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Design and Analysis of Load Frequency Control for a Two-Area Power System Using Conventional PID and FPID Controllers

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Abstract

Power system stability is required to maintain a continuous balance between power generation and load demand. Frequency control is also a major function of automatic generation control and one of the most important control problems in power system design and operation. So, a robust control system must be implemented for controlling the actual power and frequency. This paper mainly focuses on the design of a two-area power system with a rated frequency of 50 Hz, which is used in Myanmar, using the fuzzy-PID method to control the load frequency. It also aims to imply from one area to another when demand suddenly increases or decreases. It involves applying mathematical formulas and models to analyze how an automatic generation control works. The plan is first implemented in a single area before being modified to a two-area power system with and without controllers. The output results are simulated with MATLAB/ SIMULINK.

A. Introduction

Electricity is a fundamental necessity to sustain industrial, commercial, residential, and, to some extent, agricultural operations. A change in load is one of the various errors that have made the system far from stable. The industries' explosive growth makes up both the load and the demand for electricity. Therefore, in order to consistently fulfill power system generation and demand, the power system must be controlled.

This study's primary goal is to demonstrate an application of frequency control of the power system based on fuzzy logic control using a PID controller in a two-area system. One significant control issue for the stability and regulation of the electric power system is load frequency control (LFC). In the case of an imbalance between the load and the generation, the power system's frequency is changed. Demand beyond a generation results in a decline in frequency. The frequency increases when generation is less than demand. Sustaining the tie-line flow by having the frequency roughly at the nominal value of 50 Hz is a straightforward control technique for the normal mode. Each area should be capable to absorb shifting loads independently.

In this paper, the fuzzy-PID (FPID) controller is used for control of the load frequency of the system. The fuzzy logic controller based on fuzzy set theory uses the expertise of a human system operator to simulate the system's behavior[2, 4, 8, 9]. Many researchers have used conventional controllers and optimal PID controllers for controlling frequency deviation and tie-line power [16, 17]. The fuzzy logic that has been suggested performs better than the traditional controller. MATLAB software is used to compare the outcomes of intelligent controllers, such as PID, with conventional controllers.

The installed capacity of the generation side in this proposed system will be 2000 MW in the typical functioning state. There will be an imbalance in power between the turbines and the loads if a significant load is abruptly supplied to the system or if the protection equipment quickly disconnects a generating unit. This imbalance will therefore cause the system's frequency to change. It is convenient to separate this frequency change into multiple stages, which allows the dynamics corresponding to each stage to be described independently. However, it is need to describe the operation of the automatic generation control, as the frequency will change in response to a change in load.

In order to regulate generation and transmission within their respective service areas, integrated utilities established the general architecture of frequency management that is being explained. The topic of discussion will be fuzzy logic-PID controller-based frequency regulation in a power system. The present research gives the automatic load frequency control to maintain the system frequency to its nominal value and the real power to its schedule value. The simulation of frequency deviation for single-area systems under load changes is presented first, followed by a simulation of tie-line power fluctuation and two-area simple steam turbine generation systems.

This study finds that tie-line power and the frequency variation are controlled by a fuzzy logic-PID controller. The fuzzy logic-PID controller's adaptability is demonstrated under various loading scenarios. The interconnected areas' frequency and tie-line power response have been compared with regard to settling time, peak undershoot, and peak overshoot. When the response of the conventional PID controller is compared to that of the fuzzy logic controller, it is discovered that the intelligent controller responds more quickly. This study finds that the intelligent controller responds more quickly than the conventional controller under various loading conditions and compares the accomplishment of a fuzzy logic controller with classical controllers.

B. Background Theory of Load Frequency Control

This section discusses the LFC dynamic model for a two-area power system containing non-reheat thermal plants, as illustrated in Figure 1. FPID controllers, a speed-governing system, a turbine, a generator, and a load comprise each section. Each system component is modeled using transfer functions in order to simplify the evaluation of the frequency domain.

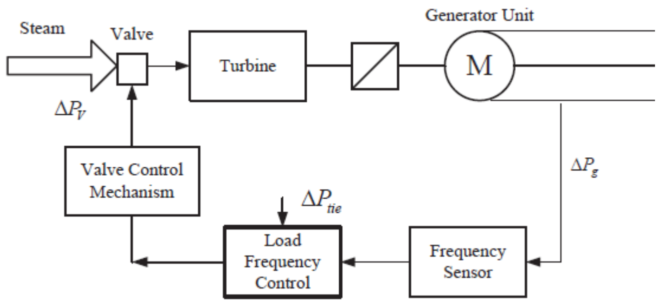

Figure 1. Schematic Block diagram for load frequency control [2]

Modeling of Single-area Power System

The mathematical modeling of the system's block diagram is the initial stage in the study and design of a control system. The governor, load, inertia model, and turbine (primary mover) make up the system's major components. The following is how these are characterized [7]:

(a) **Governor model :** The governor is designed to allow the speed of the turbine to drop when the load is increased. That is, when the change in load suddenly occurs, the speed of the turbine also changes. This change is sensed by the governor, who adjusts the turbine input valve to bring the speed to a new steady state. The difference between the power (1/R) $\Delta\omega$ and the reference set power ΔP_{ref} is the output, ΔP_g.

$$\Delta P_g(s) = \Delta P_{ref}(s) - \frac{1}{R}\Delta\omega(s) \quad (1)$$

$$\Delta P_V(s) = \frac{1}{1+T_g s}\Delta P_g(s) \quad (2)$$

(b) **Turbine (prime mover) model :** The prime mover or the source of mechanical power may be hydraulic turbines, steam turbines whose energy comes from the burning of coal, gas, nuclear fuel and gas turbine. The turbine model correlates changes in steam valve position (ΔPv) to variations in mechanical power output. The simplest prime mover model with a single time constant (T_t) results the following transfer function.

$$G_{Ts} = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1+T_T s} \tag{3}$$

(c) **Generator and load model :** Applying the swing equation, the generator model for speed variation is derived, and the motor load is sensitive to the frequency change and can be analyzed by the speed load characteristic as given in equation (4).

From Swing Equation,

$$\left(\frac{2H}{\omega_s}\right)\frac{\left(d^2\Delta\delta\right)}{\left(dt^2\right)} = \Delta P_m - \Delta P_e \tag{4}$$

In term of small deviation in speed,

$$d\frac{\frac{\Delta\omega}{\omega_{ss}}}{dt} = \frac{1}{2H}\left(\Delta P_m - \Delta P_e\right) \tag{5}$$

With speed expressed in per unit,

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}\left(\Delta P_m - \Delta P_e\right) \tag{6}$$

Taking Laplace Transform on both sides,

$$\Delta\omega(s) = \frac{1}{2Hs}\left[\Delta P_m(s) - \Delta P_e(s)\right] \tag{7}$$

The above relation is displayed in the block diagram form of the generator model. A power system's load comprises the make up of various electrical appliances. The electrical power is frequency independent for resistive loads like heating and lighting.

$$\Delta P_e = \Delta P_L + D\Delta\omega \tag{8}$$

This section explains automatic generation control (AGC) in detail, with and without the secondary loop. The equations (2), (3), (7), and (8) are represented by the block diagram shown in Figure 2. The block diagram for the model of a single area without a secondary loop is known as the primary control loop. By modifying the turbine output to correspond with the variation in load demand, it accomplishes the main objective of real power balance.

The transfer function equation of the system can be shown as:

$$KG(s)H(s) = \frac{1}{R}\frac{1}{(2Hs+D)(1+T_g s)(1+T_T s)} \tag{9}$$

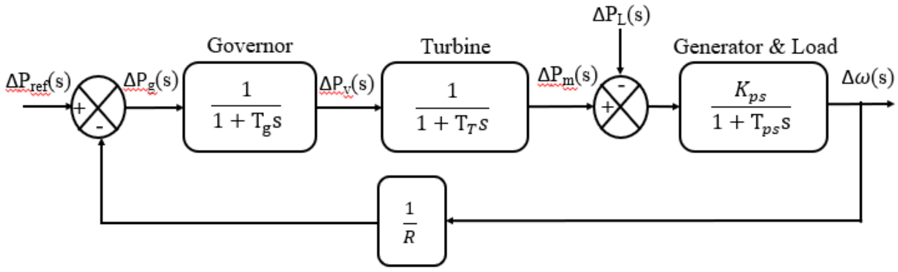

Figure 2. Schematic for Automatic Generation Control [1]

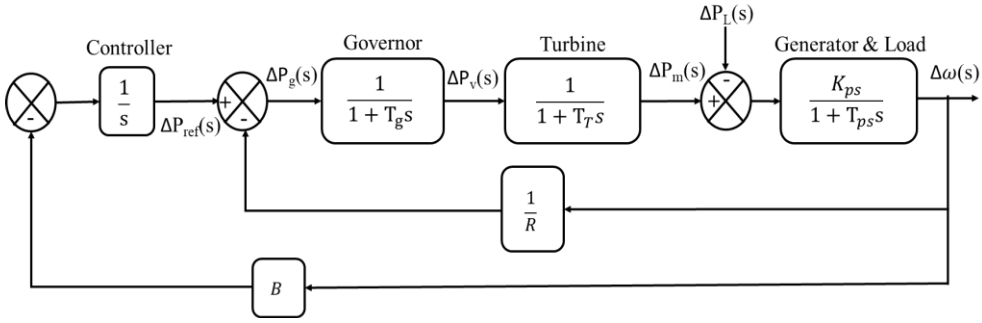

Figure 3. Schematic for Automatic Load Frequency Control [9]

Tie-line bias control

Tie-line bias control, an essential component of the typical LFC, aims to achieve zero inaccuracy in each region. The area control error is formed up of a linear combination of tie-line error and frequency.

$$ACE_i = \sum_{i=1}^{n} \Delta P_{ij} + K_i \Delta\omega \tag{10}$$

The tie-line connections can be modeled as shown in Figure 5. Where ΔPtie ij (s) is the tie line exchange power between area i and area j, and Tij is the tie line synchronizing torque coefficient between area i and j. The integral of the frequency difference between the two areas refers to the tie-line power error.

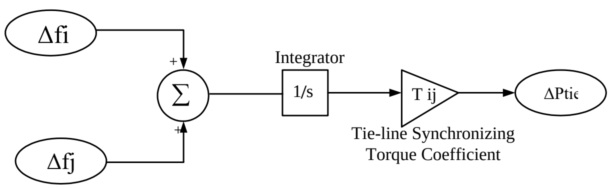

Figure 4. Representation of two-area system

Modeling of Two-area Power System

In a two-area system, two single-area systems are interconnected via a tie-line [7]. Depending on the direction, the tie-line power flow happens as a load decrease in one area and an increase in another. The block diagram for the two-area system is shown in Figure 4.

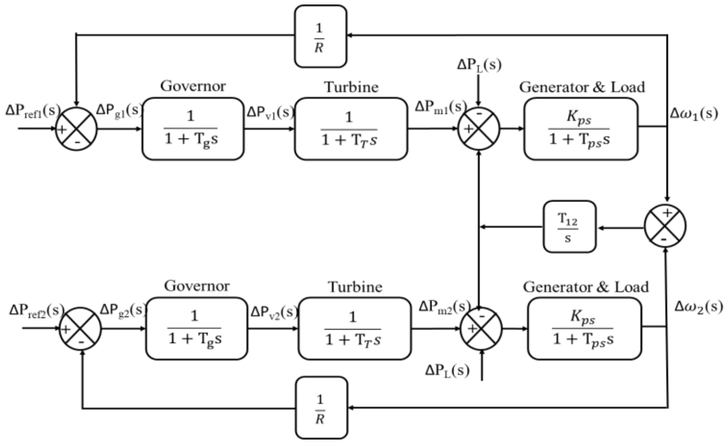

Figure 5. Representation of two-area system [3]

The equations of the area control error for area 1 and 2 are represented in the following:

$$ACE_1 = \Delta P_{12} + B_1 \Delta \omega_1 \quad (11)$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta \omega_2 \quad (12)$$

By using the above equation, the block diagram can be made as given below of a two-area power system as shown in Figure 6.

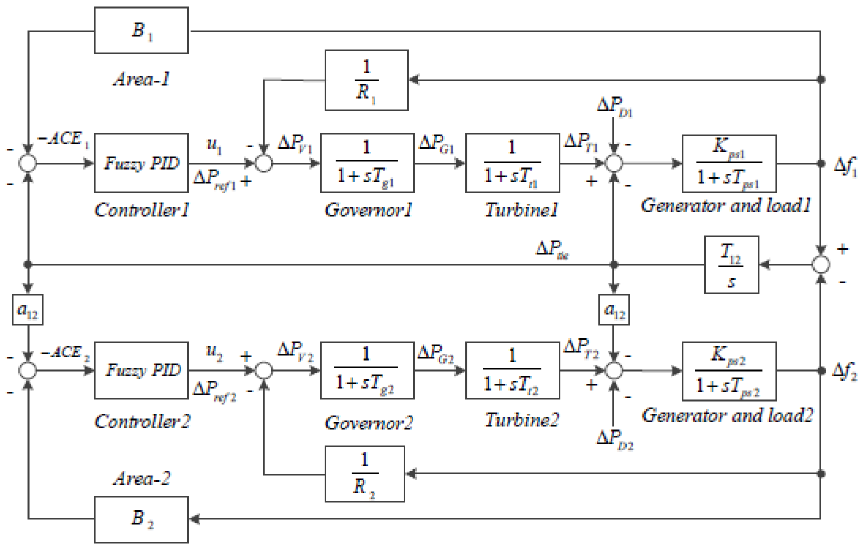

Figure 6. Block diagram of two-area interconnected system [3]

C. Proposed Controller Method

The primary goal of the proposed controller method is to minimize the two-area frequency deviations (ΔF1, ΔF2) and the tie-line power deviation between the two areas (ΔPtie-line). The controller used for each area loop in the microgrid case study system is the FPID controller [4]. In this section, the structure of a fuzzy-PID controller is designed. A parallel combination between fuzzy controllers and PID controllers is adopted, as shown in Figure 7.

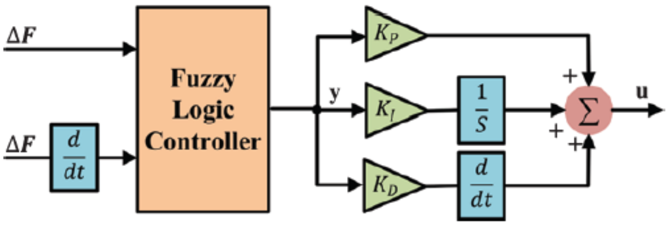

Figure 7. Structure of Fuzzy-PID controller

In this section, the structure of the fuzzy logic-PID controller is designed. A parallel combination between fuzzy and PID controllers is adopted, as shown in Figure 7. The inputs of the fuzzy logic control are the variables error (ACE) and change of error (dACE), and in the outputs of fuzzy logic, the PID parameters K_P, K_I, and K_D are calculated according to offline rules in the fuzzy logic controller.

Standard PID Controller

A PID control theory is a simple three-term controller. The PID controller's output is determined by combining the proportional, integral, and derivative terms together. The following equation is the transfer function of a PID controller:

$$U(s) = K_P + \frac{K_I}{s} + K_D\, s \tag{13}$$

Where K_P, K_I, and K_D are the gains of proportional, integral, and derivative, respectively.

Tuning

PID tuning is a method used in control systems to adjust the parameters of a PID (Proportional-Integral-Derivative) controller to achieve desired system performance. The outline of the three elements that constitute a PID controller is as described below:

(1) **Proportional (P)**: The output is directly proportional to the current error signal (the difference between the desired setpoint and the actual process variable). Increasing the proportional gain can reduce steady-state error but may lead to overshoot and oscillations if too high.
(2) **Integral (I):** The output is proportional to the accumulation of past error over time. The integral term eliminates steady-state error and can help in reducing offset, but it can also introduce instability if set too high.
(3) **Derivative (D):** The output is proportional to the rate of change of the error signal. The derivative term helps dampen the system's response, reducing overshoot and oscillations, but it can amplify noise in the system if set too high.

Tuning a PID controller involves adjusting these three parameters (P, I, and D) to achieve the desired balance between responsiveness, stability, and robustness for a specific control application. This tuning process can be done manually by trial and error, by using mathematical models of the system, or through automated tuning methods such as Ziegler-Nichols, Cohen-Coon, or tuning software tools.

Fuzzy Logic Controller

The four main elements of the fuzzy logic controller are fuzzification, fuzzy inference system (fis), rule base, and defuzzification, as shown in Figure 7. The fuzzification converts the numeric values into fuzzy sets. The fis executes all the logical operations [3]. The rule base is composed of membership functions (MFs) and control rules. The fuzzy inference system' output, i.e., the fuzzy set, must be converted to a real value by the defuzzification method.

The effect of FLC also depends on the MFs and rule base. The choice of MFs depends on the problem domain. Compared with bell and trapezoidal MFs, triangular MFs are generally used in FPID designs for real-time applications because of their simplicity and ease of computation [9, 11]. Five fuzzy sets are utilized with triangular MFs for both the inputs and the output, as shown in Table 1. The input-output relationship of FLC can be described as [3]:

$$u_{FLC} = f_{FLC}\left(K_1 ACE, K_2 \frac{d(ACE)}{dt}\right) \tag{14}$$

Table 1. Name of Input and output variables for fuzzy sets

No	Name of input/output variables	
1	HO	High Overshoot
2	LO	Low Overshoot
3	NF	Normal Frequency
4	LU	Low Undershoot
5	HU	High Undershoot

Fuzzy membership functions are selected as two input and three output variables. Using five membership functions, the fuzzifier first transforms the two input signals (error (E), change in error (CE)) to fuzzy numbers.

The range of input variables indicating the variation in frequency is from (-2) to (2). The range of output variables is also from (-2) to (2). Both of these are five membership functions, and two of the five set fuzzy input windows get 25 rule bases (using "Mamdani").

To calculate an error value as a difference between measured process variables (PV) and the desired set point (SP), PID control theory is a simple three-term controller.

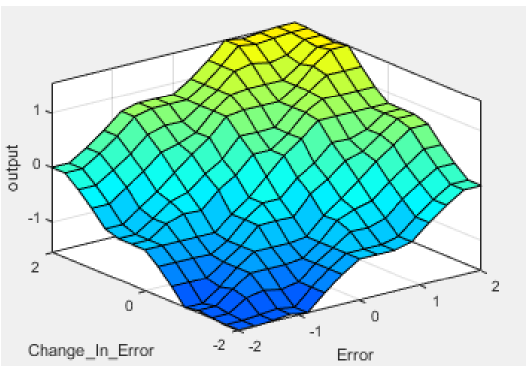

Figure 8. Surface with fuzzy rules

Table 2. Truth Table for ACE, Derivative of ACE and FLC' Output

ACE	ACE derivative				
	HO	**LO**	**NF**	**LU**	**HU**
HO	HO	HO	LO	LO	NF
LO	HO	LO	LO	NF	LU
NF	LO	LO	NF	LU	LU
LU	LO	NF	LU	LU	HU
HU	NF	LU	LU	HU	HU

The truth table for fuzzy rule bases is shown in table 2. Two of the five set fuzzy input windows get 25 rules, and it uses a "Mamdani" type rule [3].

D. Result and Discussion

The turbine's rated output is 1000 MW at a 50 Hz nominal frequency. The speed regulation of the governor is set to 0.05 per unit. A sudden change in load of 200 MW (ΔPL = 0.2 pu) occurs. The parameters for the proposed model are shown in Table 3:

Table 3. The parameters for the proposed model

No	Description	Parameters	Values
1	Installed power output	P_{out}	2000MW
2	Rated power output	P_r	1000 MW
3	System frequency	f	50Hz
4	Power system gain constant	K_{ps}	120 Hz/p.u.MW
5	Power system time constant	T_{ps}	4.19229
6	Time-line gain constant	T_{12}	0.545 p.u
7	Governor time constant	T_g	0.08 s
8	Turbine time constant	T_t	0.3 s
9	Governor inertia constant	H	2.5s ~ 5s ~ 7.5s
10	Governor speed regulation	R	2.4 pu
11	Frequency bias parameter	B	0.425 p.u.MW/Hz
12	The sudden load change	ΔP_L	0.2pu

In manual tuning method, parameters are adjusted by watching system responses K_P, K_I, and K_D are changed until desired or required system response is obtained. Firstly, these parameters are set to zero. And then, the gain parameters are tuned until the loop is acceptably to reach its reference after a load disturbance. In auto tuning method, There are some prepared software that they can calculate the gain parameters. Matlab/Simulink PID controller tuning is a kind of theorical method that can select the PID parmeters. In A sudden change in load of area 1, the simulation results of Matlab/ Simulink with and without PID controller tuning is shown in Figure 9.

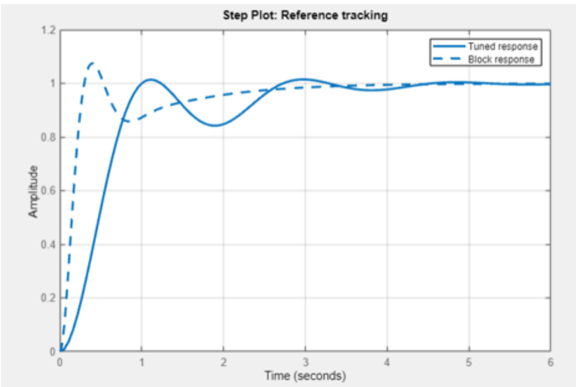

Figure 9. Simulation for the conditions of PID Tuning Response

The PID controller is used to reduce or entirely eliminate steady-state error whereas further improving dynamic response. The values of gains in the PID controller are automatically achieved when the controller is tuned in Matlab. In Figure 10, a Simulink block model is constructed for a single-area power station without and with PID controller using the MATLAB platform.

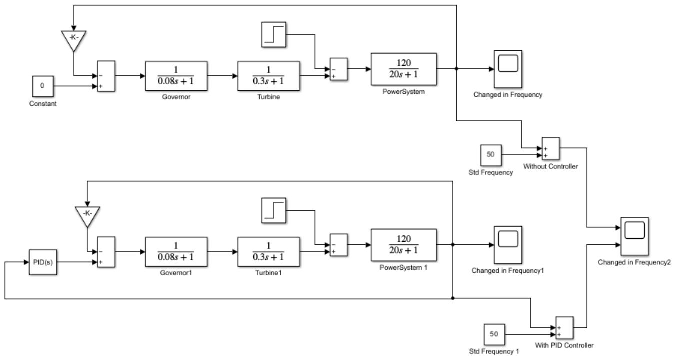

Figure 10. Model of Single Area Power System with and without PID Controller

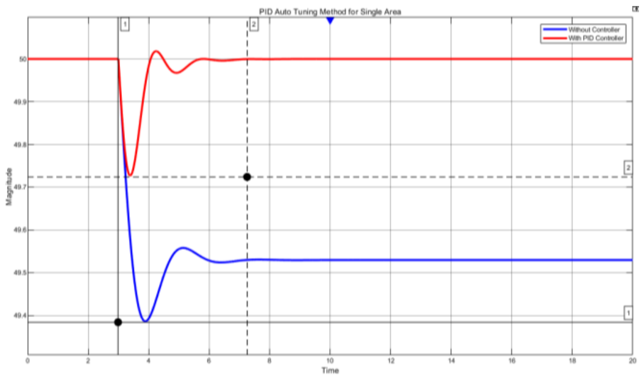

Figure 11. Frequency Deviation for a Sudden Change in Load of 50 MW with and without Controller

Figure 11 shows the result of the combined output waveforms of the steam turbine for the frequency deviation in terms of a sudden change in load of 200 MW with and without a controller. In this figure, the nominal frequency is 50 Hz (Δω = 0 pu) from t = 0 to 3 sec (or no load change). In this simulation, the first three seconds are introduced for a steady-state condition or non-error power system at the scheduled frequency (f = 50 Hz). Three seconds later, the frequency deviation will be activated. Under non-controller, the load is increased by 50 MW.

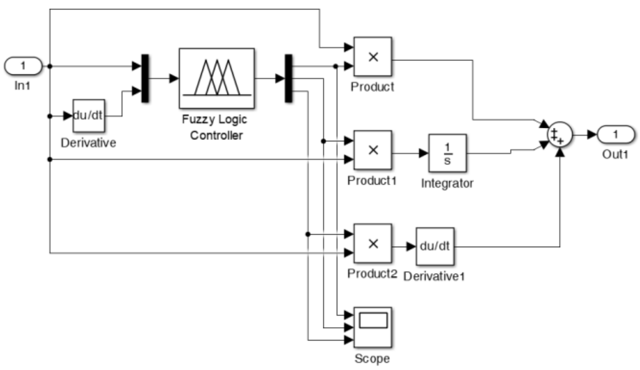

Figure 12. Simulink block of fuzzy logic-PID controller

Furthermore, the results are compared for both methods used by the PID and fuzzy logic controller. The desired output can be handled by using a fuzzy logic-PID controller with MATLAB Simulink, as shown in Figures 12 and 13.

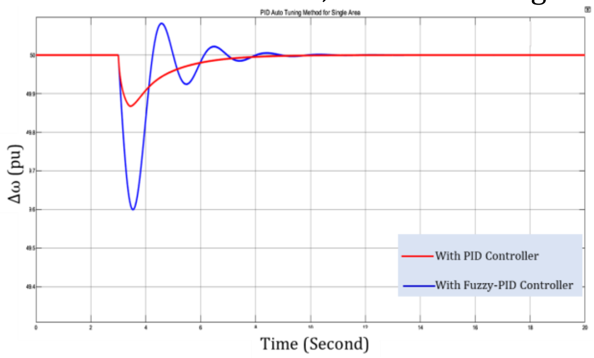

Figure 13. Frequency Deviation with PID and Fuzzy Logic Controller

The simulation is conducted in MATLAB/SIMULINK for a tie-line connection by using an integral controller.

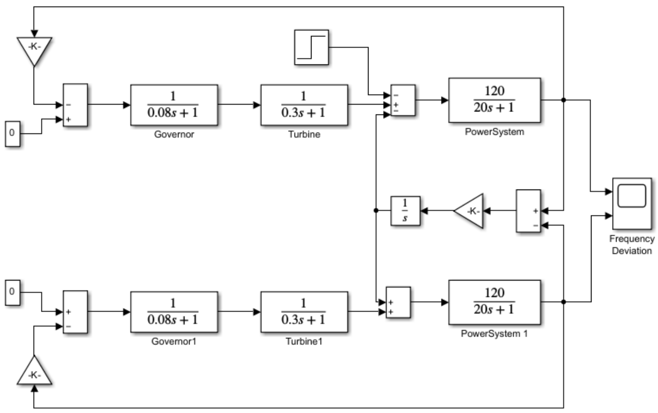

Figure 14. Model of Two Area Power System for Load Change of Area 1 and 2 without Controller

The area bias (proportional gain) determines the amount of interaction during a disturbance in the neighboring areas. When proportional gain is determined that is equal to the frequency bias factor, an overall exceptional outcome is attained. It is an expected task for users of control systems to adjust the controller parameters in order attain the desired behavior.

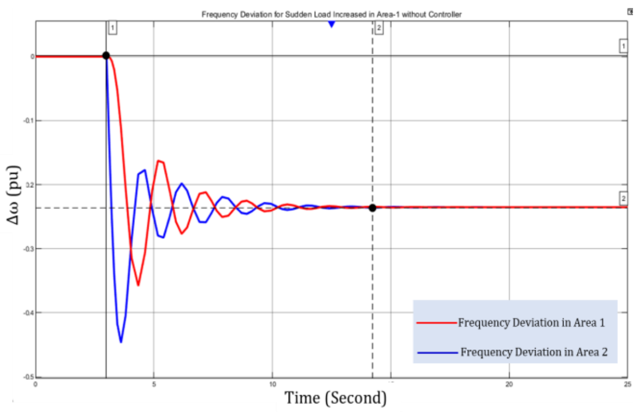

Figure 15. Frequency Deviation without Controller for Two-area Power System

In this paper, the simulation performance of frequency deviation and power variation for load changes in each area is clearly presented. The sudden load change of 200 MW in areas 1 and 2 is shown in comparison with and without the controller. The mechanical power output and direction of tie-line power flow are clearly described in the comparison between the two areas.

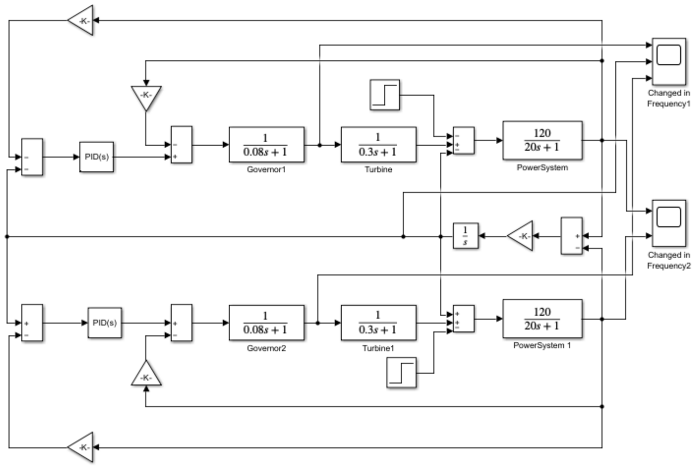

Figure 16. Model of Two Area Power System with PID Controller

In Figure 16, this is introduced for the condition of a two-area power system with a sudden load increase of 200 MW in Area 1 using a PID controller. In this simulation, the first three seconds are introduced for the case of a steady-state or non-error power system at the scheduled frequency (f = 50 Hz). Three seconds later, the frequency deviation will be activated as shown in Figure 17. Since area 1 load is increased, area 1 frequency declination is greater than that of area 2.

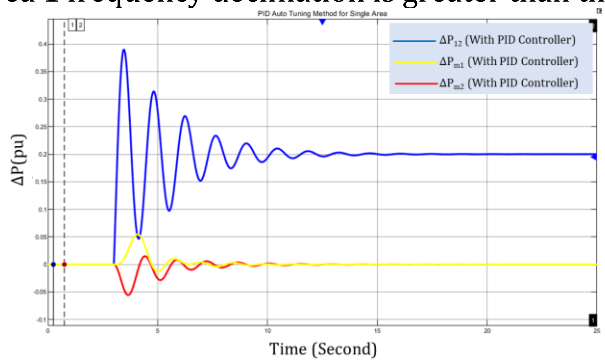

Figure 17. Power Deviation for Step Response of Area 1 and 2 with PID Controller

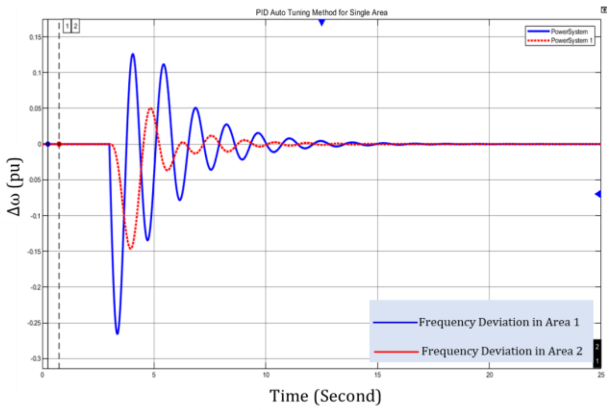

Figure 18. Frequency Deviation for Step Response with PID Controller

In Figures 17 and Figures 18, the results describe the comparison of simulation output waveforms for the power deviation and frequency deviation with PID controller. The first three seconds are introduced for the condition of a steady-state or non-error power system at a scheduled frequency (f = 50 Hz). After three seconds, the power deviation will be activated.

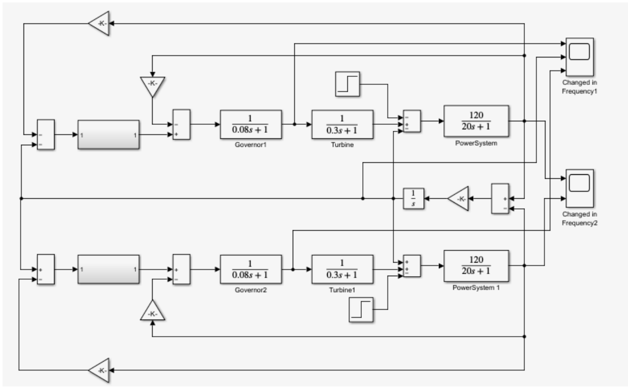

Figure 19. Model of Two Area Power System for Load Change of Area 1 and Area 2 with Fuzzy Logic - PID Controller

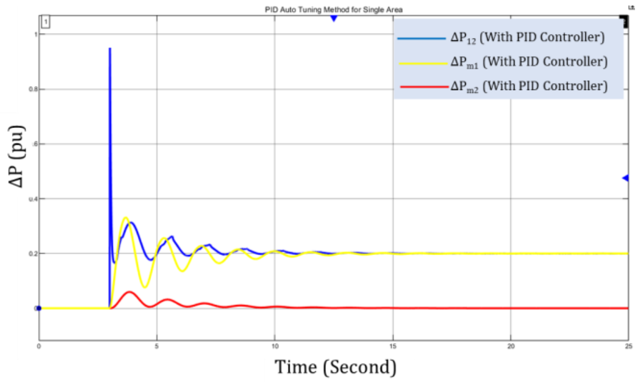

Figure 20. Frequency Deviation for Area 1 and 2 with Fuzzy Logic - PID Controller

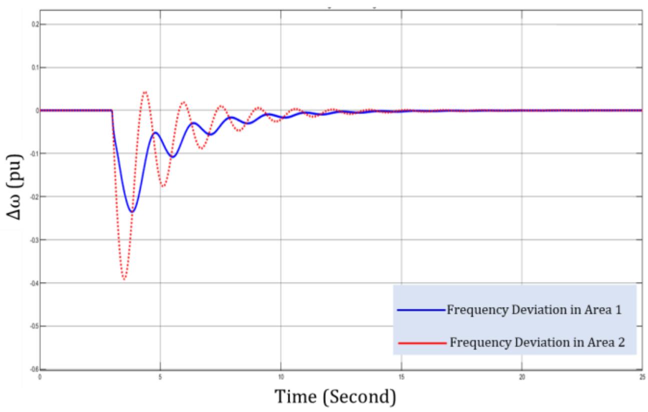

Figure 21. Power Deviation for Load Change of Area 1 and 2 with Fuzzy Logic - PID Controller

The optimal PID controller parameters can be attained by calculating the design from fuzzy set theory, as shown in Figure 18. The increase in area-1 load is met by the change in generation in area-1 and area-2, as shown in Figure 19. The fluctuations in the tie-line power flow with zero steady-state error are shown in

Figure 21. The integral gain constant is tuned for a satisfactory response. The change in tie-line power minimizes to zero. The gain constant must be selected small enough.

Table 4. Comparison of Statistic Results in Single-Area Power System

Controller System	Gain' Parameter			Settling Time (s)	Steady-state Error
	KP	KI	KD		
Without Controller	-	-	-	7.5	-0.47
PID Controller	0.798117	1.069538	0.114998	9	0
Fuzzy-PID Controller	0.542381	0.981711	0.069976	8	0

In these simulation results, load frequency control for a single area and an interconnected two-area power system is studied from Table 4 and Table 5.

Table 5. Comparison of Statistic Results in Two-Area Power System

System	Controller	Gain' Parameter			Settling Time(s)	Steady-state Error
		KP	KI	KD		
Area-1	Without Controller	-	-	-	14	-0.23
	PID Controller	1.4148	2.1053	0.17652	16	0
	Fuzzy-PID Controller	0.54238	0.98171	0.06997	12	0
Area-2	Without Controller	-	-	-	14	-0.23
	PID Controller	0.63858	0.061525	0.590	12	0
	Fuzzy-PID Controller	0.54238	0.98171	0.06997	12	0

An application of fuzzy logic-PID control-based load frequency control is applied here. The advantage is that steady-state error can be eliminated by using the fuzzy logic-PID control method in a two-area system with a tie-line system as shown in Table 4. Therefore, this paper is to show the advantages of a fuzzy-PID controller in reducing steady-state frequency deviation and tie-line error. The simulation results have indicated that the proposed fuzzy-PID controller is better than the conventional controller.

E. Conclusion

The simulation results show the usual values of the turbine time constant and inertia constant altering systems that impact the features of frequency response. By modifying the area load and area generation, AGC puts the tie-line power change to zero. Assigning the same area load to the same area generation is the obligation of AGC. The effect of controller is shown clearly below. The parameters are tuned to ensure satisfactory closed-loop performance.

In conclusion, a large amount of the inertia time constant is dependable for the operation of load frequency control in steam turbine research, whereas a small turbine time constant leads to unstable conditions. Large values of the generator and beginning time constants provide stable conditions for load frequency control operation in turbine operation studies, but tiny governor gain constants result in unstable conditions. To maintain the system frequency at its nominal value and the real power at its scheduled value, this study proposes automatic load frequency regulation. First, a description is given of the simulation of tie-line power variation and frequency deviation for single- and two-area generation systems under load variations.

F. Acknowledgment

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G. References

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