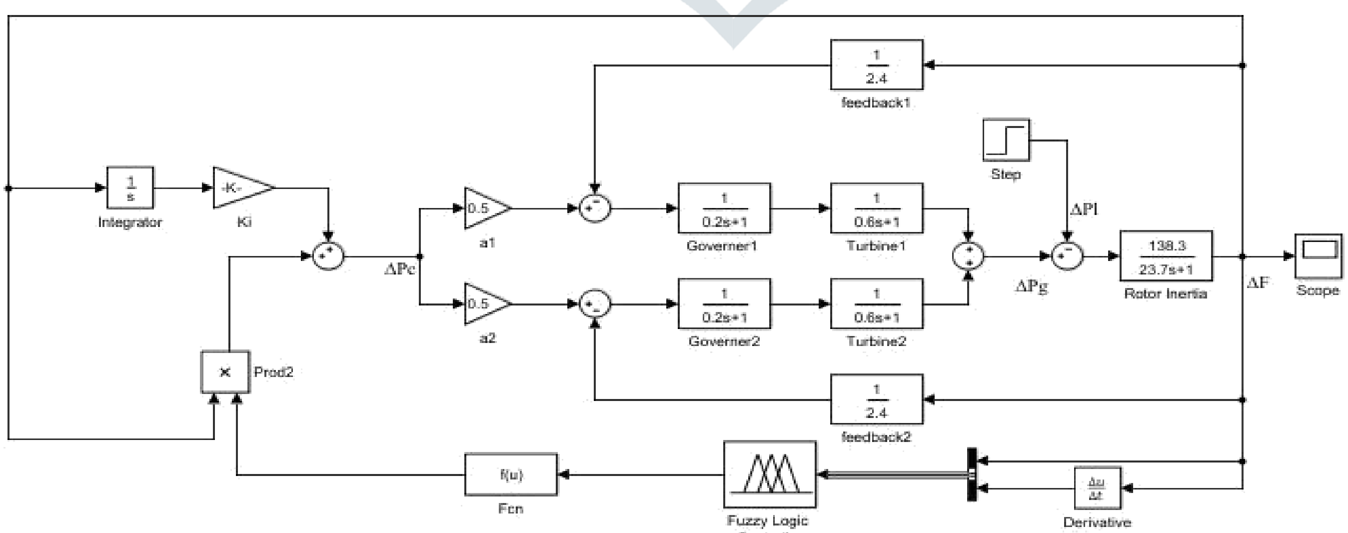

Figure 7: Fuzzy Tuned PI Controller for LFC

IV. RESULTS AND DISCUSSION

The system dynamics was modeled in MATLAB using the transfer function representation of each component. Two approaches were followed to obtain the parameter of the PI controller: PID tuner app from MATLAB control systems toolbox and Ziegler Nichols method. Settling time from the step response of the controller resulting from the two methods is then compared to obtain the proportional and integral gains which results good system performance. The controller with small settling time is chosen. Hence, PI controller tuned by Ziegler Nichols is used and the resulting proportional and integral gain is Kp = 0.3753 and Ki = 0.1766 respectively. One of the limitations of the PI controller is the gains are fixed for any system condition. Fuzzy controller feature is added on the PI controller developed to tune the proportional gain according to deviation in frequency. Therefore, with the addition of fuzzy logic the overshoot and settling time obtained are 5.7 and 15.82 respectively. The result shows improvement in the deviation of the maximum frequency value with the steady state value. The result obtained from this study can be used as a basis for future studies to add features to further improve the performance of the controller.

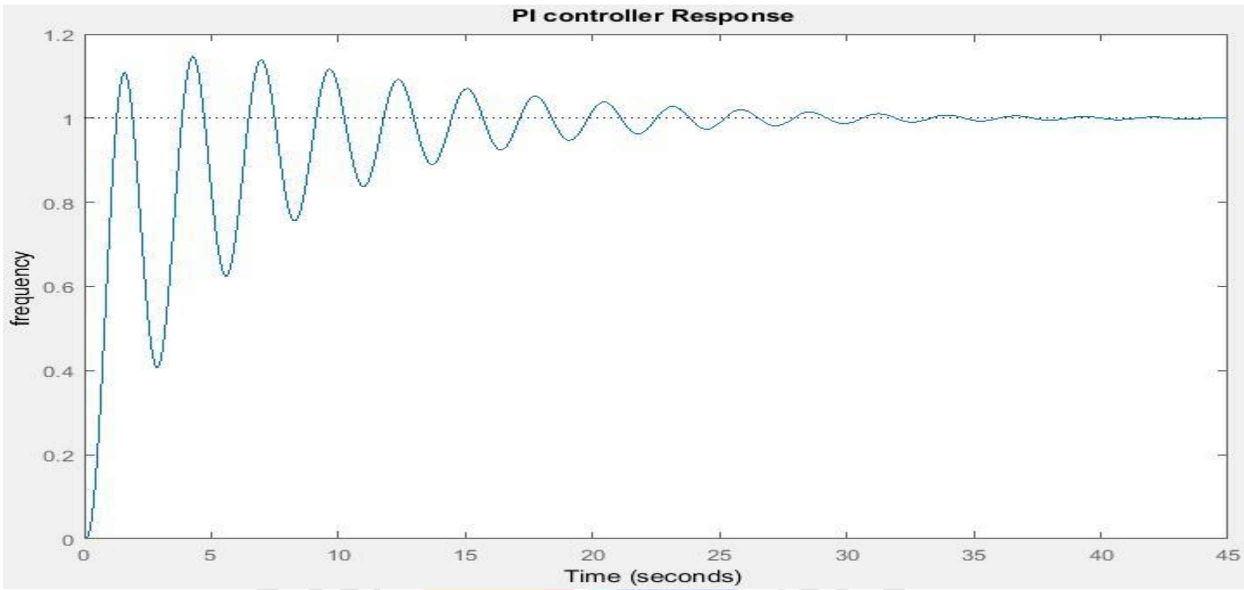

Figure 8: Step Response of PI ZN Tuned Controller

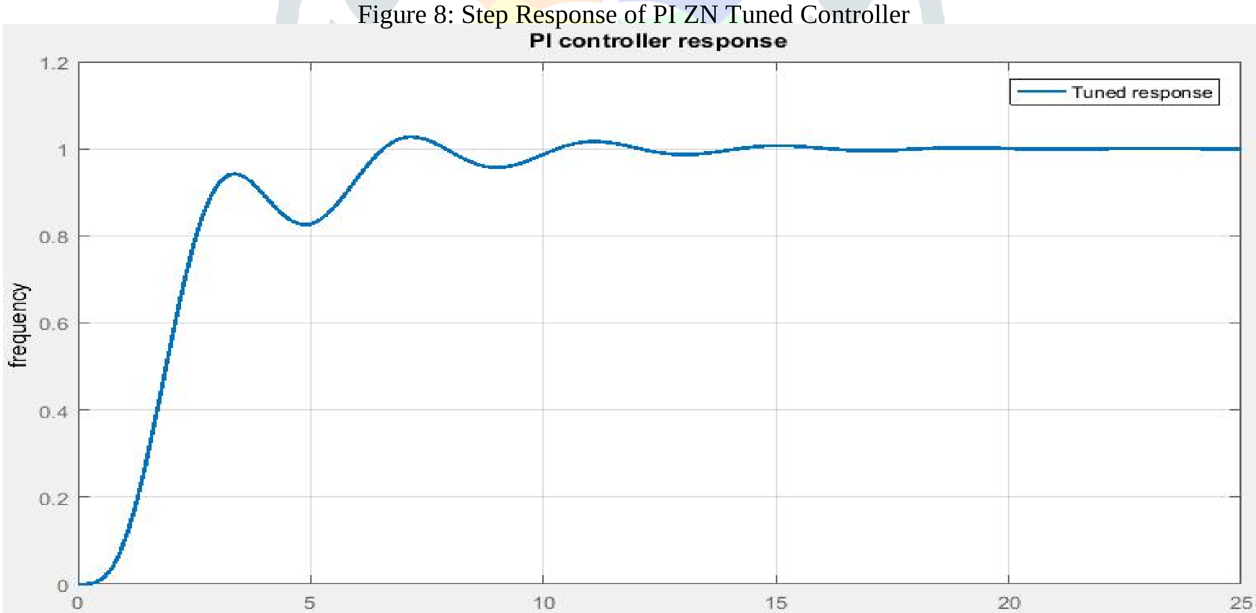

Figure 9: Step Response of PID Tuner App Tuned Controller

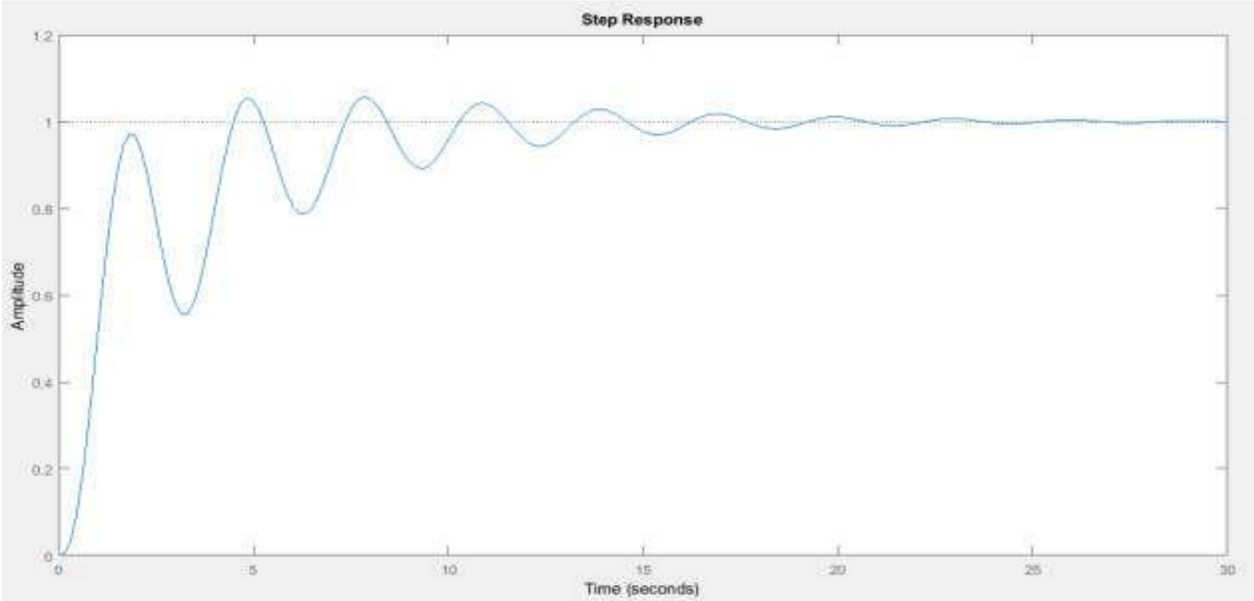

Figure 10: Fuzzy Tuned PI Controller Step Response

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