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# ANFIS method for mitigating impacts of communication delay on load frequency control

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***Abstract*— Load frequency control is one of the most important frequency management mechanisms in the modern power system (LFC). One of the unavoidable issues associated with LFC over a large area is communication delay. The delay may reduce system performance and cause system instability. This study proposes an alternative design approach for creating delay compensators for LFC in one or more control zones. A sufficient and required condition for designing a delay compensator for one-area LFC is stated. It is demonstrated that for multi-area LFC with area control errors (ACEs), if the index of coupling among the areas is less than the cutoff value established by the small gain theorem, each control area can have its own delay controller as in a one-area system. To demonstrate the effectiveness of the proposed technique, simulation studies on LFCs with communication delays in one interconnected area and multiple interconnected areas with and without time varying delays are used.**

***Keywords*— Communication delay, Delay margin, Load frequency control, Phase lead compensator***

## I. Introduction

Load frequency control (LFC) has been used to maintain the balance between load and generation in a designated control area in a large interconnected power system with various control areas spread across a vast territory [1,2]. Control signals are typically transmitted between remote terminal units (RTUs) and a control centre via dedicated communication channels in a typical centralised LFC system. In such a conventional control approach, the majority of prior research has ignored the issues caused by communication delays [3]. Furthermore, as the electricity market expands, the control procedures for ancillary services necessitate an open communication infrastructure capable of responding quickly to customers and utilities with significant information exchanges [4]. There has been much debate about how to effectively integrate all information in a deregulated and market setting, including control, processing, and communication. To meet these expanding control requirements, it is critical to provide an open architecture that fully accounts for communication delays. For example, as described in [4], a new communication mechanism for data sharing called Grid Stat has been established. The effects of communication delays should be carefully examined in order to keep the market and power system in this system secure and functional. A communication network, as shown in Fig. 1, always has a time delay, which affects the truthfulness and accuracy of information exchange and may degrade any control measures used to maintain the power grid [5]. Numerous research initiatives have recently been conducted [6-20] in an attempt to mitigate such negative effects. [6] investigated wide-area damping control of power system inter-area oscillations using a networked predictive control approach that accounts for feedback loop round-trip time delay.

A reliable PI controller was created for time delay correction in [7] and the LFC problem was stated as a restricted optimization problem. In [8], a single area LFC with time delays was designed using a controller using a genetic algorithm (GA). These methods, however, call for knowledge of the entire system. Thus, as the system size grows, the computational cost will also grow dramatically. The effectiveness of delay-involved LFC control design calculation was examined in [9]. By reducing the maximal order of the LMI as well as the number of choice factors, the calculation burden was greatly reduced. There have been concerns raised about the rebuilt model's ability to accurately capture the features of the original system. An event-trigger control approach was established in [10] to update the PI controller parameters for various communication delays. However, the characteristics of the system can influence how the PI control reacts.[11] proposed a model predictive controller and a Smith predictor-based controller for frequency restoration in an island microgrid to overcome communication channel delays. Delays in a broad area LFC system are typically measured in milliseconds to tens of milliseconds. LMI techniques have been widely used in recent years to address delay issues in LFC control. LMI-based control techniques, according to [12,13], are dependable in the face of communication hiccups and delays.

In [13], a brand-new Lyapunov-Krasovski function was used to produce less conservative results than Wirtinger's inequality. [14] used a different LMI technique to investigate the delay-dependent stability of an LFC scheme with constant and time-varying delays. To deal with time-varying delays, [15] presented a robust PID-type LFC control technique, and the delay margins for PI-type controllers in one-area and multi-area LFC schemes were obtained. [16] describes a delay margin estimation method for reliable LFC control. [17] describes a method for building a PID controller subject to LMI's optimum gain in order to improve dynamic response performance. [18] developed a robust predictive LFC control based on LMI that took into account lower computing complexity. Using the LMI approach in H control, [19] designed a delay-dependent controller for system stabilisation with multiple delays in various locations. Another LMI-based H controller design was described [20] for power systems with unpredictable delays and the upper delay boundary is known as constant values. However, an LMI-based technique only offers a stable situation that is sufficient. It is still unclear whether the system is stable or not if the LMI stability condition is not satisfied [21]. Finding a method to develop a controller that can satisfy the essential and sufficient conditions of stability is crucial. Additionally, when the system's number of areas increases, the design's complexity will also rise noticeably. Therefore, it is important to identify a method that can make the design process simpler in scenarios involving multiple areas. The following are some of this paper's contributions:

I. To begin, a conventional method is used to investigate the effect of delay on LFC in the frequency domain. In contrast to the LMI approach, a sufficient and necessary condition for developing a delay compensator for a one-area LFC scheme is presented. This condition is then applied to multiarea LFC schemes that cover a large area and have both constant and time-varying communication delays.

II. The effects of coupling between different areas linked by tie lines on frequency control and the design of the associated delay compensator are thoroughly investigated. If the index of coupling among the areas is less than the cutoff value established by the small gain theorem, it is demonstrated that the delay compensator for each control area can still be designed using a simplified method that requires only local system information [22].

The remainder of this paper is organised as follows: Section 2 examines models of single- and multiple-area LFC methods with communication delays. Section 3 describes the controller's design to mitigate the effects of communication latency. Section 4 conducts and presents simulation experiments to confirm the viability of the proposed approach. Section 5 discusses the implications of coupling between various regions in a power system with multiple control areas. The results are then presented in Section 6. Section 5 contrasts the proposed technique with LMI methods.

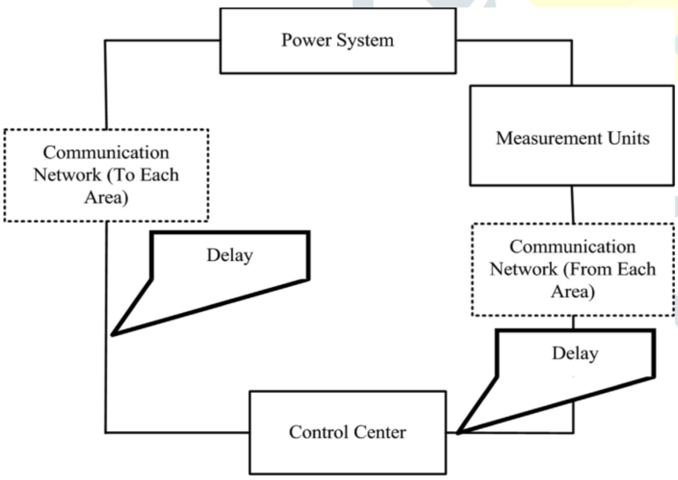


Fig. 1. Communication delay in LFC control.

## II. LFC SCHEMES WITH COMMUNICATION DELAYS

A large, networked power system may contain multiple control zones. A control area, also known as a balancing authority area, is in charge of balancing the load within its boundaries and providing real-time support for the area's interconnection frequency [1]. It consists of a collection of generation, transmission, and loads located within its boundaries. This section discusses dynamic models of single-area and multi-area LFC schemes with communication delays. When signal exchanges between the control centre and individual units, such as those for signal processing and control law updating between RTUs and the control centre, communication delays are common [15].

### 2.1 Single area LFC model

The dynamic model of a typical one-area LFC method is shown in Fig. 2. [1] includes a detailed illustration of a typical LFC design. The system state-space model is expressed as [14], where the delay $e^{-Ts}$ and delay compensator Gc are ignored.

$$\dot{x}(t) = Ax(t) + Bu(t) + F\Delta P_L(t) \qquad (1)$$

$$y(t) = Cx(t)$$

$$x(t) = \begin{bmatrix} \Delta\omega & \Delta P_e & \Delta P_m & \int ACE \end{bmatrix}^T$$

$$y(t) = [\Delta\omega]$$

$$A = \begin{bmatrix} \frac{-D}{M} & 0 & \frac{1}{M} & 0 \\ \frac{-1}{T_g R} & \frac{-1}{T_g} & 0 & \frac{-K_I}{T_g} \\ 0 & \frac{1}{T_{ch}} & \frac{-1}{T_{ch}} & 0 \\ \beta & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & \frac{1}{T_g} & 0 & 0 \end{bmatrix}^T$$

$$F = \begin{bmatrix} 0 & \frac{-1}{M} & 0 & 0 \end{bmatrix}^T$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$$

Where $u(t)$ is the control signal sent from the control center. Due to no tie-line power exchanges in the single area LFC scheme, the ACE signal is described as Eq.(2).

$$ACE = \beta\Delta\omega \qquad (2)$$

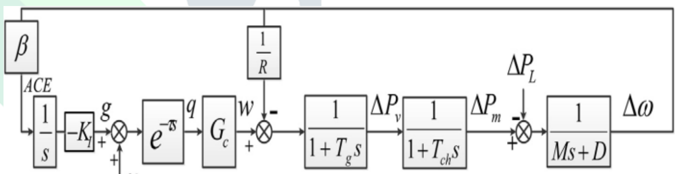


Fig. 2. Single area LFC scheme with communication delay.

### 2.2 Multi area LFC model

The dynamic model of a multi area LFC scheme with n control areas is shown in fig.3. the system state space model without considering the delay can be obtained as Eqs.(2)-(4).

$$\dot{x}(t) = Ax(t) + Bu(t) + F\Delta P_L(t) \qquad (2)$$

$$y(t) = Cx(t)$$

Where

$$x(t) = \begin{bmatrix} x_1 & \dots & \dots & x_n \end{bmatrix}^T$$

$$y(t) = \begin{bmatrix} y_1 & \dots & \dots & y_n \end{bmatrix}^T$$

$$u(t) = \begin{bmatrix} u_1 & \dots & \dots & u_n \end{bmatrix}^T$$

$$x_1(t) = \begin{bmatrix} \Delta\omega_1 & \Delta P_{vi} & \Delta P_{mi} & \int ACE & \Delta P_{tie1} \end{bmatrix}^T \qquad (3)$$

$$\Delta P_L(t) = \begin{bmatrix} \Delta P_{L1}(t) & \dots & \dots & \Delta P_{Ln}(t) \end{bmatrix}^T$$

$$A = \begin{bmatrix} A_{11} & . & . & A_{1n} \\ . & . & . & . \\ . & . & . & . \\ A_{n1} & . & . & A_{nn} \end{bmatrix}$$

$$B = diagB_i, C = diagC_i$$

$$F = diagF_i$$

$$B_i = \begin{bmatrix} 0 & \frac{1}{T_{gi}} & 0 & 0 & 0 \end{bmatrix}^T \quad (4)$$

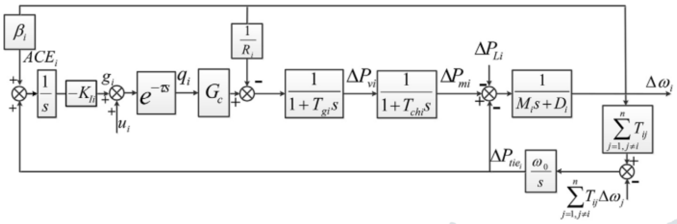

Fig. 3. Area I in a multi-area LFC scheme with communication delay.

## III. LOAD FREQUENCY CONTROL DESIGN WITH COMMUNICATION DELAY

The systems in Figs. 2 and 3 are linear time invariant (LTI) when there are no delays. As a result, a traditional approach can be used to investigate the effects of delay. A necessary and sufficient condition for the SISO system depicted in Figure 2 can be identified so that a controller can be designed to ensure the system's stability. A large power system with coupled control zones, which is frequently a multi-input, multi-output (MIMO) system, as shown in Fig. 3, presents analysis challenges. In this section, we will look at how several control regions interact in a multi-area LFC. If the coupling index between distinct areas is less than a certain threshold, the small gain theorem [22] is used to demonstrate and validate that the delay compensator for each control area can be developed independently, just as it would in a single one-area system (more discussions given later in this section).

## IV. SOFT COMPUTING /ARTIFICIAL INTELLIGENCE (AI) TECHNIQUES

The ability to process complex information is something that all evolving artificial intelligence (AI) techniques have in common. The AI approach completes all three-phase short circuit analysis offline, and the fault is quickly identified live.Different AI techniques, such as Expert Systems, Artificial Neural Networks (ANN), Fuzzy Logic, and evolutionary algorithms, were successfully used for all power system goals while outperforming traditional ones. Fuzzy logic is one of many AI-based methodologies that have been demonstrated to be useful and appealing for solving complex, ambiguous problems that would be difficult or prohibitively expensive to solve using traditional methods.

### 4.1 Fuzzy Logic Approach

An intelligent controller based on fuzzy logic is intended to help ensure smooth operation and reduce oscillation when a system is subjected to a sudden load change. The foundation for fuzzy controller is fuzzy logic, which is far more analogous to human thought and natural language than traditional logical systems.Traditional control approaches may not provide adequate results due to the complexity of the power system and the numerous changing situations. Fuzzy controllers, on the other hand, are useful in addressing a wide range of control issues due to their robustness and dependability. The following are some of the drawbacks of basic fuzzy rule-based expert systems:

- It is difficult to acquire knowledge.
- There is no adaptability, and thus it is unable to perform well in a dynamic time varying system due to system change.

### 4.2 ARTIFICIAL NEURAL NETWORK BASED TECHNIQUES

Significant advancements in ANN application have been accomplished during the past few years. This is because, unlike expert systems, neural networks, given suitable design and training, look for and detect patterns rather than relying on a knowledge (Rule) basis. A novel neural network was proposed by Chaturvedi et al. This neural network is known as a generalised neural network. The GNN was created by selecting different compensatory aggregation functions and threshold functions from the same neuron. Back propagation across time is used in this case to learn. The GNN controller has been demonstrated to be extremely suitable for rapidly controlling plant dynamics.

## V. LOAD FREQUENCY CONTROL USING ANFIS CONTROLLER

The Adaptive Network Based Fuzzy Inference System is a data-driven method for a neural network approach to function approximation problems (ANFIS). A training set of numerical samples of the unknown function to be approximated is frequently clustered to form the foundation of data-driven techniques for ANFIS network synthesis. ANFIS networks have been used successfully for categorization jobs, rule-based process control, pattern recognition, and other similar issues since their introduction. A fuzzy inference system is comprised of the fuzzy model developed by Takagi, Sugeno, and Kang to codify a methodical process for generating fuzzy rules from an input-output data set.


Fig. 4. simulation model of ANFIS function.

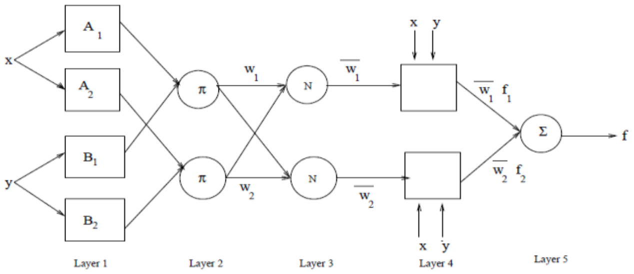


Fig. 5. Type-3 ANFIS Structure.

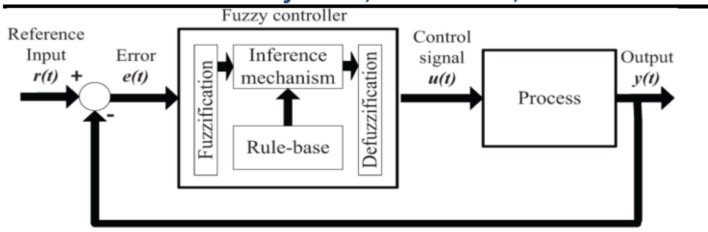


Fig. 6. Type-3 ANFIS Structure.

The fuzzy controller is made up of four major components: The knowledge is stored in the rule-base as a set of guidelines outlining the most effective methods of system management. Membership functions are used to quantify knowledge. After determining which control rules are relevant at the time, the inference process determines which ones should be activated for the plant's input. The fuzzification interface modifies the inputs so that they can be analysed and compared to the rules in the rule-base. The conclusions of the inference mechanism are converted into plant inputs via the defuzzification interface.

## V. SIMULATION RESULTS AND EXPERIMENTAL VALIDATION

The load is connected to the turbine and generator models via the simulation block, which is an integral controller and delay block with a compensator. The frequency change is repeated to the controller until it is minimal and equal to zero. The compensator compensates for the delay.
The outputs are linked to a variety of scopes, including ACE, dp, and dw. The integral controller is given a frequency bias factor of 20.8 and frequency change feedback. The governor and compensator are linked via the summing block by the governor's speed regulation droop coefficient of 0.05.

For a 0.2 p.u. load change ( $\Delta P_L$ =0.2 p.u.), the ACE signal and both display increasing oscillation amplitudes (green colour line), indicating that the system is unstable. With almost any oscillations, the suggested compensator can quickly reach the required value 0. The ACE signal also performs well, with an overrun of less than 0.01p.u. and a short settling period.

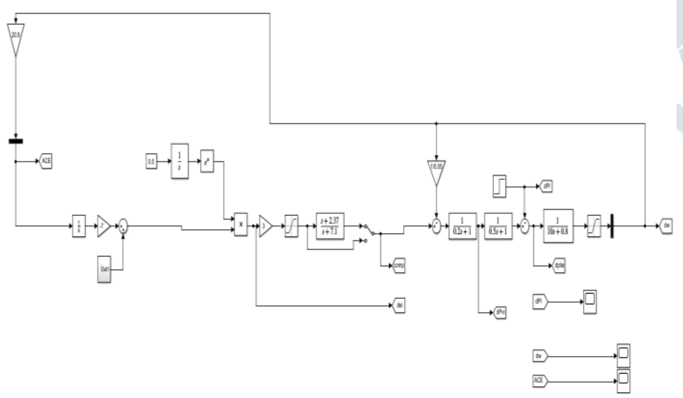

Fig. 7. Simulation block diagram for single area LFC with Integral controller.

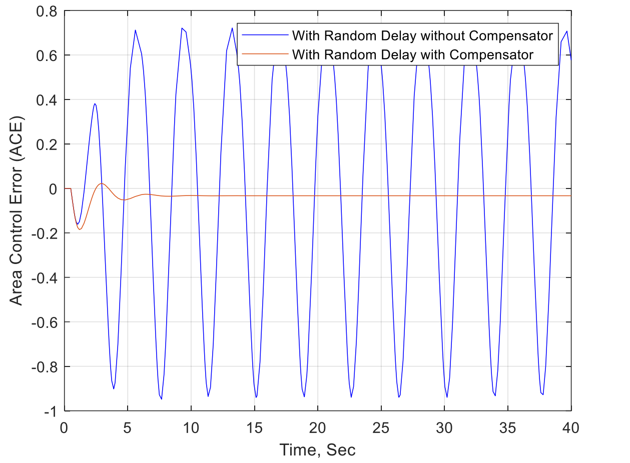


Fig. 8. ACE response of 0.5s delay following a 0.2 p.u. load change using Integral controller.

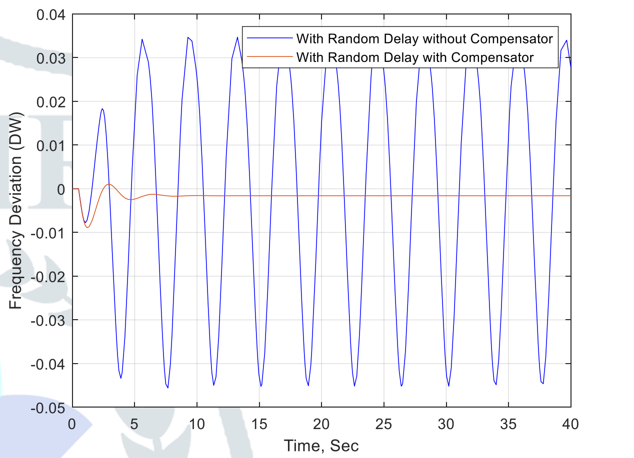


Fig. 9. $\Delta\omega$ response of 0.5s delay following a 0.2 p.u. load change using Integral controller.

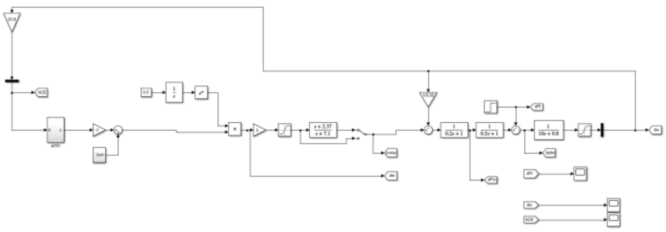

Fig. 10. Simulation block diagram for Single area LFC with communication delay with compensator using AFPI.

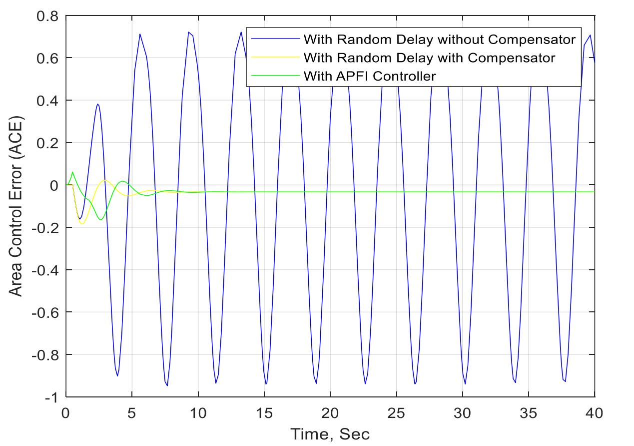


Fig. 11. ACE response of 0.5s delay following a 0.2 p.u. load change using Integral controller.

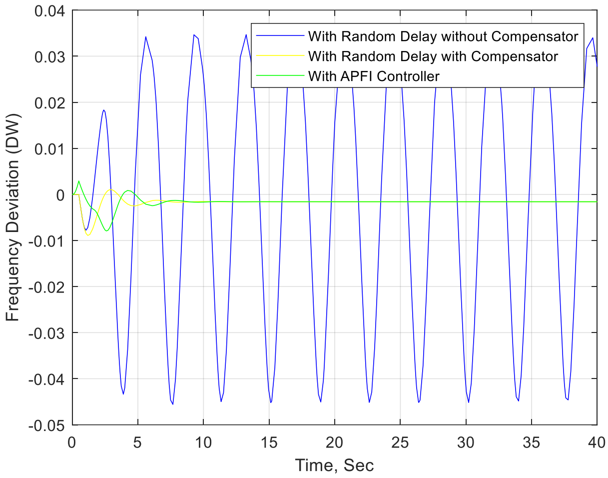


Fig. 12. $\Delta\omega$ response of 0.5s delay following a 0.2 p.u. load change using Integral controller.

The ANFIS and PI controllers are combined to form the AFPI (Adaptive Fuzzy Proportional Integral) controller. The proportional and integral controllers are connected to the ANFIS through a summing block. The turbine and generator models with the load are connected to the simulation block, which is an AFPI controller and delay block, with a compensation. The frequency change is sent back to the controller repeatedly until it is minimised and equal to zero. The delay is made up for by the compensator. The outputs are linked to a variety of scopes, including ACE, dp, and dw.

The AFPI controller receives feedback from the frequency bias factor 20.8 and frequency change. The governor's speed regulation droop coefficient of 0.05 is coupled to the compensator and governor via the summing block.

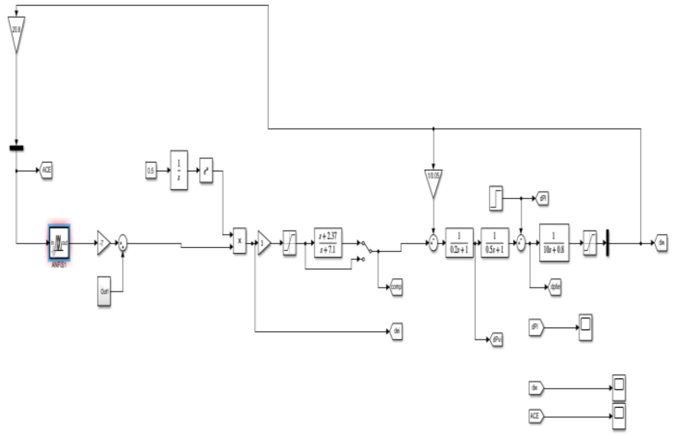

Fig. 13. Simulation block diagram for Single area LFC with communication delay with compensator using Anfis

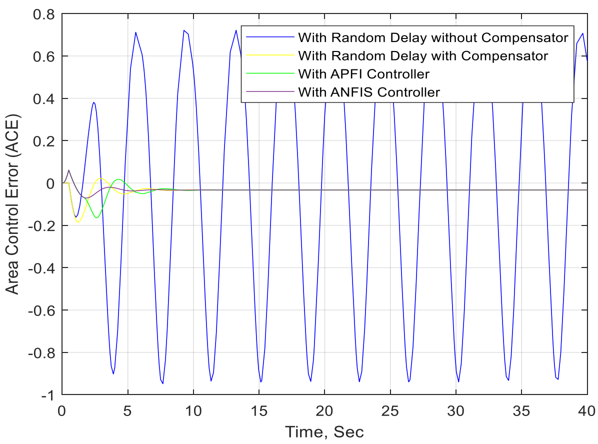


Fig. 14. ACE response of 0.5s delay following a 0.2 p.u. load change using AFPI and ANFIS controllers.

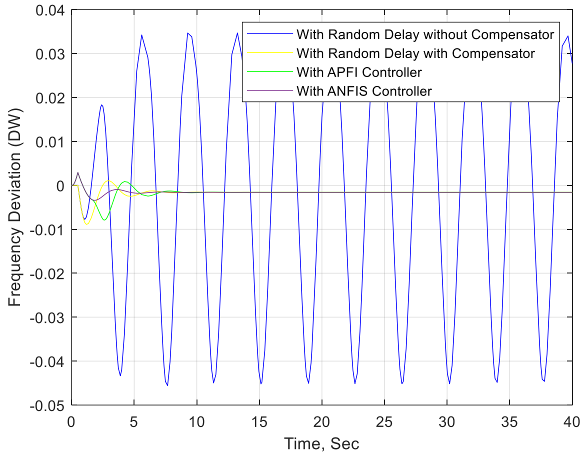


Fig. 15. $\Delta\omega$ response of 0.5s delay following a 0.2 p.u. load change using AFPI and ANFIS controllers.

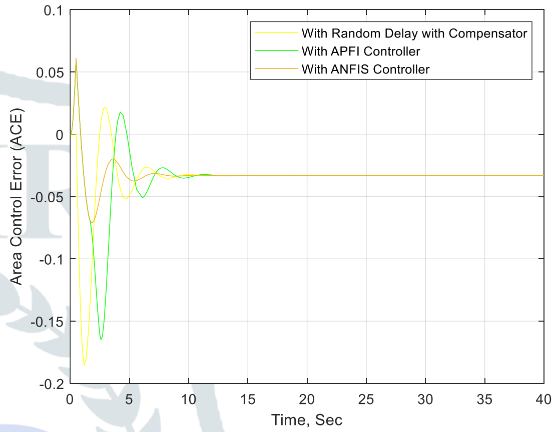


Fig. 16. ACE response of 0.5s delay following a 0.2 p.u. load change using AFPI and ANFIS controllers.

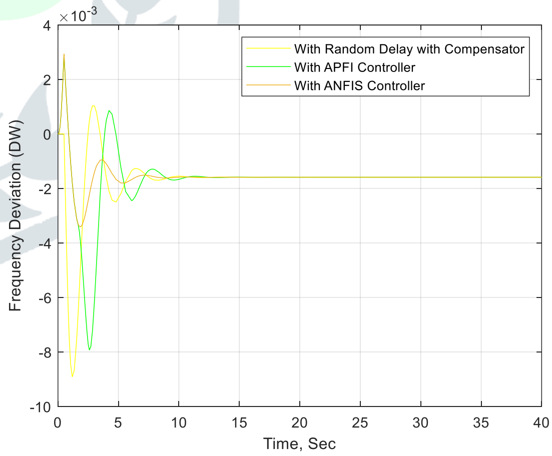


Fig. 17. $\Delta\omega$ response of 0.5s delay following a 0.2 p.u. load change using AFPI and ANFIS controllers.

The load is coupled to the turbine and generator models, which are coupled to the simulation block, which is a FIS controller and delay block. The frequency change is repeated to the controller until it is minimal and equal to zero. The compensator compensates for the delay. The outputs (ACE, dp, and dw) are linked to scope.

The comparison results with droop, PI and PSO-FOPID controllers are shown in figs.12 to 15. From these results it is concluded that the proposed PSOFOPID controller is effectively damping the oscillations and controlling the power sharing without over loading the generators as well as battery.

## VI. CONCLUSIONS

This initiative proposes a new method for developing delay compensators for LFC schemes with multiple locations and communication delays. The recommended method, unlike LMI methods, provides both a necessary and sufficient condition (i.e., /c) for developing a delay compensator for a single-area LFC scheme. During the investigation, multi-area LFC projects were also developed to cover a larger area. ANFIS is used to create controllers for individual areas/subsystems in a multi-area system while maintaining overall system stability. The small gain theorem was used to develop the AFPI controller criteria.

If the criteria are met, the design process for delay compensators can be greatly streamlined because each section only needs to address its own time delay. The proposed technique has been validated through simulation testing for single-area and multi-area LFC systems subject to random delays. There have been discussions contrasting this strategy with traditional LMI methods. The couplings between different control regions have been investigated further in order to prepare for the implementation of the proposed strategy in bulk power systems..

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