Dynamic and Transient Stability Enhancement of Multi Area Power Systems Using Fuzzy Logic Control Against Load Disturbances

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Abstract. Modern Power systems are designed for the fine tuning of frequency and less tolerance for system frequency deviation from nominal value. The Power System is dynamically subjected to the small perturbations of load leading to non-oscillatory Instability due to insufficient damping. The article entente the multi area load frequency control and dynamic and transient stability analysis. It dispenses the simulation of three area power systems with medium and large perturbations of load, with three cases for both kinds of power systems. Case1 without any controller, case2 with PI controller and case3 with Fuzzy Controllers. The simulation is carried out for three area power system with all three cases. In this article the simulation results of three area power system for all three cases have been presented. The simulation results demonstrate the effectiveness of Fuzzy Control perpetuates the frequency with in the endurable range of frequency and subsequently it ensures the dynamic as well as transient stability of both the Power systems against load disturbances.

Keywords: Fuzzy logic · Load frequency control · Small signal stability · Stability improvement · Single area power system · Two area power systems

1 Introduction

The management of modern power systems became most difficult task to ensure the system security and reliability with good quality. India is aiming at forming a single national grid with fine tuning of frequency all over the system, constituted with many of the power system components and distinct loads. The load perturbation on all over the grid is dynamically varying, leads to frequency deviations over each of the control areas. The focus of this article is to maintain the constant or tolerable range of frequency in all control areas of power grid. The single area power system is modelled as a single transfer function block diagram, comprised of governor, turbine and generator including load transfer function models. The two-area model is composed of two single areas with different individual block models of different parameters connected together with a tie line model. The Simulink models have been developed for both single area and two area power systems to carryout simulation study and analysis. These simulation model of three area power system with three different case studies viz. case I: with 5% load

disturbance with all three sub cases of (a), (b) and (c) without any controller, with PI controller and with Fuzzy controller respectively. Case II: with 5% load disturbance with all three sub cases of (a), (b) and (c) without any controller, with PI controller and with Fuzzy controller respectively. Case III: with 5% load disturbance with all three sub cases of (a), (b) and (c) without any controller, with PI controller and with Fuzzy controller respectively [1–6].

2 Single Area Power System

The power system network comprehends of many distinct loads with huge transmission and distribution networks. The complete network is categorized into different control areas based on frequency deviation over the part of power network. The small signal model is derived with individual power system components viz. Speed Governor, Turbine and Generator including load models.

2.1 Speed Governor Model

The load on power system is continuously varying may lead to speed deviation subsequently it leads to frequency fluctuations. The speed governing system is used to control these fluctuations. The speed governing system composed of fly ball speed governor, hydraulic amplifier and speed changer with linkage mechanism. The governor has two basic inputs, one is changes in reference power and the second is frequency variations are modelled into an equation, which describes both of these inputs as portray in the below equation and Fig. 1. Time constant (T_g) (as expressed in terms of a constant, depends on orifice, cylindrical geometries and fluid pressure of Hydraulic Amplifier and its typical value $_{is}$ in the range of 0.1 to 0.6 s [3–7].

$$P_v(s) = [P_{ref} - \tfrac{1}{R}F(s)] \frac{K_g}{1 + T_g} \tag{1}$$

2.2 Turbine Model

Turbine model has been derived with a single stage turbine with a single time constant of T_t and typical value is in the range of 0.3 to 0.7 s. The transfer function model of a single time constant turbine model is depicted in below equations (Fig. 2).

$$P_m(s) = P_t \frac{K_t}{1 + T_t} \tag{2}$$

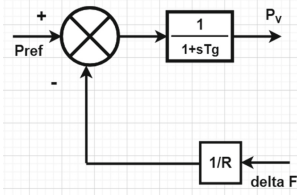$$T_t = \frac{1}{K_h} \tag{3}$$
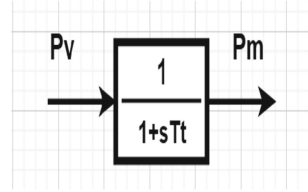
Fig. 1. Governing system model

Fig. 2. Small signal model of turbine

2.3   Generator Load Model

The incremental power input to the system can fractionated towards stored kinetic energy in the generator being proportional to square of the frequency and load changes of sensitive loads due to frequency deviations. These two events have been modelled and derived the transfer function of generator load model as depicted in the following Eq. (4) and (5) below. The inertia constant is designated as H and its typical value is about 2 to 10 s, hence the power system time constant i.e. T_{ps} lies in the range of 4 to 20 s. The following equations illustrate expressions for T_{ps} and K_{ps} in terms of inertia constant (H) and load damping factor (D) [5–12] (Fig. 3).

$$T_{PS} = \frac{2H}{DF^O} \tag{4}$$

$$K_{PS} = \frac{1}{D} \tag{5}$$

$$[P_m(s) - [P_m(s) = \frac{2HP}{F}\frac{dF}{dt} \tag{6}$$

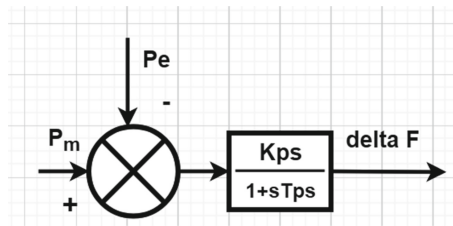$$F(s) = [P_m(s) - P_e(s)\frac{K_{ps}}{1 + T_{ps}}] \tag{7}$$

Fig. 3. Generator load model

The model of LFC as illustrated in Fig. 4, LFC with PI Controller is illustrated by the Figs. 5 and 6 shows the Single Area Load Frequency Control with Fuzzy Controller [4–12].
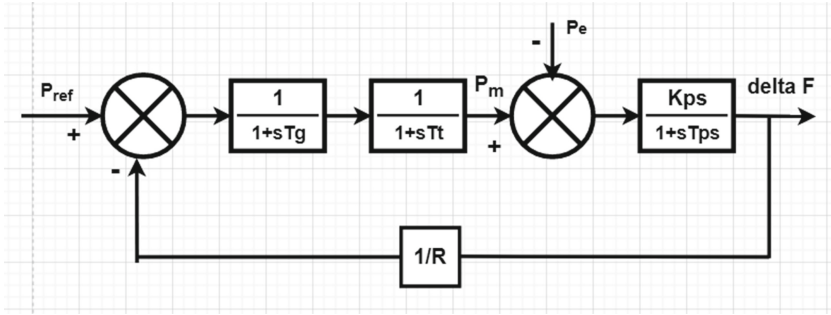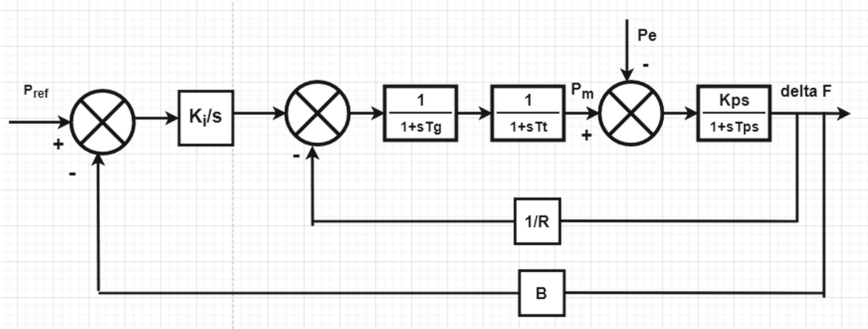
Fig. 4. LFC without Controller

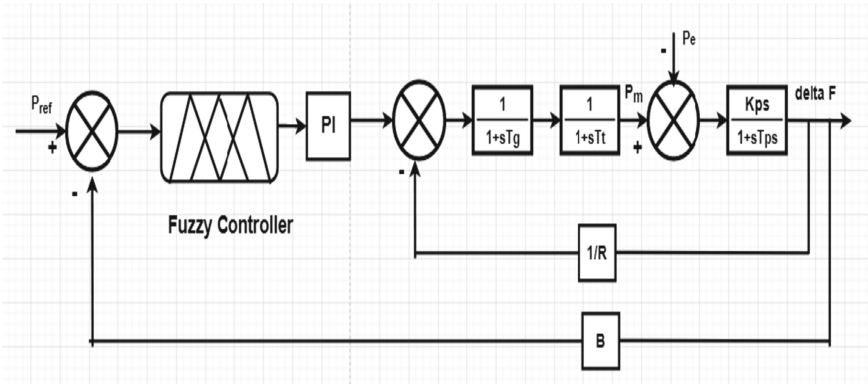**Fig. 5.** LFC with PI Controller

Fig. 6. LFC with Fuzzy Controller

3   Single Area Power System

Power Systems can be sub divided into number of areas through tie lines, without out loss of generality, consider a simple two area power system with a single tie line as depicted

by Fig. 7 as shown below. The power transfer of the tie line is P_{12} is given in Eq. (10), the synchronizing torque coefficient T_{12} as illustrated in Eq. (11), subsequently expressions have been derived for Area Control Error (ACE_1 and ACE_2) in terms of $P_{12 \text{ and }} P_{21,}$ bias factors B_1 and B_2 respectively as shown in equations from (12) to (15). Figure 8 illustrates the Block diagram model of Fuzzy controller based two area power system, with fuzzy based controller in each of the areas respectively [1–8] (Figs. 9 and 10).
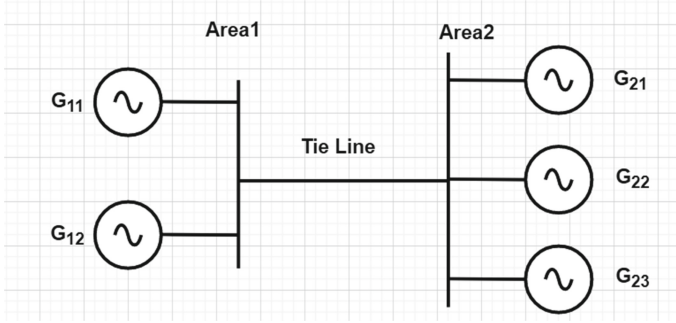
Fig. 7. Two area power system with tie line

$$P_{12} = \frac{V_1 V_2}{X_{12}} \sin(\Delta\delta) \tag{8}$$

$$T_{12} = \frac{V_1 V_2}{X_{12}} \cos(\Delta\delta) \tag{9}$$

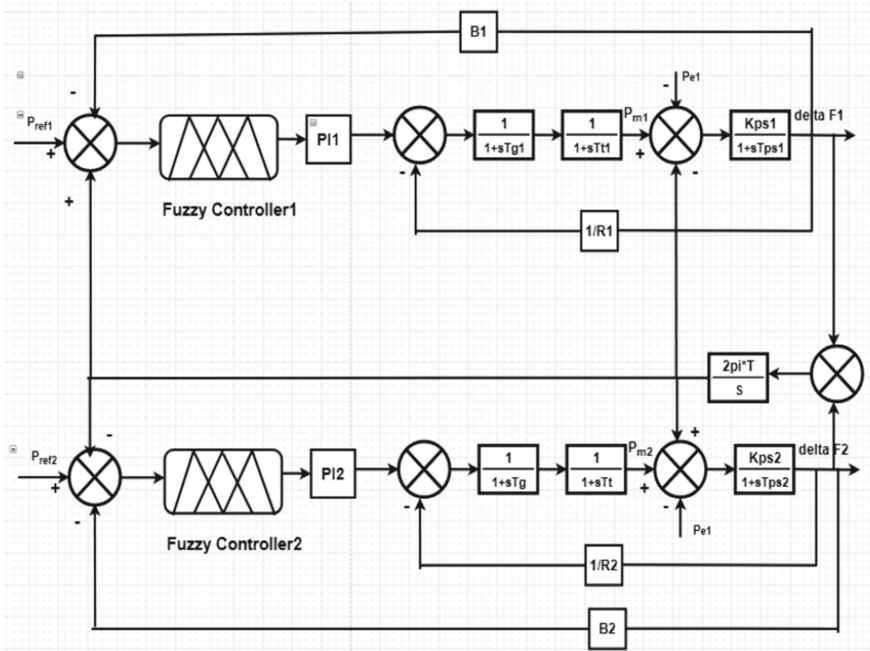$$P_{12} = 2\pi \int \Delta F \frac{V_1 V_2}{X_{12}} \cos(\Delta\delta) \tag{10}$$

$$P_{12} = 2\pi \int \Delta F T_{12} \tag{11}$$

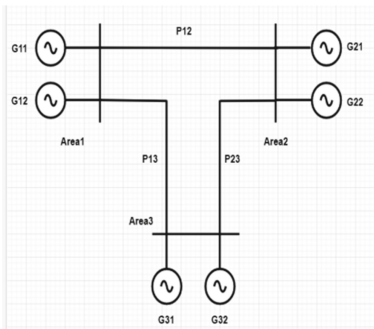$$P_{12}(s) = \frac{2\pi T_{12} \Delta F(s)}{s} \tag{12}$$

$$P_{21}(s) = -\frac{2\pi T_{12} \Delta F(s)}{s} = -P_{12}(s) \tag{13}$$

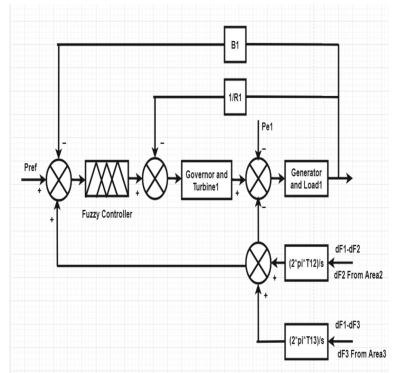$$ACE_1 = \Delta P_{12} + B_1 \Delta F_1 \tag{14}$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta F_2 \tag{15}$$

Fig. 8. Block diagram model of Fuzzy controller based two area power system

Fig. 9. Three Area Power System with tie lines

Fig. 10. Block diagram model of Fuzzy controller based multi area power system showing only one area signals

3.1   Tie Line Bias Control of Multi Area Power Systems

Each of the control area is connected with as many areas as possible in interconnected systems, with tie lines. Consider one area in the interconnected system, the net interchange with other control areas equal to the sum of tie line powers through outgoing tie lines and is given by the following equation below Eq. (16) similarly other area

controllers can be obtained.

$$ACE_i = \sum \Delta P_{ij} + B_i \Delta F_i \tag{16}$$

4 Power System Stability

Power system stability is defined as a system ability to regain its initial equilibrium state after being subjected to a disturbance and its classification are given in Fig. 11.
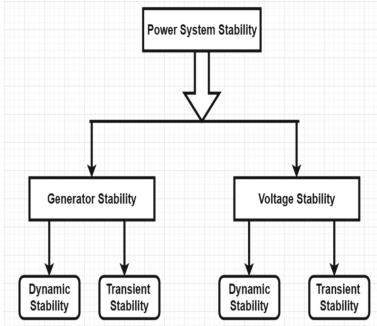
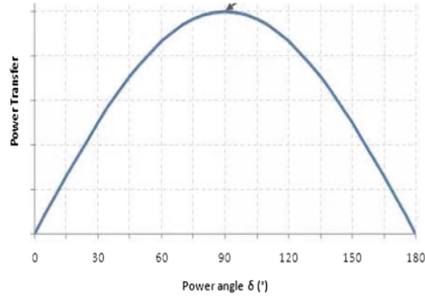**Fig. 11.** Power system stability stratification

Fig. 12. Power angle curve

4.1 Rotor Angle Stability

The system should remain in synchronism even after being subjected to the disturbance, which involves output power oscillates reflected in rotor oscillations.

4.2 Rotor Angle Stability

Relation between the power and angular position of a rotor in synchronous machine is nonlinear relation, when the synchronous generator is feeding a synchronous motor through transmission line. The power transferred to the motor from the generator is depends on the function of angular displacement between rotors of the generator and motor this is because of Motor internal angle, generator internal angle, and the angular displacement between motor and generator terminal voltage and power flow is given by the Eq. 17.

$$P = \frac{V_1 V_2}{X_T} \sin\delta \tag{17}$$

This equation say that the power transferred to a motor from generator is maximum when the angle is 90°, if the angle is further increased beyond 90°, power transferred starts decreasing is shown in Fig. 12. The maximum power transferred is directly proportional to machine internal voltage [8–12].

$$P_{max} = \frac{V_1 V_2}{X_T} \tag{18}$$

4.3 Dynamic Stability

Whenever the synchronous machine is subjected to small and medium load perturbations then the machine is subjected to rotor oscillations. These oscillations will die out very soon due to damping provided in the machine or external damping provided by the controller or compensator. The swing curves of the machine will illustrate the dynamic instability mechanism of the machine for such disturbances as illustrated in the below Fig. 13(a) and (b). The Fig. 13(a) depicts that the system is stable for small and medium disturbances with quiet effective damping and is unstable for medium disturbances with insufficient damping.

4.4 Transient Stability

Whenever the synchronous machine is subjected to medium and large load variations or contingencies then the machine is subjected to wide rotor oscillations. These oscillations will die out very soon due to damping provided in the machine or external damping provided by the controller or compensator. The swing curves of the machine will illustrate the transient instability mechanism of the machine for such disturbances as illustrated in the below Fig. 13(a) and (c). The Fig. 13(a) depicts that the system is stable for medium disturbances with suitable controller and is unstable for large disturbances without any controller [1–12].
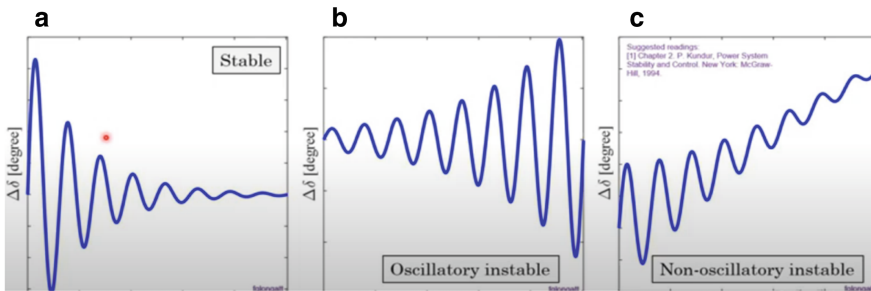
Fig. 13. Power system stability swing curves (a) Stable System (b) Oscillatory Unstable System or dynamic instability and (c) Non-oscillatory Instability or Transient Instability

5 Fuzzy Logic Control

Fuzzy control is used when vagueness in the decission making is present or when non linearities are involved in the system dynamics. Figure 14 shows Mamdani Rule based Fuzzy Logic Controller input and output functional relationship in simulink model and Fig. 15 3-d surface of the Fuzzy rules. The Table 1 shows the Fuzzy rules table for the single and two area power systems. There are two input membership functions of Fuzzy logic controller, one is error i.e. the reference voltage minus actual voltage of seven input triangular membership functions varying range of + or −16%. The second is derivative of error seven input triangular membership functions varying range of + or −16% as

depicted in Fig. 14 and seven output triangular membership functions varying range of + or −18%. The Fuzzy rules [6–12].

Table 1 shows the 49 rules framed with input1 variables viz. nb1, nm1, ns1, zo1, ps1, pm1 and pb1, similarly input2 variables viz. nb2, nm2, ns2, zo2, ps2, pm2 and pb2 and output variables viz. nb, nm, ns, zo, ps, pm and pb [4–11].
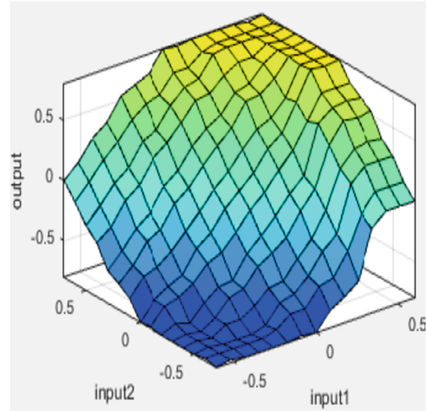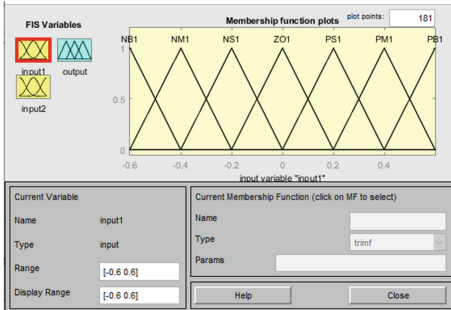
Fig. 14. Triangular input and output membership functions of fuzzy controller

Fig. 15. Fuzzy 3-D rule surface

Table 1. Fuzzy rule table

de/dt	e						
	nb1	nm1	ns1	zo1	ps1	pm1	pb1
nb2	n1	n1	n1	n1	n2	n3	zo
nm2	n1	n1	n1	n2	n2	Zo	p3
ns2	n1	n1	n2	n3	zo	p3	p2
zo2	n1	n2	n3	zo	p3	p2	p2
ps2	n2	ns	zo	p3	p2	p1	p1
pm2	n3	zo	p3	p2	p1	p1	p1
pb2	zo	p3	p1	p1	p1	p1	p1

## 6   Case Study and Simulation Results

The single area and two area power system Simulink models have been derived from the small signal transfer function models of both areas. Both of these areas have been simulated for three cases, one is without controller, second is with PI controller and third is with Fuzzy logic based controller. In subsequent part of the article single area system has been presented and succeeding part describes the simulation results of two area system.

6.1 Simulation Results of Three Area Power System

The Simulink models have been developed for three area power system for all three cases, case I (a): without any controller as depicted by the Fig. 16, case I (b): Three area system with PI Controller as shown in Fig. 17 and case I (c): Single area system with Fuzzy Controller as illustrated in Fig. 18.
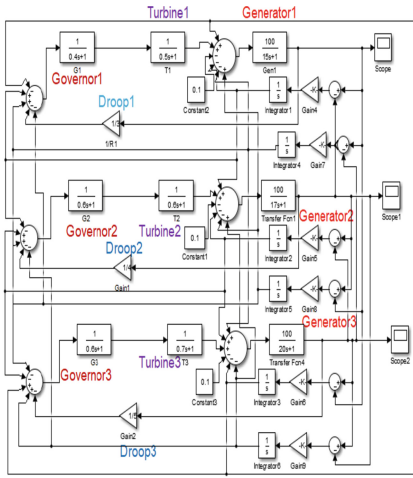
Fig. 16. Three area system Simulink model without Controller
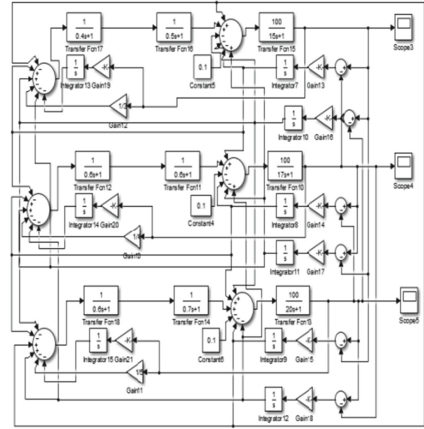
**Fig. 17.** Three area system Simulink model with PI Controller
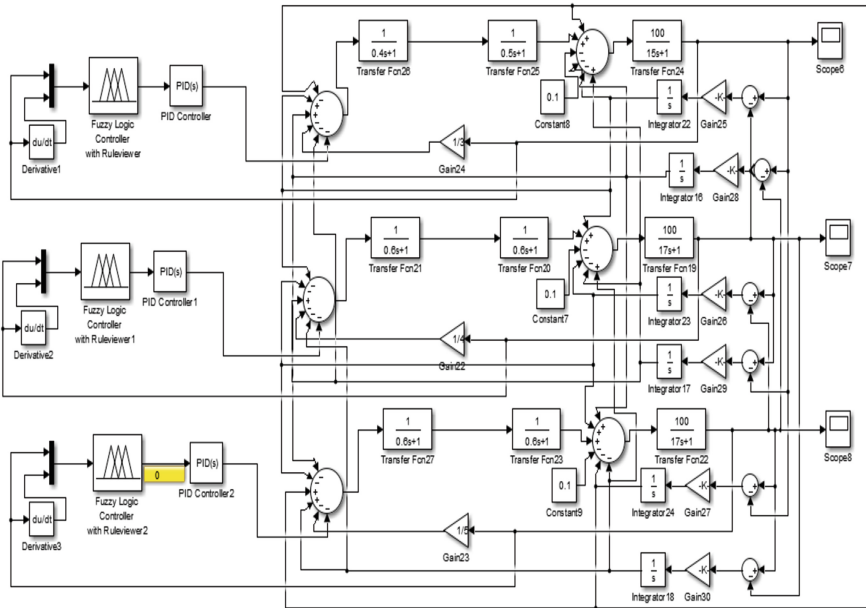
Fig. 18. Three area system with Fuzzy Controller

Case I: 5% disturbance results of three area system
Area1 frequency deviations with 5% disturbance
In Case I results have been presented with 5% disturbance only with sub cases of Case I-1 for area1, Case I-2 for area2 and Case I-3 for area3 respectively. Case I-(a) Area 1 without controller error is −15% which is not acceptable and unstable, Case I-(b) with PI Controller the peak undershoot is −22% and settling time of 25 s and Case I-(c) with fuzzy controller the peak undershoot is −12.5% and settling time of 14 s with zero steady state error which is most accepted one among all systems as illustrated by the below Fig. 19.
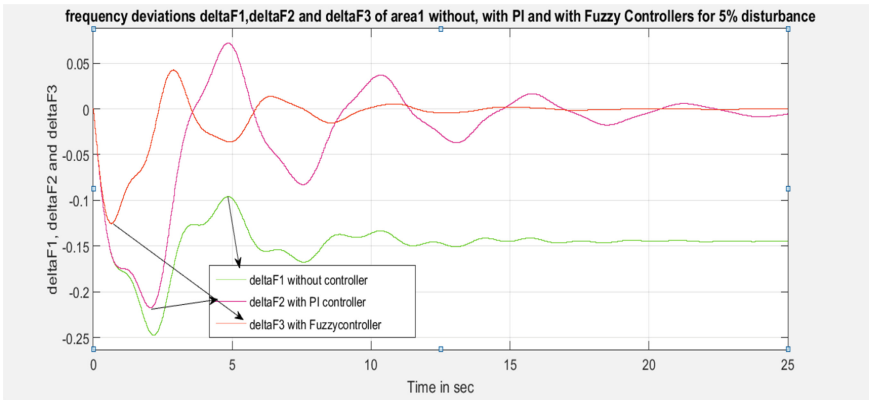
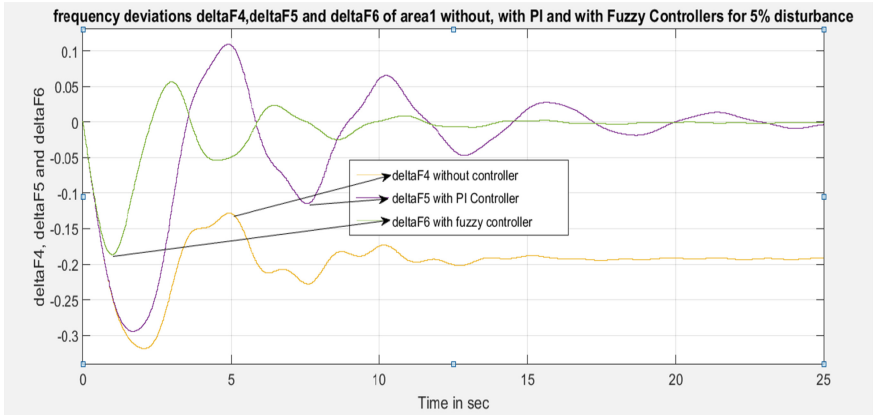**Fig. 19.** Area1 frequency deviations with 5% disturbance

Case I-2 (a) Without controller error is −19% which is not acceptable and unstable, Case I-3 (a) with PI Controller the peak undershoot is −29% and settling time of 25 s and Case I-3 (a) with fuzzy controller the peak undershoot is −18% and settling time of 14 s with zero steady state error as depicted by Fig. 20 below.

Case I-(a) without controller error is −22% which is not acceptable and unstable, Case I-3 (b) with PI Controller the peak undershoot is −43% and settling time of 25 s and Case I-3 (c) with fuzzy controller the peak undershoot is −23% and settling time of 14 s with zero steady state error and Fig. 21 shows the Area3 frequency deviations with 5% disturbance.

Case I-4 the power and delta deviation without controller it is unstable and with controllers the system is stable for small load disturbances in Area1 and the deviation is very small for fuzzy controller as depicted in Figs. 22 and 23 below.

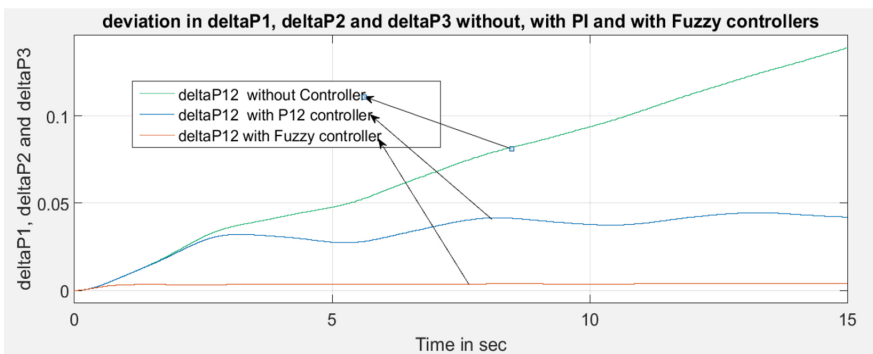**Case II: 10% disturbance results of three area system**
Case II-1 (a) without controller error is −29% which is not acceptable and unstable, Case II-1 (b) with PI Controller the peak undershoot is −49% and settling time of 15 s and Case II-1 (c) with fuzzy controller the peak undershoot is −11.5% and settling time of 6 s with zero steady state error as illustrated in the below Fig. 24.
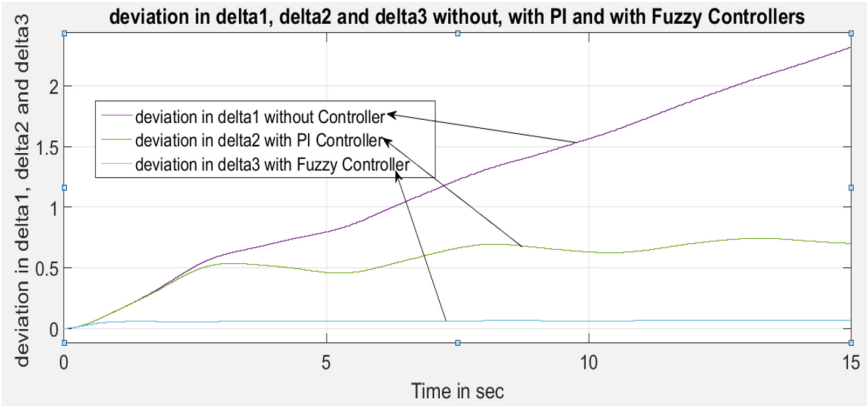
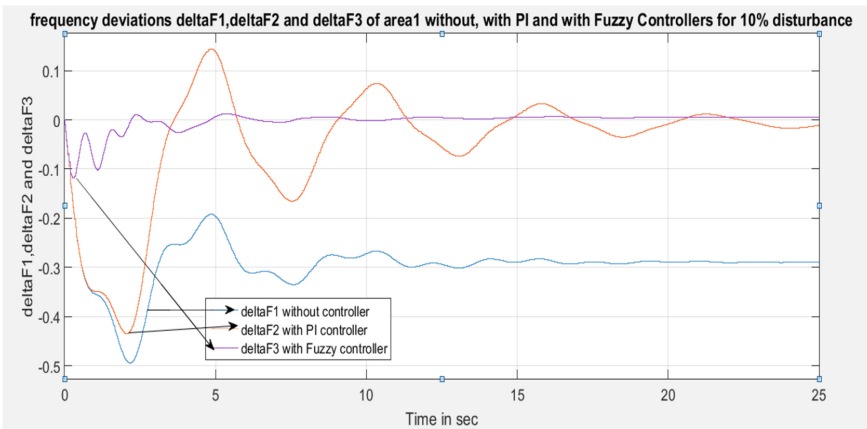**Fig. 20.** Area2 frequency deviations with 5% disturbance
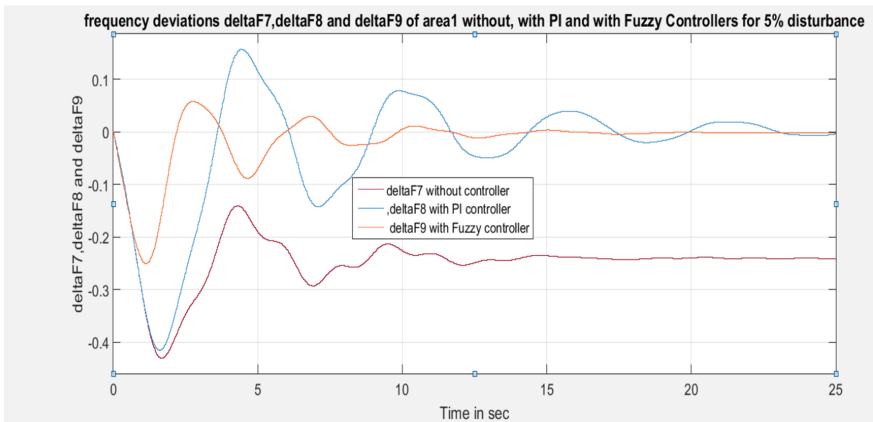
Fig. 21. Area3 frequency deviations with 5% disturbance

Fig. 22. Tie line Power in area1 without, with PI and with Fuzzy Controllers

Fig. 23. Area1 deviation in delta1, delta2 and delta3 without, with PI and with Fuzzy Controllers

Fig. 24. Area1 frequency deviations with 10% disturbance

Case II-1 (a) Without controller error is −39% which is not acceptable and unstable, Case II-2 (b) with PI Controller the peak undershoot is −64% and settling time of 16 s and Case II-2 (c) with fuzzy controller the peak undershoot is −11.5% and settling time of 12 s with zero steady state error as Fig. 25 depicts Area2 frequency deviations with 10% disturbance.

Case II-3 (a) Without controller error is −49% which is not acceptable and unstable, Case II-3 (b) with PI Controller the peak undershoot is −83% and settling time of 16 s and Case II-3 (c) with fuzzy controller the peak undershoot is −40% and settling time of 12 s with zero steady state error as Fig. 26 shows Area3 frequency deviations with 10% disturbance.

Case II-(d) the power and delta deviation without controller it is unstable and with controllers the system is stable for small load disturbances in Area1 and the deviation is very small for fuzzy controller as depicted in Figs. 27 and 28 respectively.
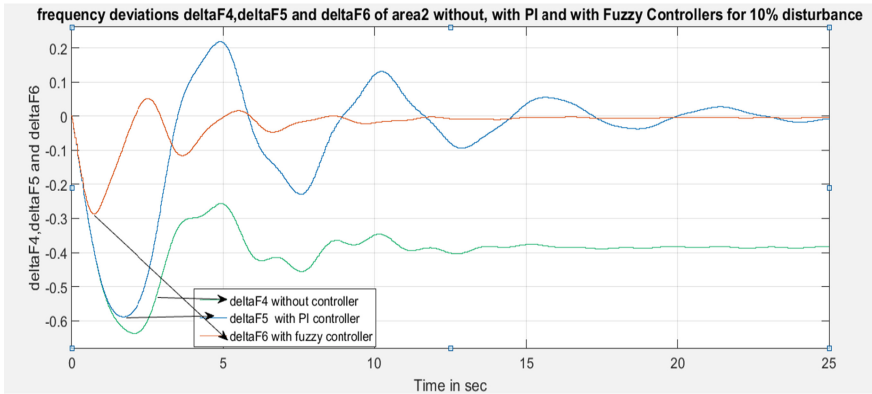
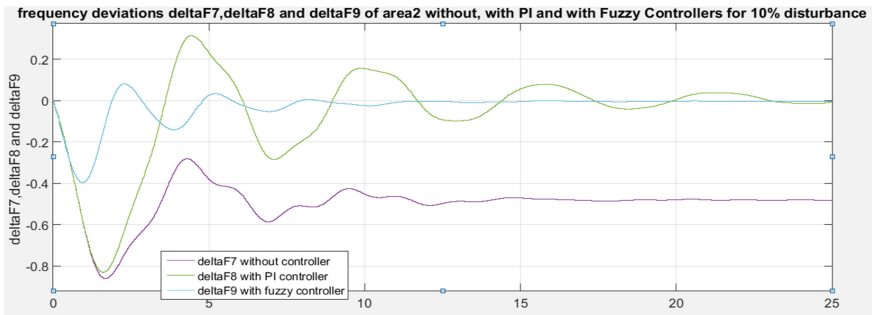**Fig. 25.** Area2 frequency deviations with 10% disturbance

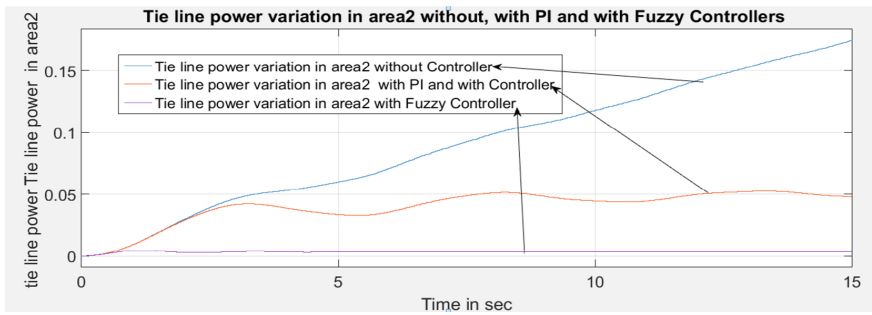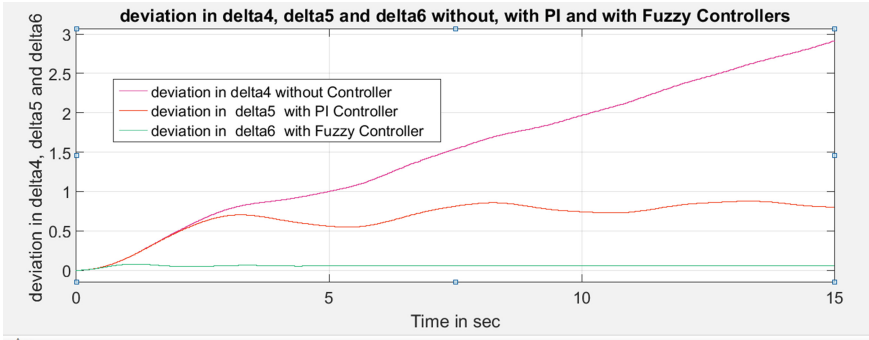**Fig. 26.** Area3 frequency deviations with 10% disturbance

Fig. 27. Tie line Power in area2 without, with PI and with Fuzzy Controllers

Fig. 28. Area2 deviation in delta4, delta5 and delta6 without, with PI and with Fuzzy Controllers, without controller it is unstable and with controllers the system is stable for small load disturbances in Area2

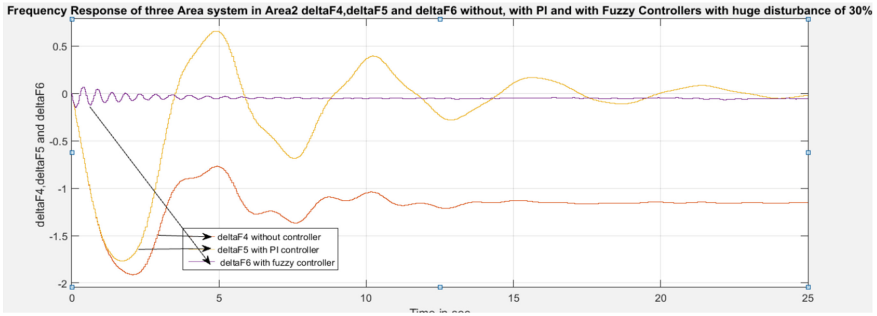## Case III: 30% disturbance results of three area system
Transient Stability Analysis

Case III-1 (a) Without controller error is -88% which is not acceptable and unstable, Case III-1 (b) with PI Controller the peak undershoot is -130% and settling time of 25 s and Case III-1 (c) with fuzzy controller the peak undershoot is -29% and settling time of 5 s with 15% steady state error as Fig. 29 depicts Area1 frequency deviations with 30% disturbance.
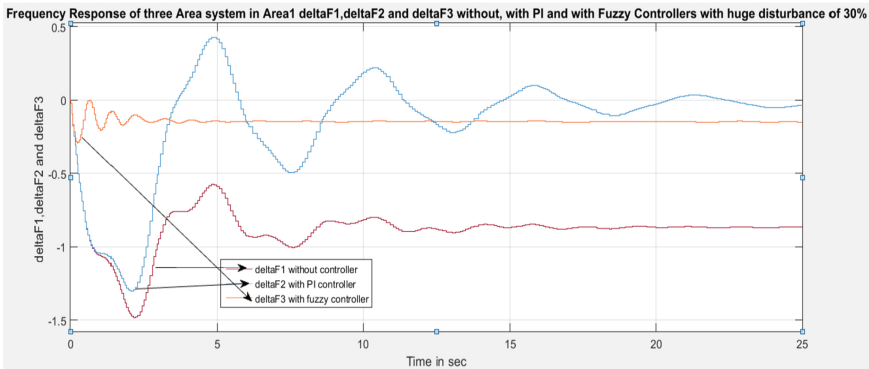
Fig. 29. Area1 frequency deviations with 30% disturbance

Case III-2 (a) Without controller error is -148% which is not acceptable and unstable, Case III-3 (b) with PI Controller the peak undershoot is -252% and settling time of 23 s and Case III-3 (c) with fuzzy controller the peak undershoot is -15% and settling time of 5.7 s with a small acceptable steady state error as Figs. 30 and 31 illustrates Area2 and Area3 frequency deviations with 30% disturbance respectively.

Frequency Response of three Area system in Area2 deltaF4,deltaF5 and deltaF6 without, with PI and with Fuzzy Controllers with huge disturbance of 30%

Fig. 30. Area2 frequency deviations with 30% disturbance

Frequency Response of three Area system in Area3 deltaF7,deltaF8 and deltaF9 without, with PI and with Fuzzy Controllers with huge disturbance of 30%
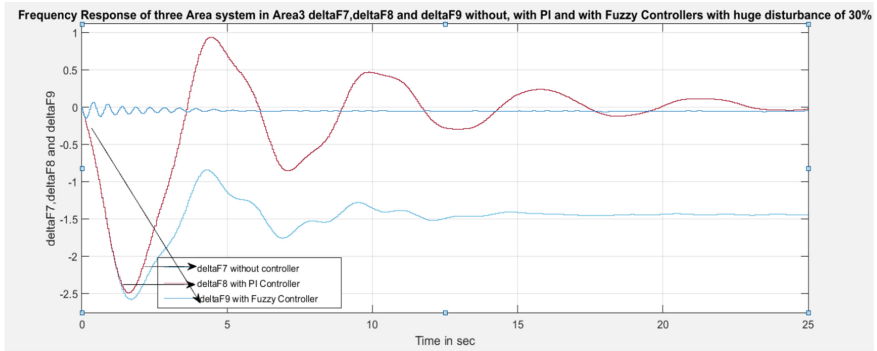
Fig. 31. Area3 frequency deviations with 30% disturbance

Case III-4 the power and delta deviation without controller it is unstable and with controllers the system is stable for small load disturbances in Area1 and the deviation is very small for fuzzy controller as depicted in Figs. 32 and 33 respectively.
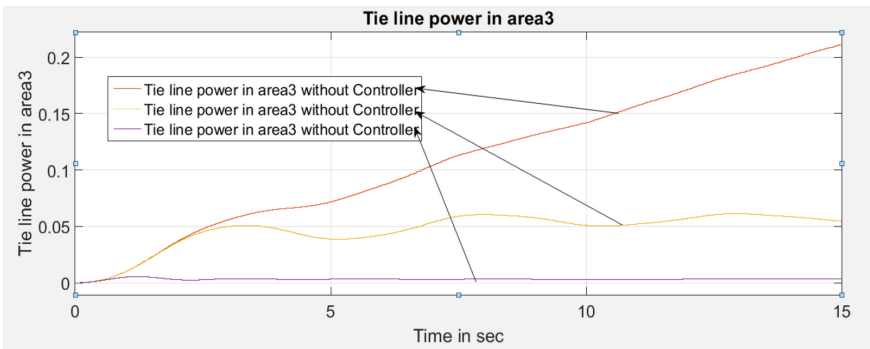
Fig. 32. Tie line Power in area3 without, with PI and with Fuzzy Controllers
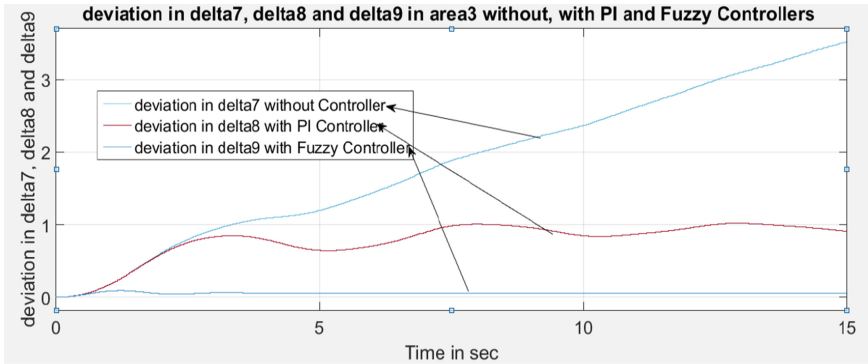
Fig. 33. Area3 deviation in delta4, delta5 and delta6 without, with PI and with Fuzzy Controllers

7   Conclusions

The article entente the three area load frequency control and dynamic and transient stability analysis. It dispenses the simulation of three area systems with small, medium and large load disturbances, with three cases. Case I with 5% load disturbances, Case II with 10% and case III with 30% load disturbances. In each of the three cases, there are three sub cases (a), (b) and (c) sub case (a) without any controller, sub case (b) with PI controller and sub case (c) with Fuzzy Controllers. For all three cases.

The simulation is carried out for all three cases of three area power system with all three sub cases of (a), (b) and (c). In the first part of the case study, the simulation results of three area power system for all three cases have been presented.

The frequency deviation for the three area system for all three cases shows that the system is working well with less settling time and zero steady state error, when it concerned with PI controller, the response is showing that the steady state error is there but still it growing and is not completely accepted as far as performance is concerned and without any controller the system performance is not accepted and it is unstable.

In the second part, the simulation results of three area power system for last part of all three cases have been presented. The power and swing curves being illustrated that for small, medium and also for large disturbances the system is completely stable with fuzzy logic controller and where as it is not accepted with PI controller and completely unstable without controller.

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