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OPTIMAL LOAD FREQUENCY CONTROL OF TWO AREA POWER SYSTEM

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ABSTRACT

Modern power systems are operated under various constraints which are meant to ensure an appropriate delivery of service. Meanwhile power system faces imbalance in power generation and its consumption in which the higher the load consumption the lower the frequency of operation. The governor-turbine combination will then experience a devastating reduction in its frequency of operation due to disturbance that may lead to system collapse. Both governor and turbine are included in the model of this power system. The control objective is to regulate the frequency error, tie-line power error and area control error despite the presences of external load disturbance (0.01 pu) and system uncertainties. Various control policies were investigated using various combinations of system parameters on a platform of a series of combination of the PI, fuzzy logic and neuro-fuzzy controller with the power system for better stability. This could be found in the other approaches. The neuro-fuzzy based controller load frequency controller is simulated on this two-area interconnected nonlinear power system. To verify the performance of the various controllers, the data from a typical hydrothermal power grid was adapted for the study. From the simulation results; it was recorded the neuro-fuzzy controller enjoyed a settling time of 5 seconds while under the same operating condition the system stability is achieved at 12 seconds using the PI controller. This, thus, demonstrates the robustness of the neuro-fuzzy controller in contrast to the fuzzy logic and proportional-integral (PI) controllers. This thus shows that the neuro-fuzzy logic controller is superior to the other two considered in this work. Hence for a two-area network, the neuro fuzzy approach is recommended for the steady state operation of the system so as to ensure the dynamic stability of the network.

Keywords: *Power system, load frequency, neuro-fuzzy, controller, hydro-thermal, proportional-integral.*

INTRODUCTION

In a modern power system, several sources of electric energy are integrated to meet the increasing national energy demand. In doing this, diverse energy sources are combined to supply the load centres. These may include gas, hydro, thermal, nuclear, photovoltaic, etc. Due to these distinct sources supplying a transmission network that needs to operate at a nominal frequency of 50 Hz; then it is crucial to optimally maintain reliability and quality of supply by instituting the principle of control strategy. The ability to optimally match the load demand to power generated as well as a fast system response to frequency variation helps to improve power system performance. Stable operation of power system requires matching the total generation with total load demand at little or no system losses. Due to the dynamism in load demand with respect to time, the real and reactive power balance is disturbed. This results in deviation of system frequency and tie-line interchange power from their scheduled value. High deviation of system frequency can lead to system collapse. This has necessitated the design of load frequency controller (LFC) for system states (such as area frequency, and tie-line interchange power) regulation. LFC is one of the most important ancillary services required for a smooth and secure operation of power system (Qian *et al*., 2013; Prakash *et al*., 2015).

In any interconnected power system, the dynamic load variation is a common phenomenon; especially in hydro-thermal power systems. In other words, demand for energy keeps varying; this change in demand always influences the system frequency. If this frequency is not properly managed; it may result impact the system reliability and quality of the power output. If this continues unabated; it may lead to system collapse. To achieve high design capabilities of load frequency control, different controllers based on fuzzy logic controller (FLC) as well as conventional controllers are considered by researchers. The peak overshoot and settling time of fuzzy controllers have been generally shown to be lower than those of conventional proportional integral (PI) controllers (Zamee *et al*., 2013; Ammisetty *et al*., 2016). Fuzzy logic controllers also give better dynamic performance and reduce the oscillation of frequency of deviation when compared to conventional PI controller (Chaturvedi and Dwivedi, 2014). Conventional controllers are very simple to implement and sometimes give acceptable dynamic response. However, they are limited by slow response, lack of efficiency and poor handling of system nonlinearities when system complexity in real-time solution occurs due to increasing load variation without equitable change in generation which may influence further system disturbance.

This study aim is to optimize the control of load frequency in a hydro thermal power system. In order to achieve this aim, this study considered modelling of speed governor, turbine, generator, and load of a hydro plants and thermal plant, developing a mathematical model of load frequency control of the hydro thermal power system, and developing an optimal load frequency control technique suitable for the hydro-thermal system.

The frequency of power transmission system is determined by the active power which in turn is determined by the system's power generation/load mismatch. Therefore, in order to control the frequency of the system, it is imperative that there is need to take into account the speed of the electric governor system (primary control) as well as provide a speed droop control mechanism (secondary control) for the system. This ensures that while the load increases tasking the generator for more power output; the droop system reduces the governor reference speed. Hence, the control systems consist of two control levels. The primary control which relates to the governor and turbine dynamics is a mechanical system with a relatively slow response time. On the other hand, the secondary control relates to the droop control mechanism and has a relatively faster dynamics. In addition to these control loops, the power system typically consists of supplementary and auxiliary controls such as the power system stabilizer. In order to design a control system, it is imperative to get the power system model with adequate complexity. Most of the works reported in the literature have been carried out by considering various linearized model of thermal/ hydro of single area or multi-area power systems.

Integral of the control error are taken as control signals for conventional control strategies of the LFC problem. In order to obtain a desired gain and phase margins in the classical control techniques, Bode and Nyquist diagrams, as well as root locus, are usually often deployed. This reveals that closed loop transient response will result to poor dynamic performance, especially in the advent of instability necessitated by increasing load demand which further complicated by its negative influence on the reactive power variation in the system. This results in parameter variations and nonlinearities (such as the noticeable relatively large overshoots and transient frequency deviation), even when the design is straight forward, easy and controllable for practical implementation (Elgerd *et al.*, 1970; Das *et al.*, 1990).

Quazza (1966) proposed the approach with non-interaction between frequency and tie-line power control and each control area responsible for its own load variations. The technique based on coordinated system-wide correction of time error and inadvertent interchange is incorporated for AGC study by Cohn, 1971; Choi, *et al.*, 1981). The suboptimal LFC regulator designs, to deal with the practical limitations in the implementation of LFC based on feedback of all state variables. The design method employs model and singular perturbation techniques to ensure the decoupling of the interconnection of power system into its subsystem components (Choi, *et al.*, 1981). In the beginning, the LFC problem was based on centralized control strategy, however, the implementation of global controller requires information about all the states of the power system.

Elgerd *et al*. (1970) suggested a feedback and loop gain to eliminate the disturbance, and new feedback control law is developed by using a state variable model and the state regulator problem of optimal control theory. Decentralized control system divides composite system to subsystems each with a separate control, to overcome the problems arising from centralized control. It also reduces the computational and communication burden between different systems and makes the control more feasible and simple. Yang *et al*. (1998) proposed decentralized LFC based on structured singular values. Shayeghi *et al*. (2008) technique is presented in 3-area interconnected power system. Two-level or multi-level control scheme is used to overcome instability in power system due to strong interactions between control areas (Babahajiani *et al*., 2016; Parvaneh *et al*., 2016; Satheeshkumar and Shivakumar, 2016). Premakumaran *et al*. (1982) proposed some aspects of multilevel LFC of a two-area power system. Their study incorporates the effects of governor controls and an excitation system.

A global controller, capable of exploiting the possible beneficial aspects of interconnections, has been applied in the LFC study (Ray and Rani 2001) whereby favourable results were reported. Pande and Kansal (2015) investigated the influence of the integral controller on the hybrid of the conventional method of LFC with the artificial intelligence (AI) technique based fuzzy logic controller to solve with the power system collapse or system instability problem for multi-area system. This work was reported to have considerably reduced the unscheduled tie-line power flow between neighbouring control areas. Furthermore, these controllers provided a robust system which was more stable and reliable and helped the system to regain its nominal operating condition with zero steady state error after any disturbance. The system stabilized with less settling time but there was a little deviation from the nominal frequency value at the application of integral controller with the fuzzy controller; thus the system stabilized with less settling time at zero steady state error.

However, the Artificial Intelligence (AI) techniques such as FLC and Artificial Neural Network (ANN) have been applied for load frequency control to overcome these limitations of the conventional methods (Aravindan *et al*., 2009). It was discovered that the ANN-based approached tend to perform better when the power system is non-linear and of high complexity. As the power system model utilised in this study contains such high non-linearity and complexity, an ANN-based approach is considered in this study because its proficient satisfactory control performance when compared with conventional controllers in such a situation (Surya *et al*., 2013). Sharma and Bhadoriya (2015) discussed the dynamic performance of automatic load frequency control of a three-area power system using Proportional-Integral-Derivative (PID) controller to reduce settling time and oscillations as well as to improve the response time. Shayeghi *et al*. (2006), developed a multi-stage controller that utilized the fuzzy switch to blend a proportional derivative (PD) fuzzy logic controller with an integral fuzzy logic input. This revealed its tendency of high insensitivity to large load changes and disturbances in the presence of plant parameter variations and system nonlinearities. The benefit was that it didn't require an accurate model of the AGC problem, and the design process is lower than that of the other fuzzy PID controllers. Parvaneh *et al*. (2016) developed optimum load LFC of a multi-area power system using PID controller parameter regulation based on a heuristic optimization technique called seeker optimization algorithm to eliminate the power system oscillations. The result of controller of provides better damping in comparison genetic algorithm and particle swarm optimisation based PID controllers. Zamee *et al*. (2013) proposed the use of conventional PI controller and artificial intelligence to study the load frequency control of interconnected power system. In the proposed scheme, a control methodology is developed using conventional PI controller and FLC for interconnected hydro-thermal power system. The control strategies guarantee that the steady state error of frequencies and inadvertent interchange of tie-lines power are maintained in a given tolerance limitations. Thus, FLC performed better than conventional PI controller when some disturbance in load is given to the system.

Altas and Neyens (2006) designed a simulation model of a fuzzy logic based load frequency controller model for power systems and it was compared with the classical regulating systems in order to verify and show the advantages of the model and controller developed. The results obtained showed that the output of the load change was controlled with less overshoot and shorter settling time. Qian *et al.* (2013) proposed a neural sliding-mode load method for LFC of power systems with the governor dead band (GDB) nonlinearity; an additional state is introduced to the control system. A sliding-mode controller is designed for the linear nominal system with no GDB, and a neural compensator is proposed to compensate GDB. In this case, the controller and compensator work together to realize robust control of the nonlinear system. The weight update formula of the network is deduced from Lyapunov direct method. It is proven that the controller and compensator are able to ensure that the control system is of asymptotic stability. Simulation results illustrate the validity and robustness of the proposed method via a single-area power system with governor dead band (GDB).

Pande and Kansal (2015) and Prakash *et al*. (2015) discussed two-area-hydro-thermal power system connected through tie-lines, the perturbation of frequencies at the areas and resulting tie-line power flows arise due to unpredictable load variations that cause mismatch between the power generated and demanded. The performance of the intelligent adaptive neuro-fuzzy interface system (ANFIS) controllers was compared with ANN, fuzzy and conventional PI, PID based approaches and thus showed better dynamic response. Shree and Kamaraj (2016) proposed a hybrid neuro-fuzzy for automatic generation control in restructured power system; its control strategy is insensitive to load variations and disturbances in the advent of system nonlinearities and variance in the plant parameters. This was deployed on a three-area-hydropower generation system.

From foregoing, there are some areas of research that was not covered by the past research. Among which are the control strategy of the hybrid hydrothermal generation systems. The classical control and heuristic control methods have been severally explored as control strategies for the power system stability and control. This latest research shall investigate the neuro-fuzzy controller for the assessment of hydrothermal power system.

MATERIALS AND METHIOD

Materials

Some of the tools for executing this research are the PI controllers which is employed for generating the conventional results, so also was the fuzzy logic controllers which was for training the data collected for the sake of the analysis; the data of the two-area hydrothermal power system with tie line. A single area power system is as shown in Figure 1 while the tie line is as depicted in Figure 2.

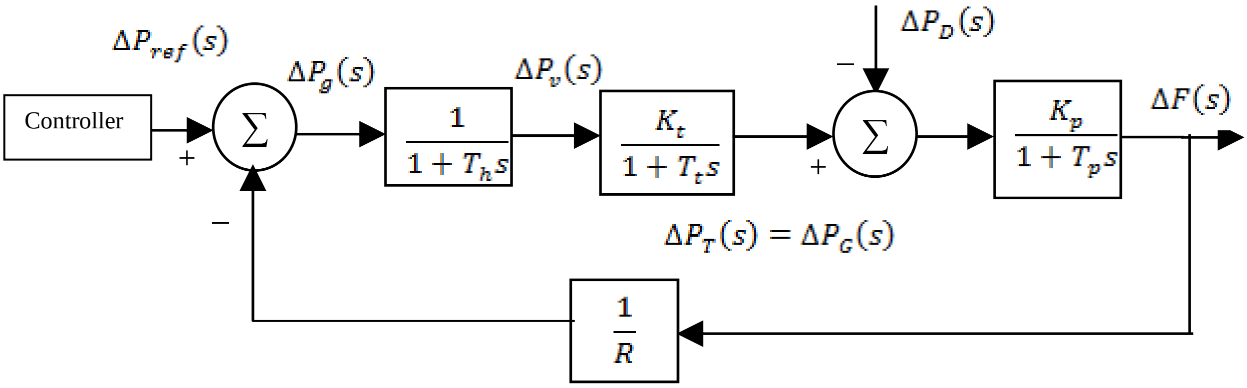

Figure 1: Block diagram representation of single area

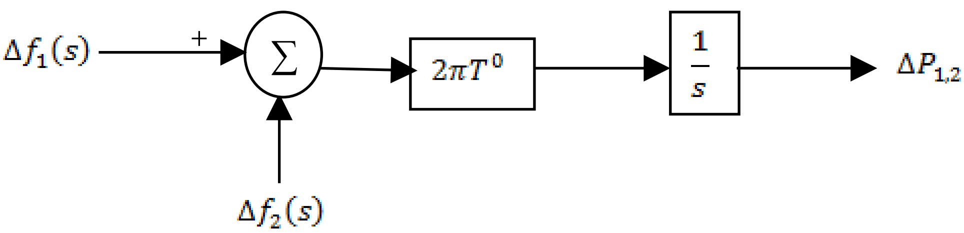

Figure 2: Block diagram representation of a tie line

Method

This involves the deployment of mathematical model and simulation of same to achieve the desired goal. This is done using the control strategy.

Mathematical Model

The tie line model is developed from first principle by considering power from Area 1 to 2 (Equation 1). When the direction of power transfer is change from Areas 2 to 1, Equation (1) becomes Equation (2).

$$P_{1,2} = \frac{|V_1||V_2|}{X}\sin(\delta_1 - \delta_2) \quad (1)$$

$$P_{1,2} = \frac{|V_1||V_2|}{X_{1,2}}\sin(\delta_1 - \delta_2) \quad (2)$$

where, δ_1 and δ_2 represents are power angles of end voltages V_1 and V_2 of equivalent machine in the two area, respectively, $X_{1,2}$ represents the reactance of the tie line which also shows positive direction in the flow of tie line power, $\Delta\delta_1$ and $\Delta\delta_2$ represents small deviations in δ_1 and δ_2, respectively.

The relational change in power can be expressed as Equation (3). This therefore formed the basis of further analysis of the tie line model (Equation 4).

$$P_{1,2} \text{ to } (P_{1,2} + \Delta P_{1,2}) \quad (3)$$

$$P_{1,2} + \Delta P_{1,2} = \frac{|V_1||V_2|}{X_{1,2}}\sin[\delta_1 + \delta_2 - (\Delta\delta_1 + \Delta\delta_2)] \quad (4)$$

$$= \frac{|V_1||V_2|}{X_{1,2}}[\sin(\delta_1 - \delta_2)\cos(\Delta\delta_1 + \Delta\delta_2) + \cos(\delta_1 - \delta_2)\sin(\Delta\delta_1 - \Delta\delta_2)] \quad (5)$$

Since $\cos(\Delta\delta_1 + \Delta\delta_2) \cong 1$ for small values and $\sin(\Delta\delta_1 - \Delta\delta_2) = \Delta\delta_1 - \Delta\delta_2$, Equation (5) is expressed as Equation (6).

$$\Rightarrow P_{1,2} + \Delta P_{1,2} = \frac{|V_1||V_2|}{X_{1,2}}\sin(\delta_1 - \delta_2) + \frac{|V_1||V_2|}{X_{1,2}}\cos(\delta_1 - \delta_2)(\Delta\delta_1 - \Delta\delta_2) \quad (6)$$

By considering Equation (2), this study modified Equation (6) as Equation (7). This is also modified by considering Torque product (Equation 8). This equation is defined as the synchronizing co-efficient of a line owing to the *t* electric stiffness of synchronous machines.

$$\Rightarrow \Delta P_{1,2} = \frac{|V_1||V_2|}{X_{1,2}}\cos(\delta_1 - \delta_2)(\Delta\delta_1 - \Delta\delta_2) \quad (7)$$

$$\Delta P_{1,2} = T^0\,(\Delta\delta_1 - \Delta\delta_2) \quad (8)$$

where, T^0 = Torque product.

The change in frequency is considered in order to eliminate the small deviations in δ_1 and δ_2 in Equation (8). The relationship between frequency and change in power angles is expressed as Equation (9).

$$\Rightarrow \Delta\delta = 2\pi\int_0^t \Delta f\,dt \quad (9)$$

$$\Delta f = \frac{1}{2\pi}\frac{d(\delta + \Delta\delta)}{dt} = \frac{1}{2\pi}\frac{d(\Delta\delta)}{dt} \quad (10)$$

$$\Rightarrow \frac{d(\Delta\delta)}{dt} = 2\pi\Delta f \quad (11)$$

By considering Equation (9), Equation (8) is modified as Equation (12). Laplace transform is used to convert Equation (12) to Equation (13). However, when power transfer is from Area 2 to 1, Equation (13) becomes Equation (14).

$$\Delta P_{12} = 2\pi T^0\left[\int_0^t \Delta f_1 dt - \int_0^t \Delta f_2 dt\right] \quad (12)$$

$$\Delta P_{12}(s) = \frac{2\pi T^0}{s}[\Delta f_1(s) - \Delta f_2(s)] \quad (13)$$

$$\Delta P_{1,2}(s) = \frac{2\pi T^0}{s}[\Delta f_2(s) - \Delta f_1(s)] \quad (14)$$

From the Figure 1, the power balance equation is written as the incremental power balance equation for a single area (Equation 15). This equation changes to Equation (15) when two areas are being considered.

$$\Delta P_G - \Delta P_D = \frac{2H_1}{f_0}\frac{d}{dt}(\Delta f_1) + B_1\Delta f_1 \quad (15)$$

$$\Delta P_G - \Delta P_D = \frac{2H_1}{f_0}\frac{d}{dt}(\Delta f_1) + B_1\Delta f_1 + \Delta P_{12} \quad (16)$$

Based Figure 2 and Equation (16), the expression for normal operation of power on the tie line is given as Equation (17).

$$\Delta P_G - \Delta P_D = \frac{2H_1}{f_0}\frac{d}{dt}(\Delta f_1) + B_1\Delta f_1 + \Delta P_{12} \quad (17)$$

Given that $\frac{2H_1}{f_0}B_1 = \frac{1}{K_{p1}}$ and $\frac{1}{B_1} = T_{p1}$,

Equation (17) becomes Equation (18). By substituting Equation (17), Equation (18) was obtained as the expression for change in frequency of a power system.

$$\Rightarrow \Delta P_G(s) - \Delta P_D(s) - \Delta P_{1,2}(s) = \frac{1}{K_{p1}}\Delta f_1(s)[T_{p1}s + 1] \quad (18)$$

$$G_{p1}(s) = \frac{K_{p1}}{1 + T_{p1}s} \quad (19)$$

Given Equation (19), this study modified Equation (18) as Equation (20).

$$\Rightarrow \Delta f_1(s) = G_{p1}(s)[\Delta P_G(s) - \Delta P_D(s) - \Delta P_{12}(s)] \quad (20)$$

Thus,

$$\Delta P_{12} = \Delta P_{21} \quad (21)$$

To eliminate steady state error in frequency in tie line power flow, tie-line bias control is used. This takes care of the net interchange and also the ration the frequency control, of the area. Given that the area control error for Areas 1 and 2 are ACE_1 and ACE_2, respectively, the area control errors are linear combination of frequency and tie line error for each area (Equation 22 and 23).

$$ACE_1 = \Delta P_{12} + b_1\Delta f_1 \quad (22)$$

$$ACE_2 = \Delta P_{21} + b_2\Delta f_2 \quad (23)$$

where, b_1 and b_2 are frequency bias of Areas 1 and 2, respectively.

By considering ΔPA_1 and ΔPA_2 as mode integral of ACE_1 and ACE_2, respectively (Equations 24 and 25), Laplace transform is used to generate the expressions for ΔPA_1 and ΔPA_2 (Equations 26 and 27).

$$\Delta PA_1 = -Ki_1 \int_0^t (\Delta P_{12} + b_1 \Delta f_1) dt \qquad (24)$$

$$\Delta PA_2 = -Ki_2 \int_0^t (\Delta P_{21} + b_2 \Delta f_2) dt \qquad (25)$$

$$\Delta PA_1(s) = \frac{-Ki_1}{s} [\Delta P_{12}(s) + b_1 \Delta f_1(s)] \qquad (26)$$

$$\Delta PA_2(s) = \frac{-Ki_2}{s} [\Delta P_{21}(s) + b_2 \Delta f_2(s)] \qquad (27)$$

Step changes in ΔPA_1 and ΔPA_2 are applied simultaneously in Control Areas 1 and 2, respectively. At steady state condition the output signals of all integrating block will be constant and their input signal will be zero (Equations 28 to 35).

$$\Delta P_{12} + b_1 \Delta f_1 = 0 \left(\text{Input of integrating block } \frac{-Ki_1}{s}\right) \qquad (28)$$

$$\Delta P_{21} + b_2 \Delta f_2 = 0 \left(\text{Input of integrating block } \frac{-Ki_2}{s}\right) \qquad (29)$$

$$\Delta f_1 - \Delta f_2 = 0 \left(\text{Input of integrating block } \frac{2\pi T^0_{12}}{s}\right) \qquad (30)$$

$$\Delta P_{12} = \Delta P_{tie,1} \text{ and } \Delta P_{21} = \Delta P_{tie,2} \qquad (31)$$

$$\Rightarrow \frac{\Delta P_{tie,1}}{\Delta P_{tie,2}} = \frac{T_{12}}{T_{21}} = -\frac{1}{a_2} = \text{Constant} \qquad (32)$$

$$\Rightarrow \Delta P_{tie,1} = \Delta P_{tie,2} = 0 \qquad (33)$$

$$\Rightarrow \Delta PA_1 = \Delta PA_{12} \qquad (34)$$

$$\Rightarrow \Delta f_1 = \Delta f_2 = 0 \qquad (35)$$

Clearly under steady condition change in tie-line power and frequency in either area is zero, which is shown by integration of ACEs in the feedback loops of either area.

Simulation of a typical two area non-reheat power system
Simulink was used to design and simulate a typical two area non-reheat power system. The model is designed and configured appropriately to actualize design philosophy. This led to the investigation of the operating scenario under various combinations of parameters. In other words, the next three diagrams (i.e. Figures 3 to 5) provided a platform for a series of combination involving PI, fuzzy logic and neuro-fuzzy controller as depicted by Figures 3, 4 and 5 respectively.

From Figure 3, the PI controller was pass through perturbation with a disturbance of magnitude of 0.01 pu, while in the case of Figure 4, a fuzzy logic controller is experienced a disturbance of 0.01 pu; the resulting Simulink is as shown.

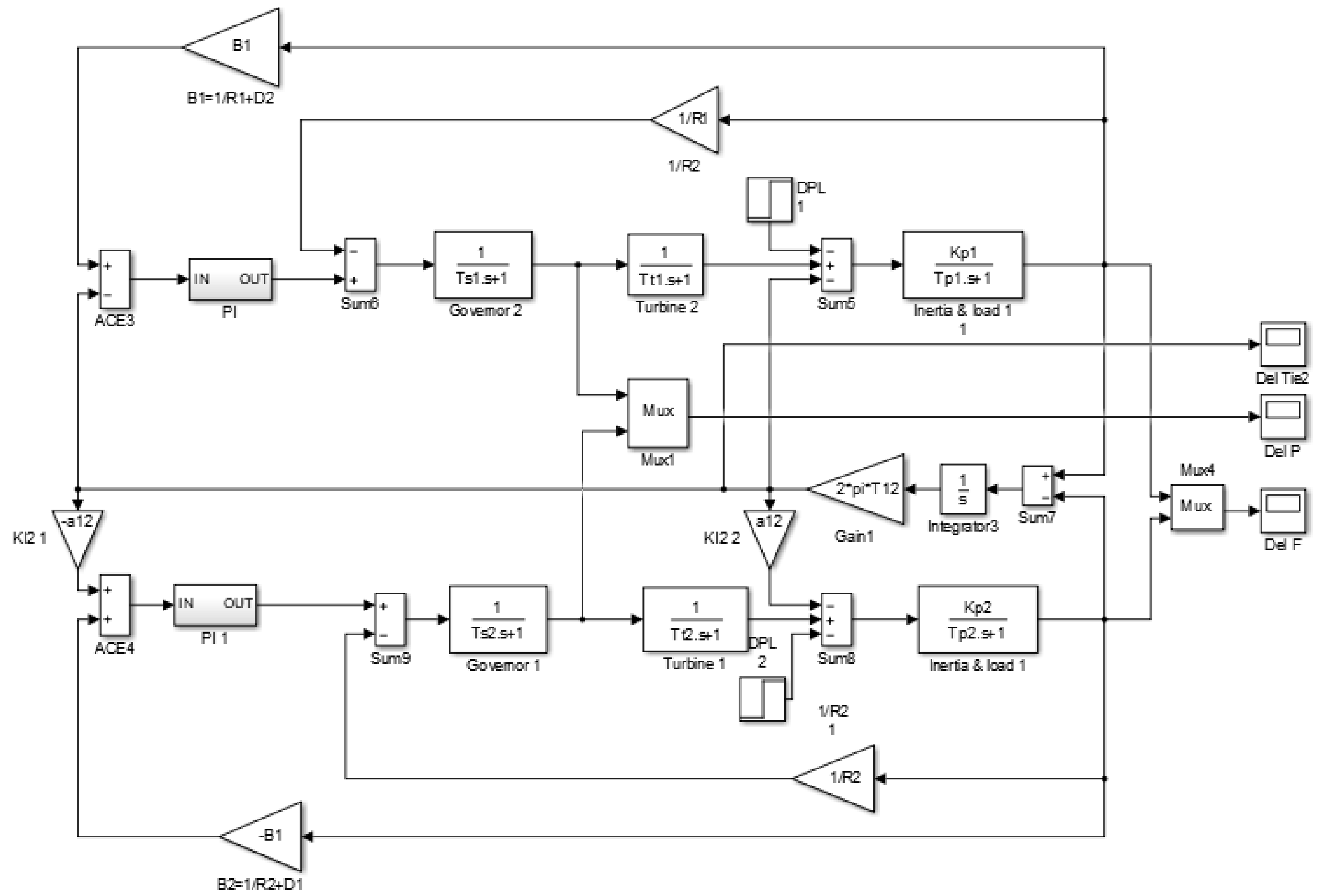

Figure 3: A two area LFC using PI controller

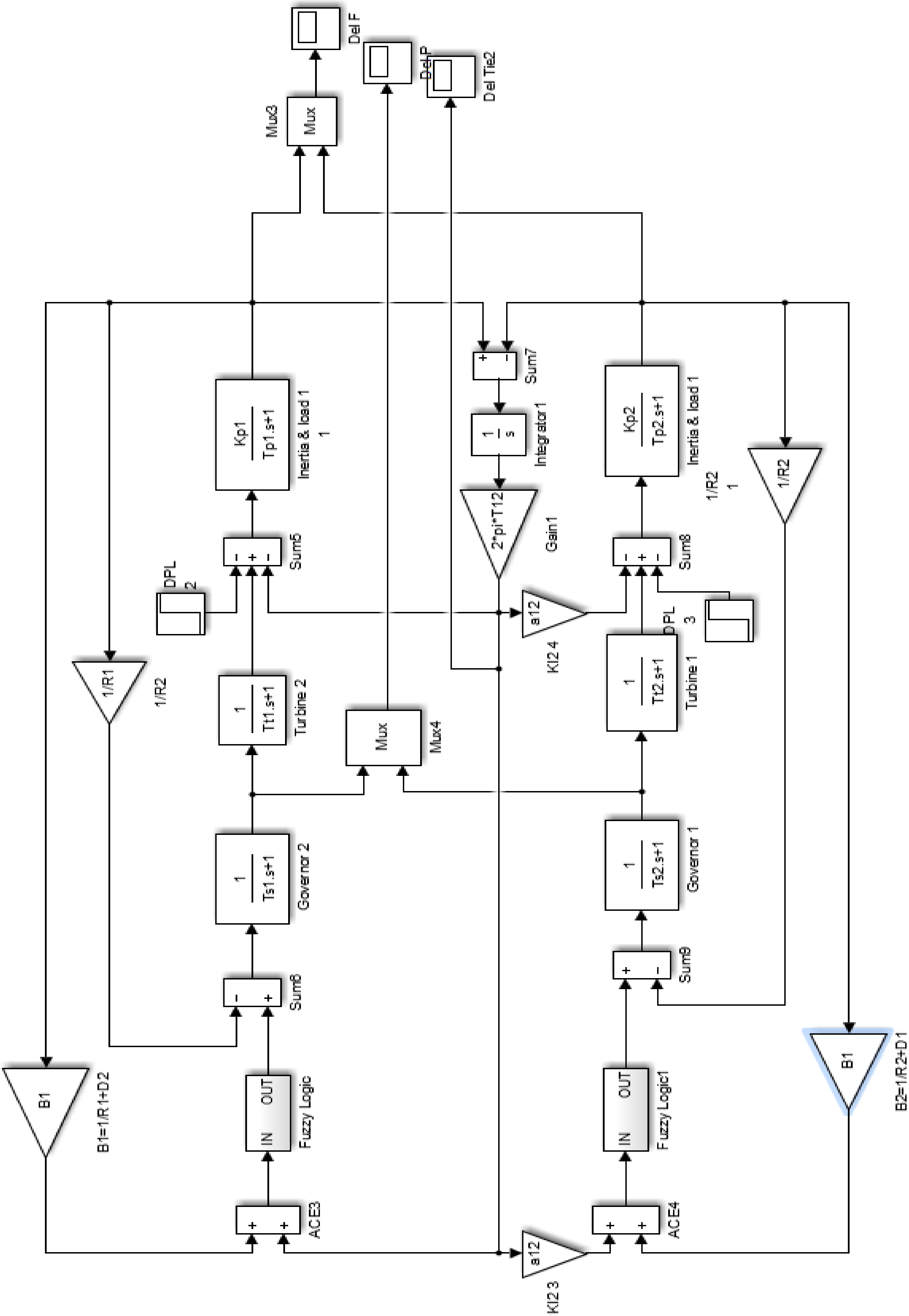

Figure 4: A two area LFC using fuzzy logic controller

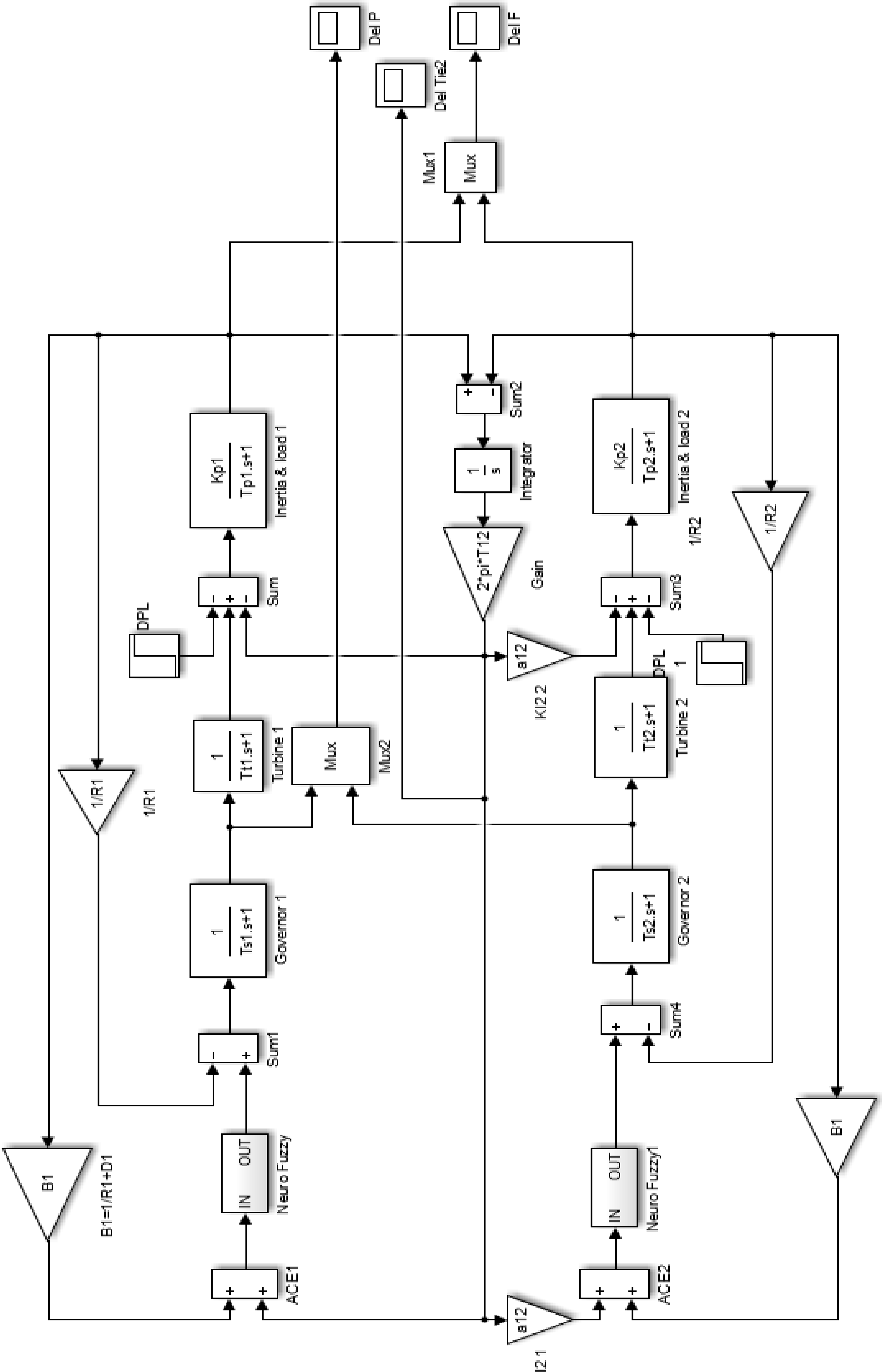

Figure 5: A two area LFC using neuro-fuzzy controller

So also, from Figure 5; the neuro-fuzzy controller is used with the data collected; this is thus trained by ANFIS. Clearly under steady condition change in tie-line power and frequency in either area is zero, which is shown by integration of ACEs in the feedback loops of either area. Thus critical review of the results of these investigations is as presented in Section 4.

RESULTS AND DISCUSSION

In this study, the simulation results were generated for the power system control, and then the PI controllers are used to get conventional results. In case of the fuzzy logic controllers, for better performance, the training data were collected from the fuzzy logic control and used for analysis. After that the neuro-fuzzy controller is designed for LFC of power system and its results are compared with conventional PI, fuzzy logic load frequency controller for a two-area power system.

Simulation of a Typical Two Area Non-Reheat Power System

Simulink was deployed to design and simulate a typical two area non-reheat power system. The model is designed and configured appropriately to actualize the system design philosophy. Thus this section presents the results of the various analysis under different scenarios for te examination of network behaviour to the variation in system parameter under the advent of disturbance. This is done using the philosophy of the load frequency control of interconnected two area power system using PI, fuzzy logic and neuro-fuzzy controller, respectively. The effectiveness of neuro-fuzzy controller which was tuned with bi-section method is validated through the simulation results. The responses shown below are the dynamic responses of each area frequency as well as the nature of the power flow of tie line, for the two-area power system model. In this study, first an optimal control law is generated for the power system control, and then the PI controllers are used to get conventional results. In case of the fuzzy logic controllers, for better performance, the training data were collected from the fuzzy logic control and used for analysis. After that the neuro-fuzzy controller is designed for LFC of power system and its results are compared with conventional PI, fuzzy logic load frequency controller for a two-area power system.

Change in Frequency

The results for change in frequency from the PI, fuzzy logic and neuro-fuzzy controllers were different as there are variations in the levels at which they attain stability in change in frequency (see Figures 6 to 8). The neuro-fuzzy controller was able to achieve early stability (5 sec) in change in frequency when its performance was compared with that of the PI and fuzzy logic controllers (see Figure 8). The level of fluctuation in frequency of the PI controller is greater than that of the fuzzy logic and neuro-fuzzy controllers (see Figures 7 and 8). It took the PI controller about 12 seconds before it was able to attain stability. The change in frequency from the PI controller exhibited the same pattern as the fuzzy logic controllers (Figures 6 and 7).

From Figure 5 neuro-fuzzy controller is used with the data collected and trained by ANFIS.

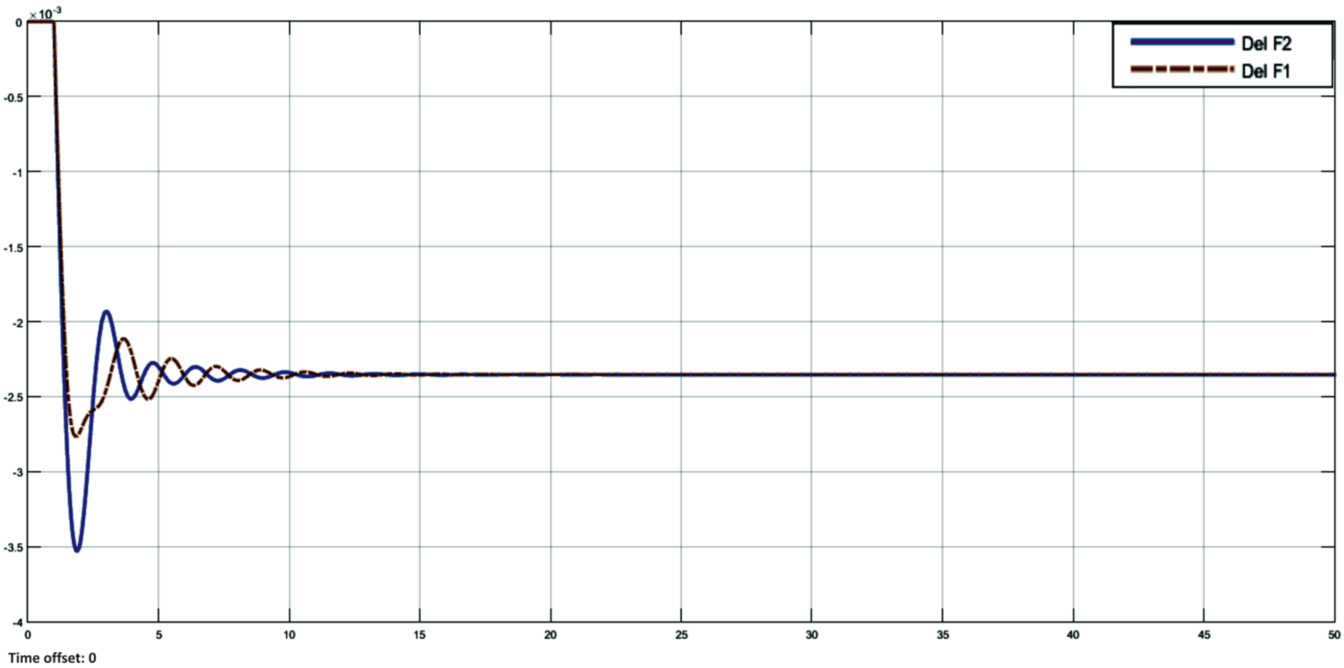

Figure 6: Change in frequency using a PI controller

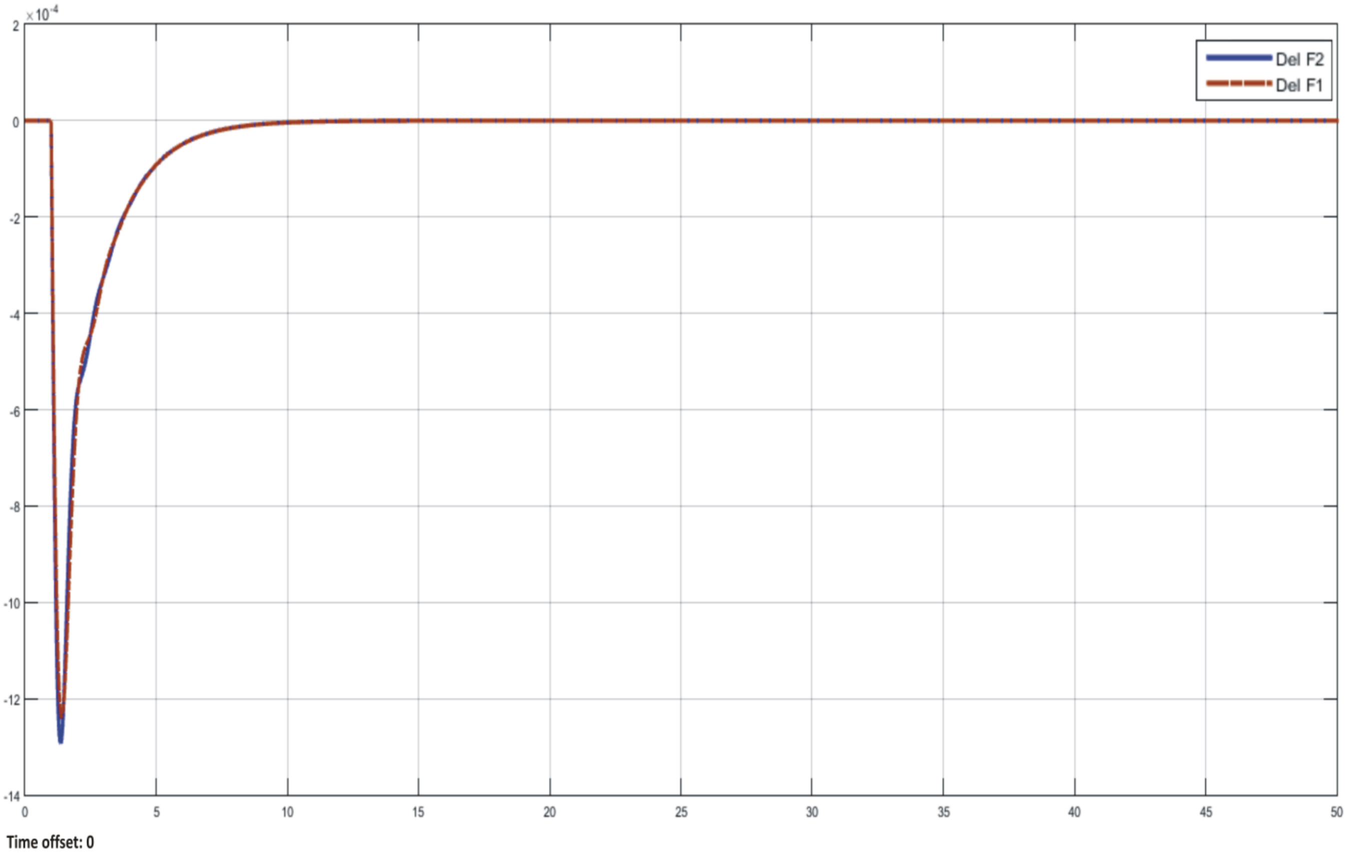

Figure 7: Change in frequency using a fuzzy logic controller

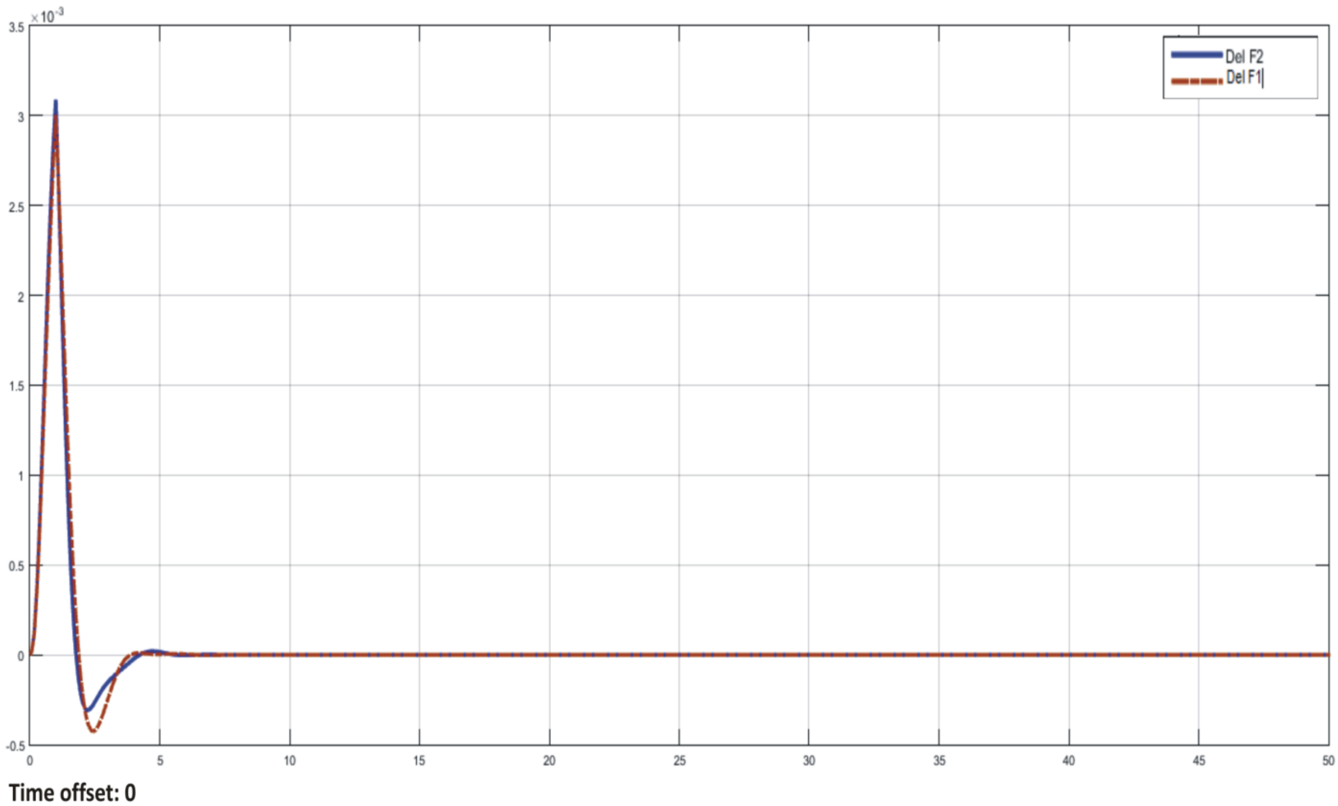

Figure 8: Change in frequency using a neuro-fuzzy controller

However, the fuzzy logic controller was able to return to a zero change in frequency, while the PI controller returned to a stable change in frequency of about - 2.4 Hz. The fuzzy logic controller exhibited a smooth rise in change in frequency before it attains a stability state. This feature was not exhibited by the neuro-fuzzy controller. The characteristic of the neuro-fuzzy controller before it attained a stability state was a rise and fall pattern (Figure 8).

Change in Power

Figures 9 to 11 showed that the analysis of change in power of a hydro-thermal plant is dependent on the type of controller that is considered. None of the three controllers exhibited the same trend in terms of change in power. However, the PI and fuzzy logic controls showed that they had an initial increase in change in power, while the neuro-fuzzy controller exhibited an initial decrease in change in power. The level of change in power from the PI controller is less than that of the fuzzy logic and neuro-fuzzy controllers (see Figure 10 and 11). However, the average change in power from the fuzzy controller is more than that of the neuro-fuzzy controller, while they both attained stability at almost the same time (5 sec). In addition, the fuzzy control had more number of fluctuations before attaining stability than the neuro-fuzzy controller.

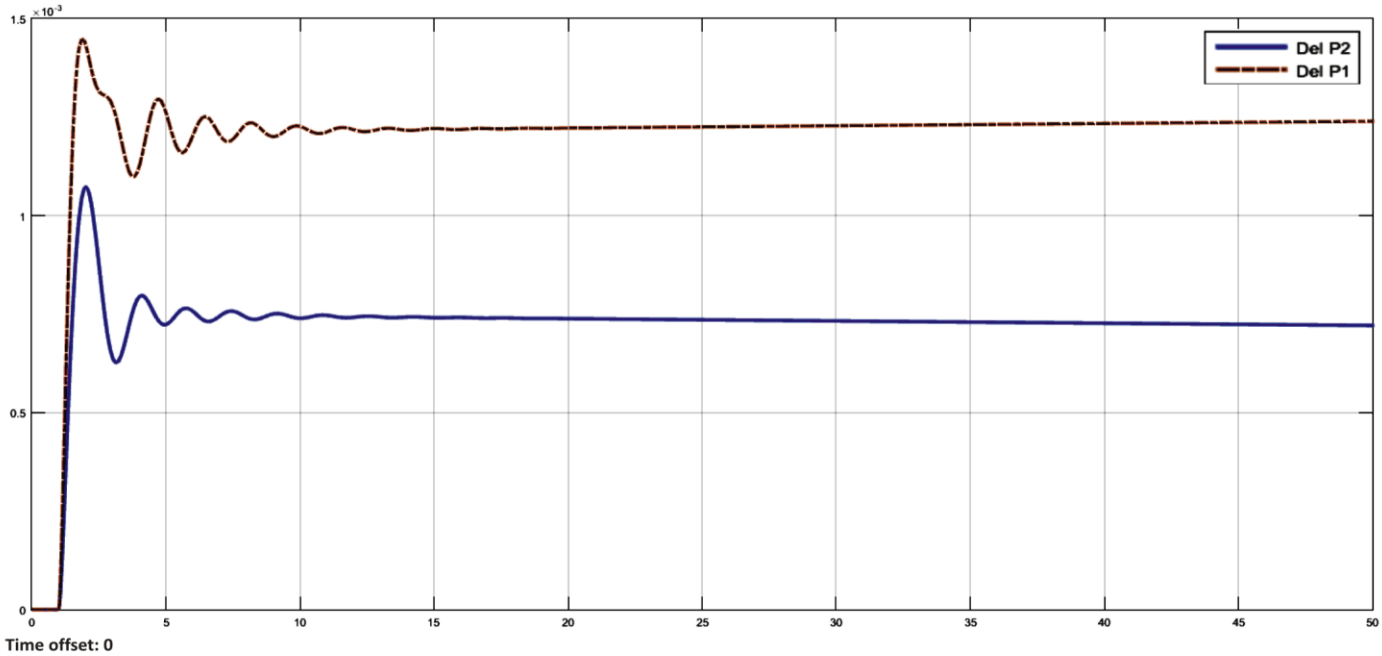

Figure 9: Change in power using a PI controller

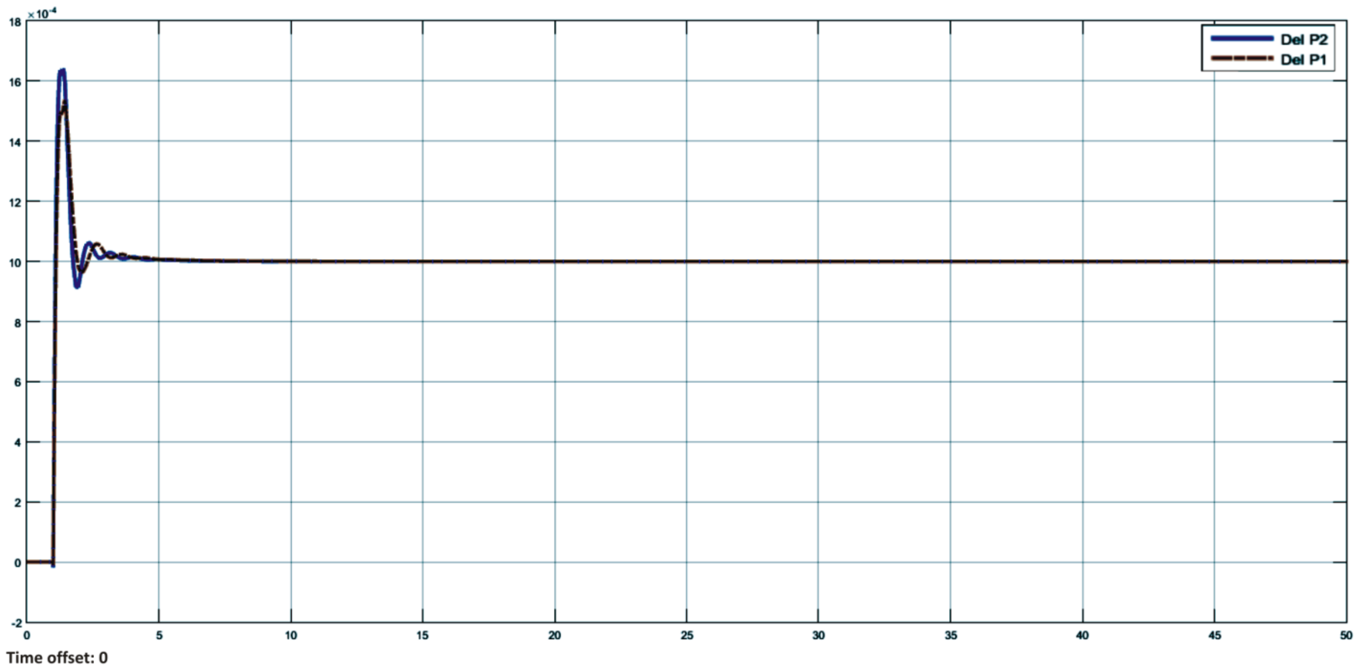

Figure 10: Change in power using a fuzzy logic controller

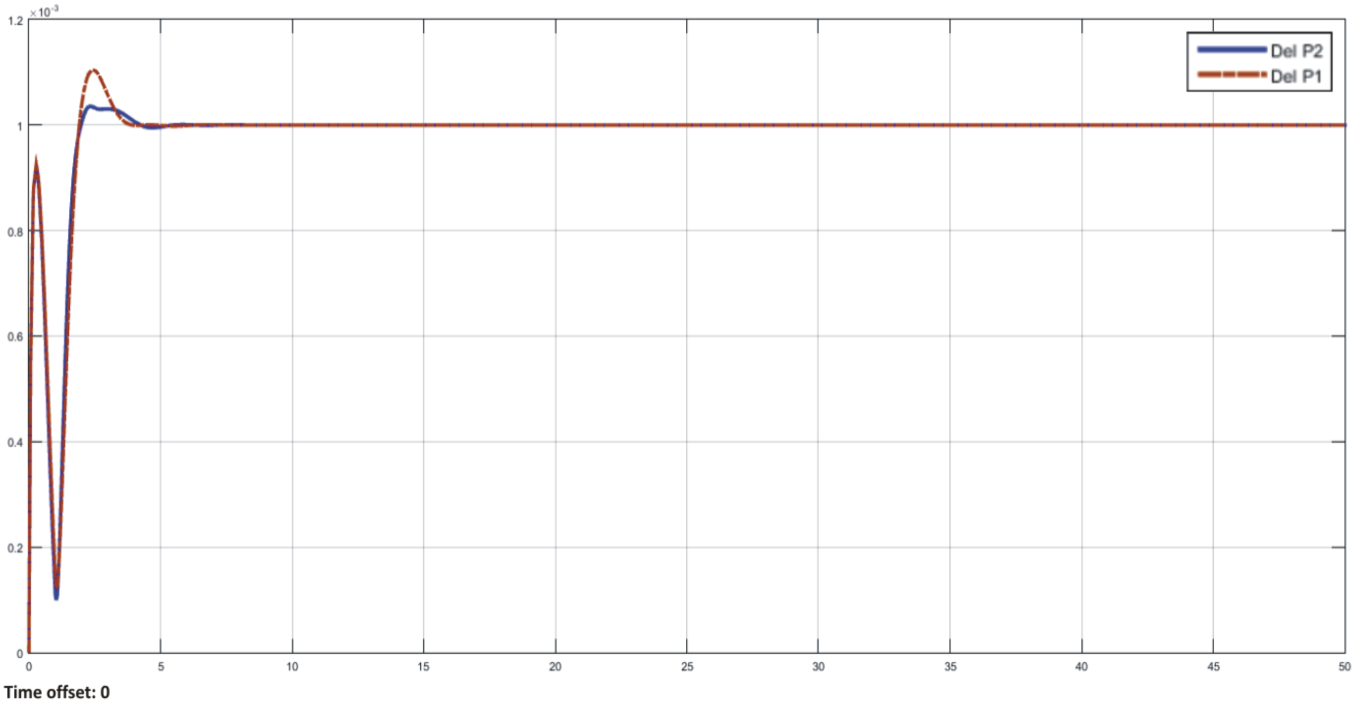

Figure 11: Change in power using a neuro-fuzzy controller

POWER DEVIATION IN TIE LINE

The power deviation graphs of the PI, fuzzy logic and neuro-fuzzy controllers (Figures 12 to 14) did not exhibit the same attributes. The PI controller results for power deviation showed that it took more time to reach a stable power deviation when compared with the fuzzy logic (Figure 13) and neuro-fuzzy controllers (Figure 14). The PI controller showed its lacks the ability to return back to a zero power deviation, while fuzzy logic and neuro-fuzzy controllers were able to return about to zero power deviations. The performance of the neuro-fuzzy controller showed that it has the capacity to stabilise power deviation of the hydro-thermal plant within a short period. However, it exhibited an abnormal feature at an early stage of trying to achieve stability in power deviation (Figure 14). This characteristic of the neuro-fuzzy controller is different from that of the fuzzy logic controller which showed an abnormal decrease in power deviation that was followed by an abnormal increase in power deviation (Figure 13). In addition, the fuzzy logic control exhibited more instability in power deviation before attaining its stability when compared with the neuro-fuzzy controller.

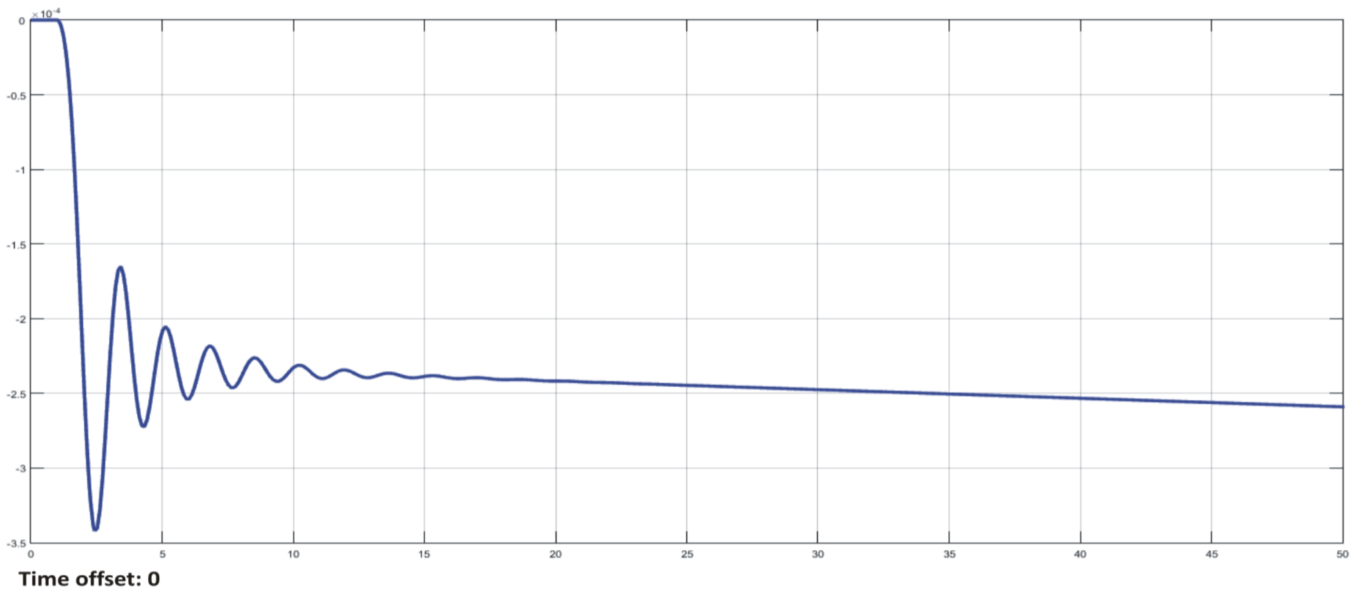

Figure 12: Power deviation in tie line using a PI controller

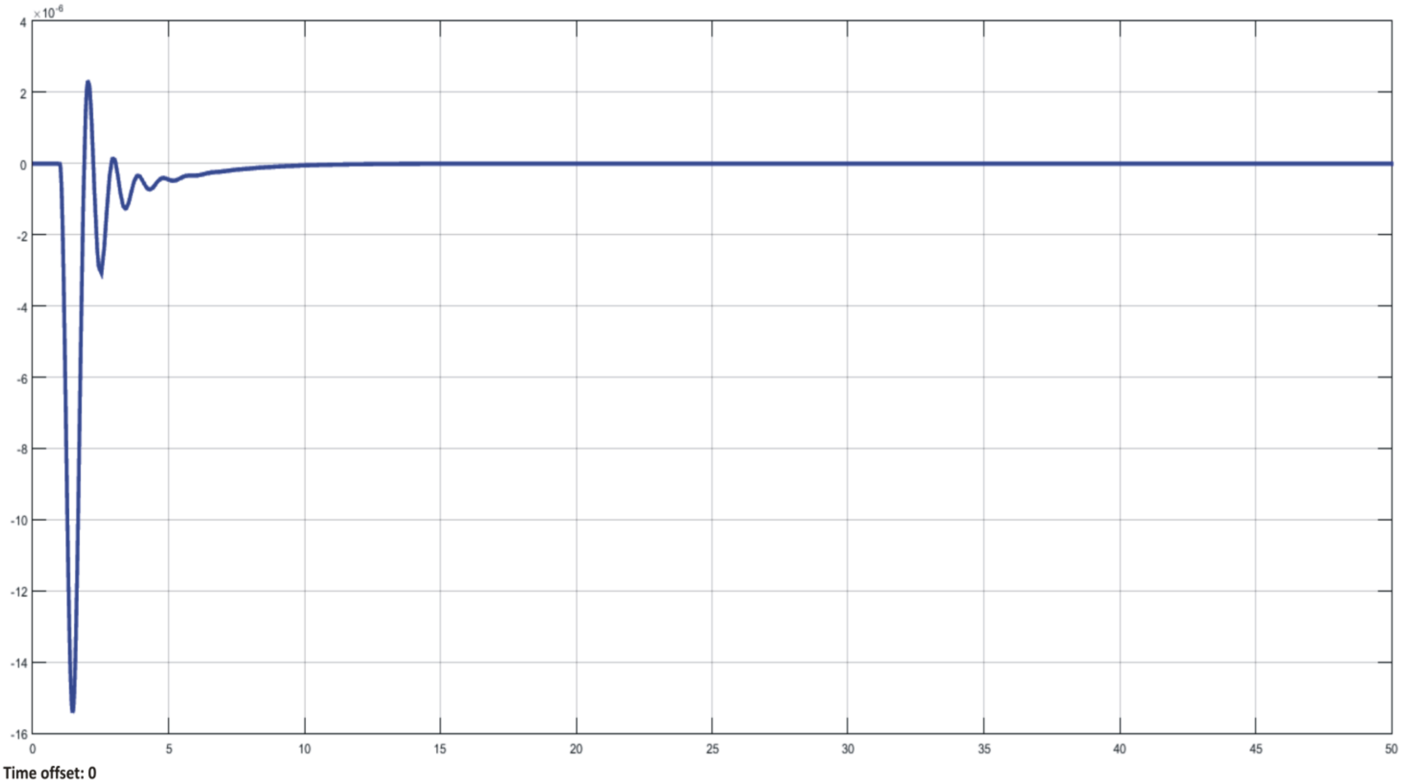

Figure 13: Power deviation in tie line using a fuzzy logic controller

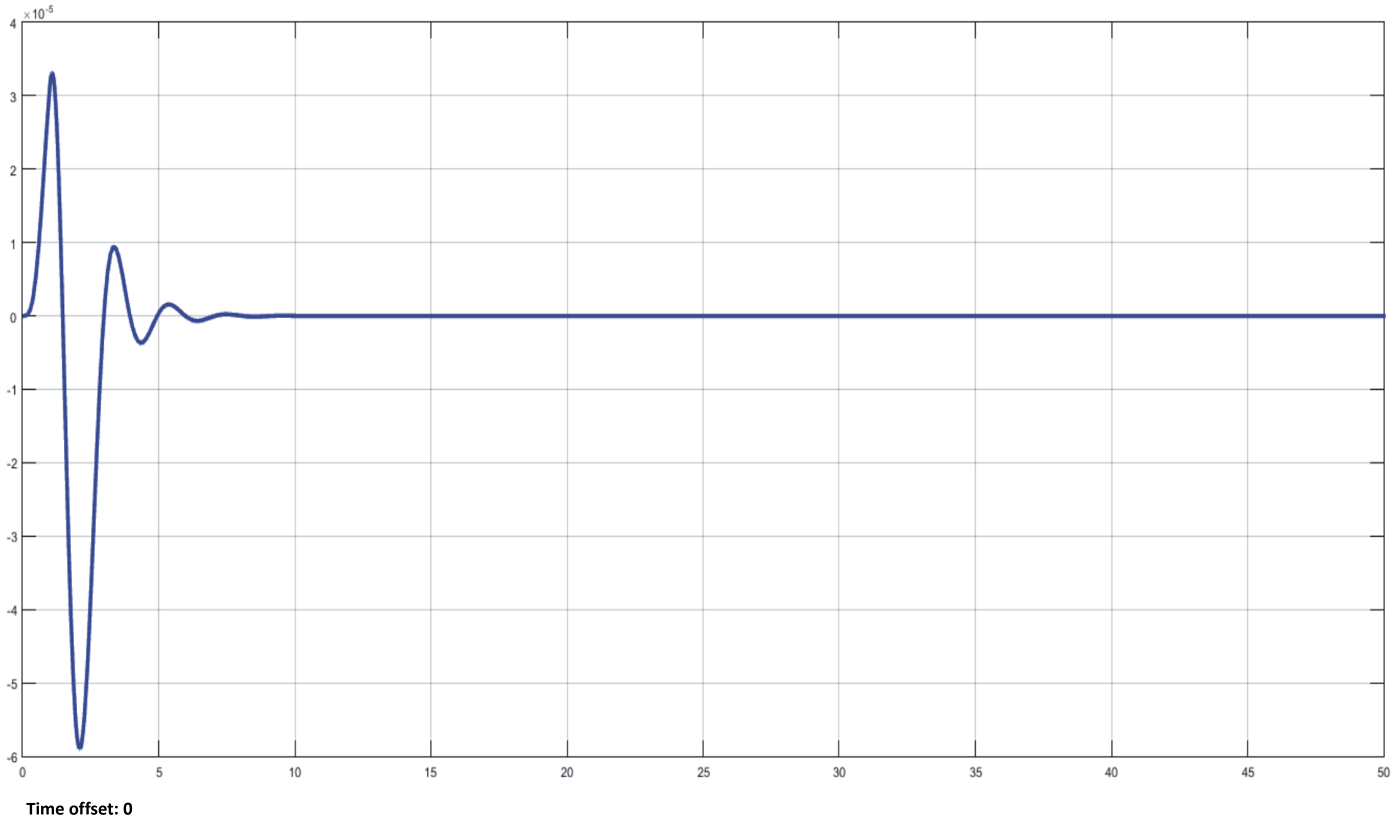

Figure 14: Power deviation in tie line using a neuro-fuzzy controller

Table 1: Comparative study of the transient response of different controllers

		ΔF			ΔP			ΔTie		
		Settling time (sec)	**Over shoot**	**Under shoot**	**Settling time (sec)**	**Over shoot**	**Under shoot**	**Settling time (sec)**	**Over shoot**	**Under shoot**
Neuro-fuzzy	A1	5.4	0.0032	0.0001	6.0	0.00104	0.0	7.0	0.000032	0.00016
	A2	4.5	0.0031	0.0002	5.0	0.00110	0.0			
Fuzzy logic	A1	8.4	0.0	0.0013	6.8	0.00165	0.1	7.5	0.000020	0.00006
	A2	8.2	0.0	0.0012	6.9	0.00154	0.2			
PI	A1	9.8	0.0	0.0033	14.4	0.00128	0.0	18.0	0.0	0.00034
	A2	9.7	0.0	0.0034	13.8	0.00132	0.0			

CONCLUSIONS

From the simulation results, it was observed that the chattering behaviour of neuro-fuzzy controller was in the time responses of tie-line power errors (especially at the beginning of simulation). The two reasons which can lead to chattering relate to the systems in canonical space; fast dynamics which were neglected in the ideal model and utilisation of digital controllers with finite sampling rate. The neuro-fuzzy controller uses training data from PI or fuzzy logic, in this study data was gotten from fuzzy logic model. Also, it was observed that deviations in frequency, power and tie line power for LFC can be controlled and returned to the preset valves. For a load disturbance of a two-area interconnected power system the deviation is not shared equally. The simulation results verified the robustness of the controller method LFC. The simulation results also show the superiority of the neuro-fuzzy controller in LFC to PI and fuzzy logic controllers in terms of settling time and overshoot percentage.

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