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Controlling the Mitigating Impacts of Communication Delay on Load Frequency Control with an Adaptive Method

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Abstract: Load Frequency Control is one of the most essential frequency management technologies in modern power systems (LFC). When employing LFC over a vast region, communication latency is unavoidable. A delay might not only affect system performance but also cause system instability. An alternate design strategy for constructing delay compensators for LFC in one or more control areas utilising an AFPI controller and ANFIS is proposed in this paper. For one-area LFC, a sufficient and required condition for designing a delay compensator is described. It is demonstrated that for multi-area LFC with Area Control Errors (ACEs), each control area can have its own delay controller designed as if it were a one-area system if the index of coupling among the areas is less than the small gain theorem's threshold value. The effectiveness of the proposed technique is validated by simulation experiments on LFCs with communication delays in one and multiple interconnected areas with and without time variable delays.

Keywords:
Communication delay, Delay margin Load Frequency Control, Small gain theorem, Phase lead compensator

I. INTRODUCTION

Load frequency control (LFC) has been widely used to maintain the balance of load and generation in a specific control area as well as a large interconnected power system with numerous control areas distributed across a broad territory [1,2]. Dedicated communication channels were used in a typical centralised LFC configuration to deliver control signals between Remote Terminal Units (RTUs) and a control centre. Previous study has neglected the difficulties caused by communication delays in such a common control mechanism [3].Furthermore, as the energy market evolves, the control mechanisms involved in auxiliary services demand an open communication infrastructure capable of responding quickly to clients and utilities while exchanging massive volumes of information [4]. The issue of how to correctly integrate all information, such as control, processing, and communication, in a deregulated and market environment has received a lot of attention. It is vital to have an open architecture that overcomes communication delays in order to support such expanding control needs. For example, as indicated in [4], a new data interchange communication mechanism known as Grid State has been established. The consequences of communication delays should be recognised and adequately analysed in this system in order to maintain a secure and successful electricity system and market. Time delay is always present in a communication network, influencing the truthfulness and accuracy of information flow and may damage any control measures used to stabilise the power grid [5]. Various research initiatives have recently been carried out in order to alleviate such harmful ramifications. Several research endeavours have recently been undertaken in order to mitigate such negative consequences [6]. Looked into a networked predictive control technique for wide-area damping management in power system inter-area oscillations, taking into consideration the feedback loop's round-trip time delay.

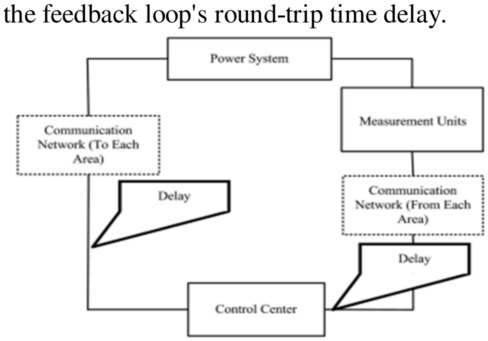

Fig.1. Communication delay in LFC control.

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These delays are typically in the millisecond to tens of millisecond range, which is small in comparison to the delays that can occur in a wide area LFC system. Linear Matrix Inequality (LMI) approaches have been widely used in recent years to overcome delay issues in LFC control. In [12, 13], LMI-based control approaches were proposed and claimed to be resilient in the face of communication delays and failures. A unique Lyapunov-Krasovski function was used to provide a less conservative solution than Wirtinger's inequality. An additional LMI approach was utilised to explore the delay-dependent stability of an LFC scheme with fixed and variable delays. In, the delay margins for PI-type controllers in one-area and multi-area LFC systems were established using a robust, multi-area LFC methodology. The remainder of this paper is organised as follows: The second section looks at models of one-area and multi-area LFC systems with communication delays. Section 3 explains how to build a controller to compensate for the impacts of communication delays. Section 4 outlines simulation tests that were carried out to validate the efficacy of the proposed technique.

II. LFC SCHEMES WITH COMMUNICATION DELAYS

A big integrated power system can have multiple control areas. A control area, also known as a balancing authority area, is in charge of keeping the area's load balanced and supporting the region's interconnection frequency in real time [1]. It is made up of a collection of generation, transmission, and load assets under its supervision. This section investigates dynamic models of single-area and multi-area LFC methods with communication delays. When signals are conveyed between the control centre and individual units, such as when telemetered signals are transferred between RTUs and the control centre for signal processing and control rule updating [15], communication delays are typical. For the sake of analysis in both one-area and multi-area LFC approaches [3,] all delays are treated as an overall equivalent delay in this study.

A. *One-area LFC model*

The dynamic model of a typical one-area LFC scheme is depicted in Fig 2. [1] Includes a detailed illustration of a typical LFC design. The system state-space model is as follows, without taking into consideration the delay $e^{-\tau s}$and the delay compensator G_C: [14]:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + F\Delta P_L(t) \\ y(t) = Cx(t) \end{cases} \qquad (1)$$

$$x(t)= [\Delta\omega \quad \Delta P_v \quad \Delta P_m \int ACE]^T$$

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

$$A = \begin{bmatrix} -D/M & 0 & 1/M & 0 \\ -1/T_g R & -1/T_g & 0 & -k_1/T_g \\ 0 & 1/T_{ch} & -1/T_{ch} & 0 \\ \beta & 0 & 0 & 0 \end{bmatrix}$$

$$B= [\, 0 \quad 1/T_g \quad 0 \quad 0]^T$$

$$F= [\, 0 \quad -1/M \quad 0 \quad 0]^T$$

$$C= [\, 1\ 0\ 0\ 0]$$

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

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

Where β = + 1/R D. The total equivalent communication delay is represented as $_e$-τs in Fig. 2. By defining a new virtual state q, as shown in Fig. 2, the following equations can be obtained:

$$q(t)= [\, 1\ 1\,]\begin{bmatrix} g(t-\tau) \\ u(t-\tau) \end{bmatrix}$$

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$$= [1\ 1]\begin{bmatrix} C''(t-\tau) \\ u(t-\tau) \end{bmatrix} \qquad (3)$$

$$C'' = [0\ 0\ 0 - K_I]$$

In addition, the state-space representation of the controller Gc, which is to be designed in Section 4.1, can be written as:

$$\begin{cases} \dot{z}(t) = A_c Z(t) + B_c q(t) \\ \omega(t) = C_c Z(t) + D_c q(t) \end{cases} \qquad (4)$$

The delayed system including the compensator can be written as Eq. (5):

$$\begin{cases} \dot{f}(t) = A' f(t) + A_d f(t-\tau) + A_d f(t-\tau) + F' \Delta P_L(t) \\ y(t) = C' x(t) \end{cases} \qquad (5)$$

Where

$$f(t) = \begin{bmatrix} x(t) \\ z(t) \end{bmatrix} A' = \begin{bmatrix} A & BC_c \\ 0 & A_c \end{bmatrix}$$

$$A_d = \begin{bmatrix} BD_c C'' & 0 \\ B_c C'' & 0 \end{bmatrix}$$

$$B' = \begin{bmatrix} BD_c \\ B_c \end{bmatrix} \qquad (6)$$

$$F' = \begin{bmatrix} F \\ 0 \end{bmatrix}$$

$$C' = [C''\ \ 0]$$

A one-area LFC's transfer function can be easily determined by describing it as a Single-Input-Single-Output (SISO) system. Later in the controller design process, a frequency domain study will be undertaken to reduce the impact of delay. The delay compensator, seen in Fig. 2, is meant for the complete system, which includes an integral controller (i.e., I controller) utilised in the LFC to help with frequency regulation.

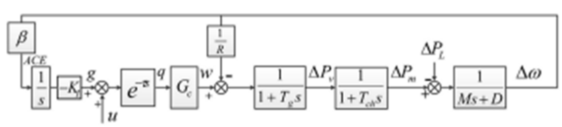

Fig.2. One − area LFC scheme with communication delay:

It makes no difference if the original system employs a different form of controller, such as a PI or PID controller, for the delay compensator design. 2.2. Multiple-area LFC model. The dynamic model of a multi-area LFC method with n control regions is depicted in Fig. 3 Eq. (7)–(9), [10]: The system state space model can be obtained without taking the delay into account.

$$\begin{cases} \dot{x}(t) = Ax(t) + u(t) + F\Delta P_L(t) \\ y(t) = Cx(t) \end{cases} \qquad (7)$$

Where

$$\dot{x}(t) = [\Delta\omega_i \Delta P_{vi} \Delta P_{mi} \int ACE\ \Delta P_{tiei}]^T$$

$$y_i(t) = [\Delta\omega_i] \qquad (8)$$

$$\Delta P_L(t) = [\Delta P_{L1}(t)\ \ \ldots \Delta P_{Li}(t) \ldots \Delta P_{Ln}(t)]^T$$

$$A=\begin{bmatrix} A_{11}\cdots A_{1i}\cdots A_{1n} \\ \vdots \ \ddots \ \vdots \ \ddots \ \vdots \\ A_{i1}\cdots A_{ii}\cdots A_{in} \\ \vdots \ \ddots \ \vdots \ \ddots \ \vdots \\ A_{n1}\cdots A_{ni}\cdots A_{nn} \end{bmatrix}$$

F= diagF_i, B_i = [0 1/T_{gi} 0 0 0 $]^T$

$$A_{ii} = \begin{bmatrix} -D_i/M_i & 0 & 1/M_i & 0 & -1/M_i \\ 1/T_{gi}R_i & 1/T_{gi} & 0 & -K_{Ii}/T_{gi} & 0 \\ 0 & 1/T_{chi} & 1/T_{chi} & 0 & 0 \\ \beta_i & 0 & 0 & 0 & 1 \\ E_i & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$A_{ij} = \begin{bmatrix} 0 & 0000 \\ 0 & 0000 \\ 0 & 0000 \\ 0 & 0000 \\ -\omega_0 T_{ij} & 0000 \end{bmatrix}$$

$$F_i = [0 \ \frac{1}{M_i} \ 0\ 0\ 0]^T$$

$$C_i = [1\ 0\ 0\ 0\ 0\ ]$$

$E_i = \omega_0 \sum_{j=1,j\neq 1}^{n} T_{ij}$

In a multi-area system, notations are similar to those used in one-area LFC, but with subscript I for Area i. Subscript j denotes signals from another area (the jth area) that is linked to area I through a tie line. All control zones are identified by the numbers 1, 2... n. The ACE signal can be written as:

$ACE_i = \ \Delta P_{tiei} + \beta_i \Delta\omega_i$

The delayed system with n sub-areas can be represented as Eq (10):

$$\begin{cases} \dot{f}(t) = A'f(t) + \sum_{\iota=1}^{n} A_{d\iota} f(t-\tau_\iota) \ B'u(t-\tau_\iota) + F'\Delta P_L(t) \\ y(t) = C'x(t) \end{cases} \quad (10)$$

Where

$A_{di} = diag[0 \ldots \begin{bmatrix} B_i D_{ci} C_i^" & 0 \\ B_{ci} C_i^" & 0 \end{bmatrix} \ldots 0]$

U(t)= [$u_1 \cdots u_i \cdots u_n]^T$

$C_i' = \mathrm{diag}\,[C_i']$

$C_i' = [C_i^" \ 0], C_i^" = [0 \ \ 0 \ \ 0 \ \ {-K_{Ii}} \ \ 0]$

B’ = diag [$B_1^, \cdots B_i^, \cdots B_n^,$]

Other notations are the same as those in Eq. (6) with subscript i indicating area i..

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III. LOAD FREQUENCY CONTROL DESIGN WITH COMMUNICATION DELAY

Systems shown in Figs. 2 and 3 are Linear Time Invariant (LTI) systems when delays do not present. As a result, the impact of delay can be assessed using a traditional method. For the SISO system depicted in Fig. 2, a necessary and sufficient condition for constructing a controller to ensure system stability may be achieved. Analyzing a big power system with coupled control areas, which is in general a Multi–Input–Multi–Output (MIMO) system, as shown in Fig. 3, is difficult. This section discusses the relationships between multiple control regions in a multi-area LFC. The small gain theorem [22] is used to demonstrate and verify that the delay compensator for each control area can be designed separately as if it were a single one-area system if the coupling index between various areas is less than a certain value (more discussions given later in this section).

A. Delay Margin

For a SISO LTI and open-loop stable system, its transfer function is assumed to be G(s) and the frequency response is G (jω) when there is no delay. If the gain crossover frequency of this delay-free system is ω_c, the corresponding phase margin will be $\varphi_\omega = \angle + {}^\circ$ (180) $j\omega_c$ .When a delay of τ is introduced to the open-loop system, the delay does not change the gain curve, and hence the new gain crossover frequency of the system is still ω_c. Nevertheless, the delay introduces an extra phase lag of $-\tau\omega_c$, at ω_c, leading to a new phase margin, $\varphi_{new} = \varphi_\omega - \tau\omega c$.

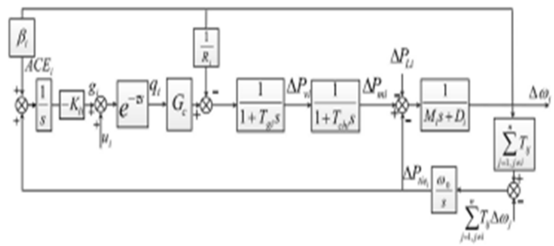

Fig.3. Area i in a multi – area LFC scheme with communication delay.

B. Compensator Design for One-area LFC with Communication Delay

The SISO system depicted in Fig. 2 is a one-area LFC scheme. The system's communication delay can be treated as one equivalent delay in the transmission of ACE [14]. Let G(s) denote the open loop system transfer function and the delay compensator. G(s) can be calculated using its state space model in Eq (1). Let $e^{-\tau s}$ represent the communication delay and Gc(s) represent the compensator to be designed. As an illustration, the design of a phase lead compensator is shown below. The phase lead compensator structure for system G(s) can be written as

$$G_c(s) = \propto \frac{s+1/\propto T}{s+1/T} \qquad (11)$$

Denoting $\varphi_{\varphi d}$ as the desired phase margin, $\varphi_{\varphi u}$ as the uncompensated phase margin, and $\varphi_{\varphi s}$ as the safety factor, α can be calculated based on Eq. (12) [24]:

$$\propto = \frac{1+sin\varphi}{1-sin\varphi} \qquad (12)$$

The frequency ωm is identified, the compensator G_c (s) can be calculated based on

$$\frac{1}{T} = \sqrt{\alpha}\omega_m$$

C. Multi-area LFC with Communication Delays

Due to different load changes in different areas and tie-line power interactions, the controller design in a multi-area LFC scheme becomes a MIMO system-based design, and the couplings among individual areas must be carefully studied. On the one hand, because different control areas are linked together via tie-lines, changes in load in one area will have an effect on the other areas. Furthermore, each area has its own ACE-based control, with one of the control objectives being to keep power flows at a constant level along the tie-lines. In other words, until a new set of tie-line power references is issued, each control area is controlled to take care of its own load changes under a certain equilibrium point. As a result, if different areas are “not strongly coupled,” the delay compensator design procedure for a MIMO system can still be the same as that developed for the one-area LFC scheme.

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It is worth noting that later in this section, a criterion (the condition of Eq (18)) will be developed to determine whether the areas in a multiarea system are strongly coupled or not. . Many multi-area systems with highly integrated areas via tie lines, as discussed in Sections 4 and 5, meet the criterion of Eq (18). That is, if the condition of Eq (18) is met, the delay compensator for each control area can still be designed independently. Taking a two-area LFC scheme for instance, a more generic diagram representation is shown in Fig. 5. H12 and H21 are the feedback transfer functions from Δω1 to Area 2 and Δω2 to Area 1, respectively. The relationship between the inputs u and outputs y can be found in Eq (13)

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = P_2 \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} - M_2 \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \qquad (13)$$

Where

$$M_2 = \begin{bmatrix} G_1 G_{c1} e^{-\tau_1 s} H_{11} & G_1 G_{c1} e^{-\tau_1 s} H_{21} - C_{21} \\ G_2 G_{c2} e^{-\tau_2 s} H_{12} - C_{12} & G_2 G_{c2} e^{-\tau_2 s} H_{22} \end{bmatrix}$$

$$P_2 = \begin{bmatrix} G_1 G_{c1} e^{-\tau_1 s} & 0 \\ 0 & G_2 G_{c2} e^{-\tau_2 s} \end{bmatrix}$$

The closed-loop transfer function of the two-area LFC scheme can be obtained as:

$$Y=(I+M_2)^{-1} P_2 . u \qquad (14)$$

The stability criteria of system in Eq (14) is that $[I+M_2]^{-1}$ is stable, since P2 is stable.

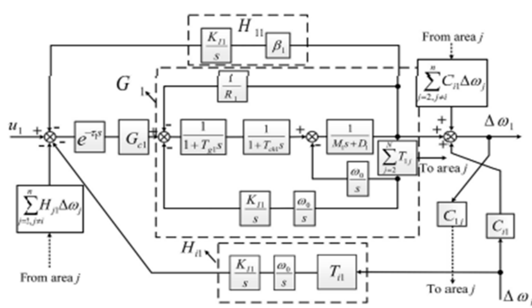

Fig.4. Area 1 to the ith area of a multi – area LFC scheme.

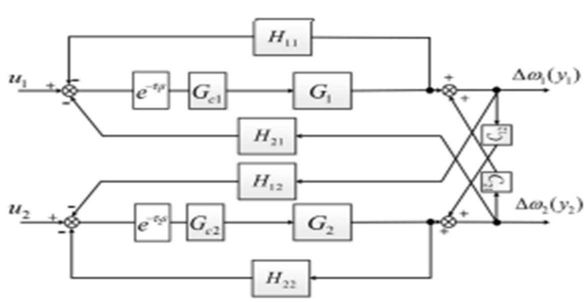

Fig.5. A generic two – area LFC scheme

$$(I+M_2)^{-1} = \left(\begin{bmatrix} 1 + G_1 G_{c1} e^{-\tau_1 s} H_{11} & 0 \\ 0 & 1 + G_2 G_{c2} e^{-\tau_2 s} H_{22} \end{bmatrix} + \begin{bmatrix} 0 & G_1 G_{c1} e^{-\tau_1 s} H_{21} - C_{21} \\ G_2 G_{c2} e^{-\tau_2 s} H_{12} - C_{12} & 0 \end{bmatrix} \right)^{-1}$$

Let

$$N_2 = \begin{bmatrix} 1 + G_1 G_{c1} e^{-\tau_1 s} H_{11} & 0 \\ 0 & 1 + G_2 G_{c2} e^{-\tau_2 s} H_{22} \end{bmatrix}$$

$$\Delta_2 = \begin{bmatrix} 0 & G_1 G_{c1} e^{-\tau_1 s} H_{21} - C_{21} \\ G_2 G_{c2} e^{-\tau_2 s} H_{12} - C_{12} & 0 \end{bmatrix}$$

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Define the coupling index I2 of this two-area LFC scheme as − || Δ || N2 ∞ I_2 . In order to determine the stability of (14),

$$I_2 = \|N_2^{-1}\Delta_2\|_\infty < 1 \qquad (15)$$

Should be satisfied [25].

Eq. (15) can be further written as Eq. (16)

$$\|N_2^{-1}\Delta_2\|_\infty \leq \|N_2^{-1}\|_\infty . \|\Delta_2\|_\infty \leq 1 \qquad (16)$$

Thus, the stability criterion of system in Eq (14) is Eq. (17):

$$\|\Delta_2\|_\infty < \frac{1}{\|N_2^{-1}\|_\infty} \qquad (17)$$

The discussion on the two-subsystem system can be extended to a multi-area system (e.g., an n-area LFC scheme). The coupling index

$$I_n = \|N_n^{-1}\Delta_n\|_\infty < 1 \qquad (18)$$

or equivalently

$$\|\Delta_n\|_\infty < \frac{1}{\|N_n^{-1}\|_\infty} \qquad (19)$$

Where

$$N_n = diag\,[1 + G_i G_{ci} e^{-\tau i s} H_{ii}]$$

$$\Delta_n = \begin{bmatrix} 0 & \cdots G_n G_{cn} e^{-\tau_1 s} H_{n1} - C_{n1} \\ \vdots & \ddots \quad \vdots \\ G_i G_{ci} e^{-\tau_1 s} H_{1i} - C_{1i} & \cdots G_n G_{cn} e^{-\tau_1 s} H_{n1} - C_{n1} \\ \vdots & \ddots \quad \vdots \\ G_n G_{cn} e^{-\tau_n s} H_{1n} - C_{1n} \cdots & 0 \end{bmatrix}$$

IV. ANFIS CONTROLLER

*Adaptive Neuro Fuzzy Inference System*is an adaptable neuro-soft assurance mastermind or adaptable structure based fleecy thinking framework (ANFIS) is a kind of fraud neural structure that relies on Takagi– Sugeno cushy enlistment organizes. The system was made in the mid-1990s. Since it forms both neural frameworks and padded introduce measures, it can get the upsides of both in a lone structure. Its enlistment form considers to a procedure of padded IF– THEN picks that have learning ability to incorrect nonlinear limits. Thusly, ANFIS is acknowledged to be an entire estimator. For using the ANFIS as somewhat of a more productive and perfect way, one can use the best parameters obtained by innate calculation.

ANFIS is a class of adaptable systems that are in every practical sense indistinct to fluffy surmising structures.

1) *ANFIS* address Sugeno e Tsukamoto padded models.
2) *ANFIS* uses a mutt getting the hang of figuring.

The fundamental thought of neuro-fuzzy structures is that they are regardless of what you look like at it approximates with the ability to ask for interpretable IF-THEN rules. The possibility of neuro-delicate structures wires two clashing necessities in cushy showing up: interpretability versus precision. Inside and out that truly matters, one of the two properties wins. The neuro-warm in padded demonstrating research field is isolated into two zones: semantic delicate exhibiting that is centred around interpretability, generally the Mamdani show; and right fuzzy showing that relies upon precision, in a general sense the Takagi-Sugeno-Kang (TSK) delineate. Tending to fuzzification, fuzzy inciting and defuzzification through multi-layers feed-forward connectionist structures.

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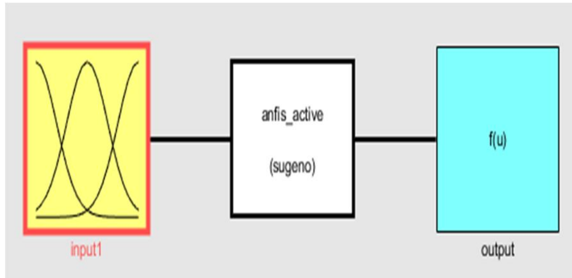

Fig.4.1 simulation model of ANFIS

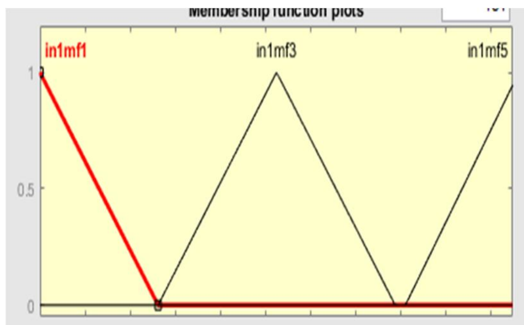

Fig.4.2 Input

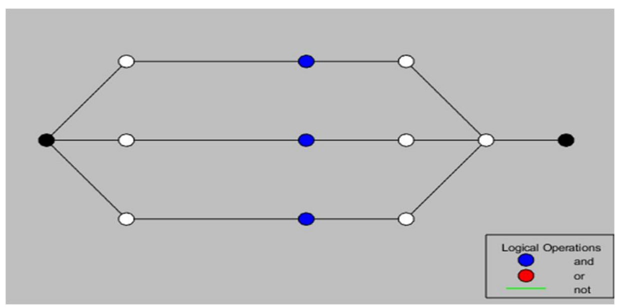

Fig.4.3 ANFIS Structure

V. SIMULATION RESULTS

A. Simulation Results with System Delay and Compensator

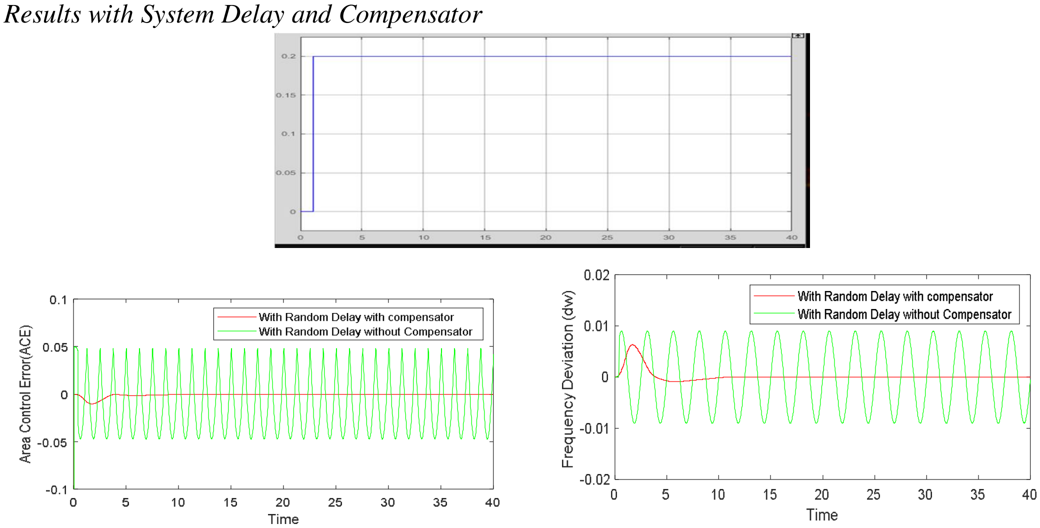

Fig.5.1.1 one area system response of 0.5s delay following a 0.2 p.u.load change using proposed compensator and without compensator

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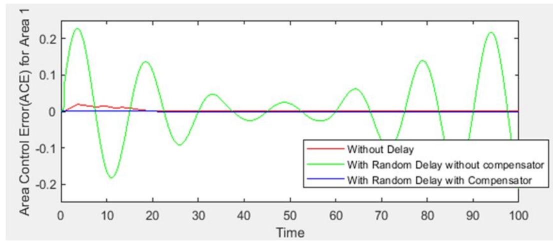
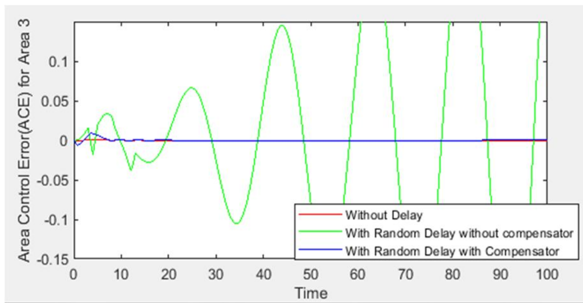
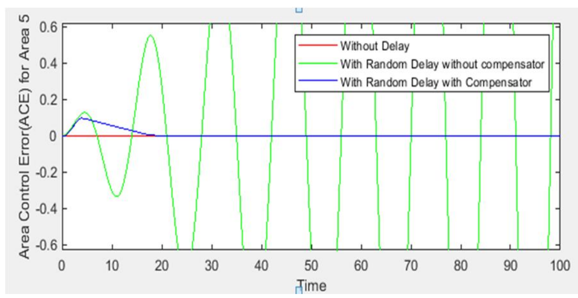
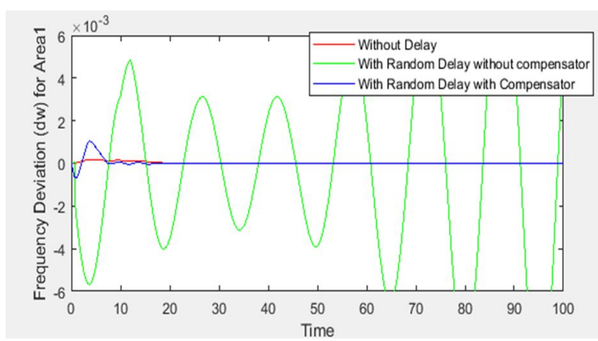
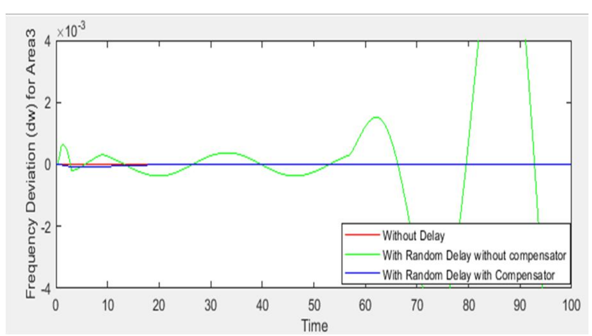
Fig.5.1.2 represents a scenario in which there are communication delays in all five domains. Increasing oscillations in ACE and Ptie imply that communication delays have a negative impact on system performance and stability in all three areas. The responses of the system in the absence of compensators show that the system loses stability in all five domains.











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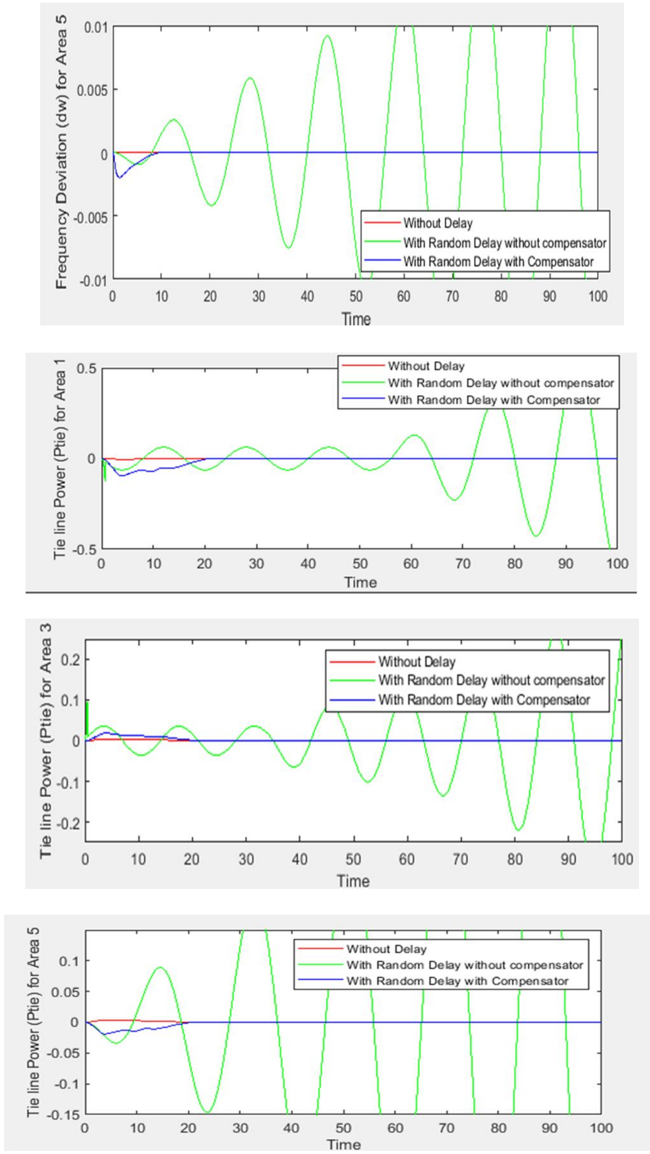
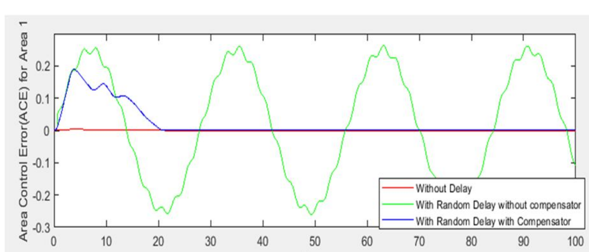


Fig.5.1.2 Proposed method in a 5area system.

The communication delay in each area is 4 s,5 s,4s s,6 s,3 s,*respectively*.

Fig.5.1.3 depicts an LFC with ten regions and changing delay. Because delays can occur at random, this simulation study employs time-varying random delays that vary within the range [max max /3,] (s max = 12). The delay compensator can be constructed for the worst-case scenario, allowing any delay less than max to be potentially alleviated. The ten-area LFC system was subjected to a separate time-varying random delay.



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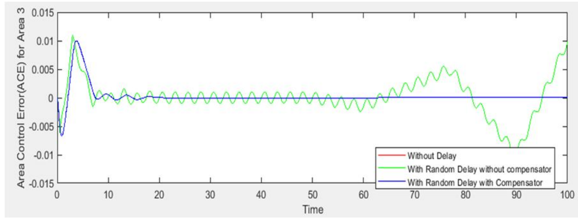

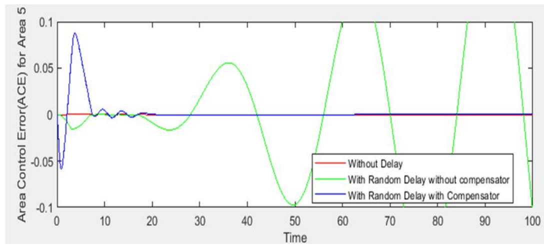

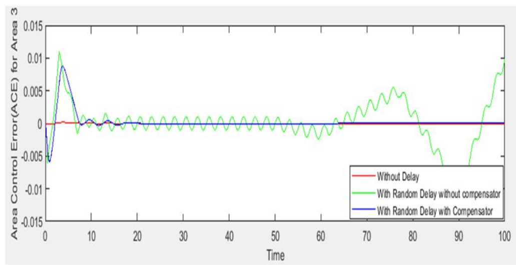

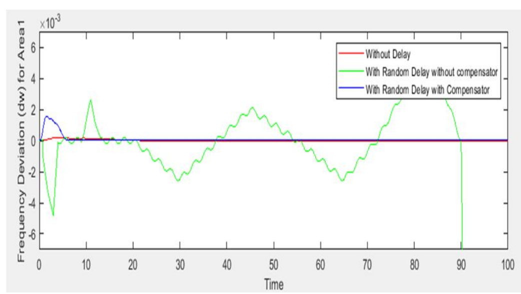

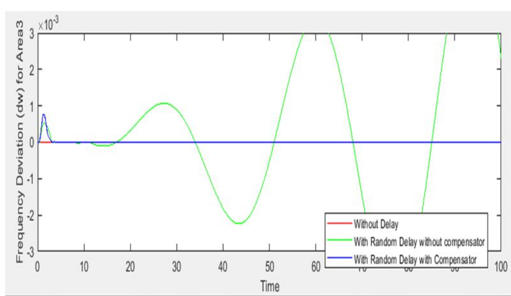

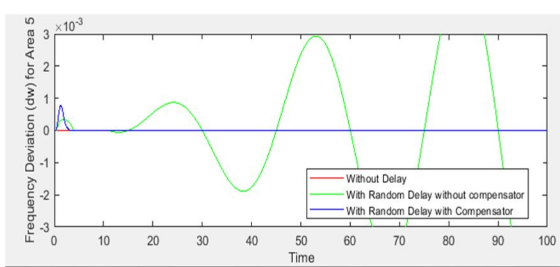

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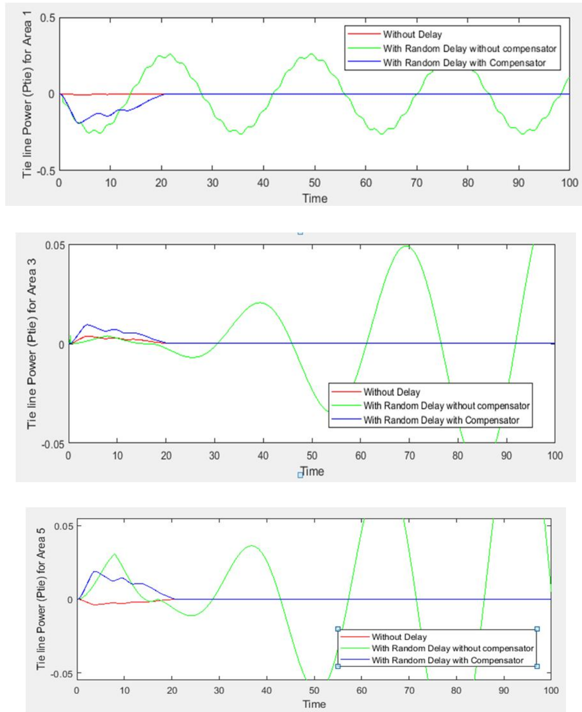

Fig.5.1.3 area system LFC with random delay
(Only three areas are shown. The time – varying
random delays in these three areas are shown at the bottom of this figure)

B. Simulation Results with AFPI and ANFIS

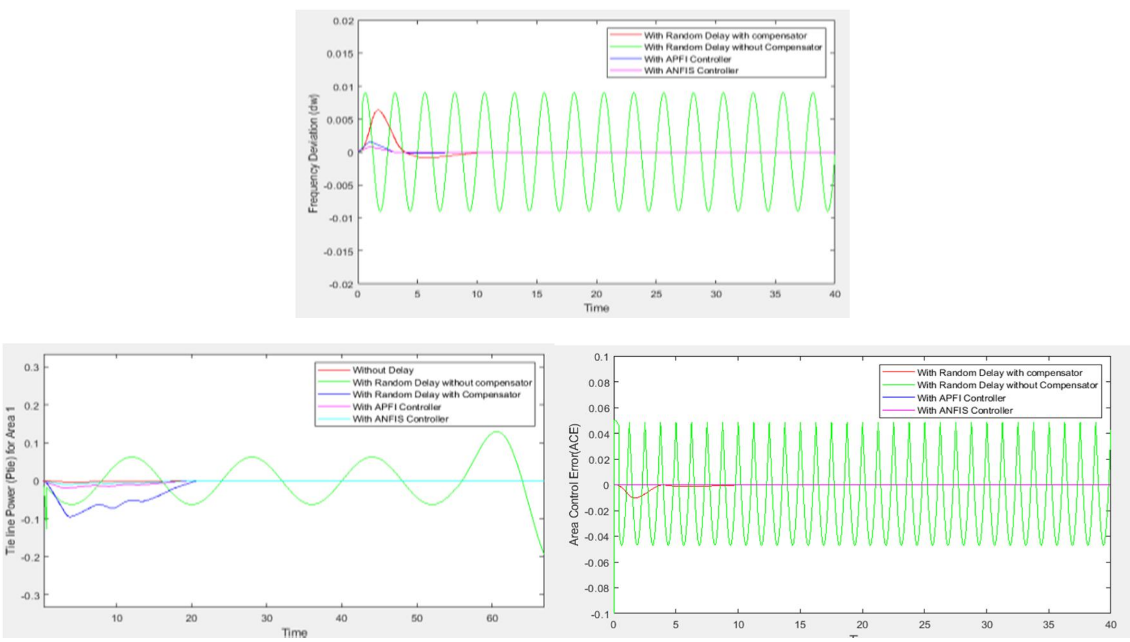

Fig.5.2.1 one area system response of 0.5s delay
following a 0.2 p.u.load change using proposed
compensator and without compensator
with AFPI and ANFIS Controller

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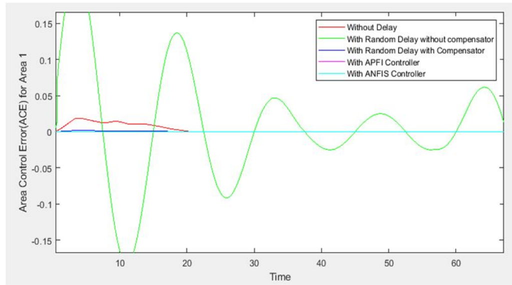
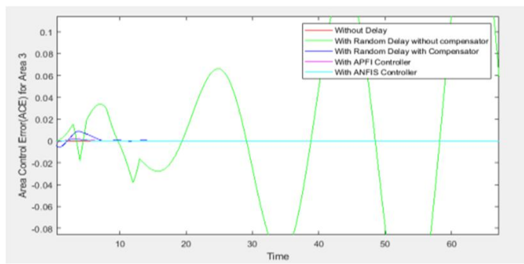
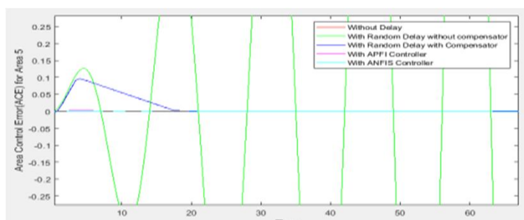
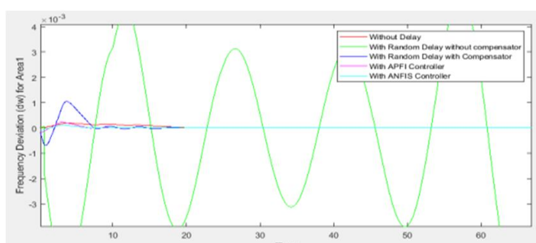
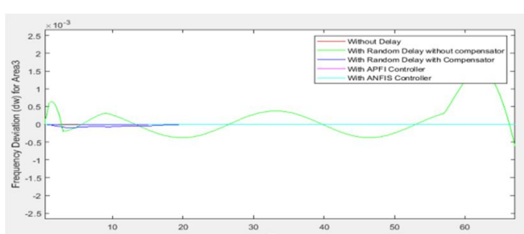
Fig.5.2.2 represents a scenario in which there are communication delays in all five domains. Increasing oscillations in ACE and Ptie imply that communication delays have a negative impact on system performance and stability in all three areas. The responses of the system in the absence of compensators show that the system loses stability in all five domains.

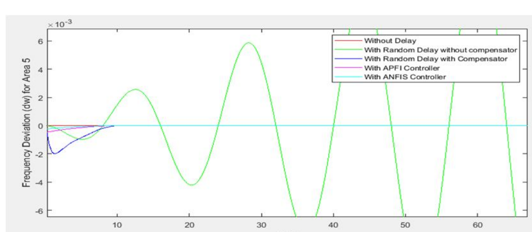












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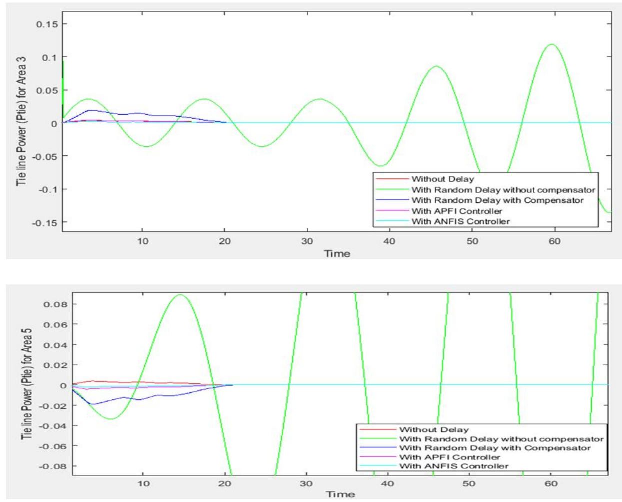
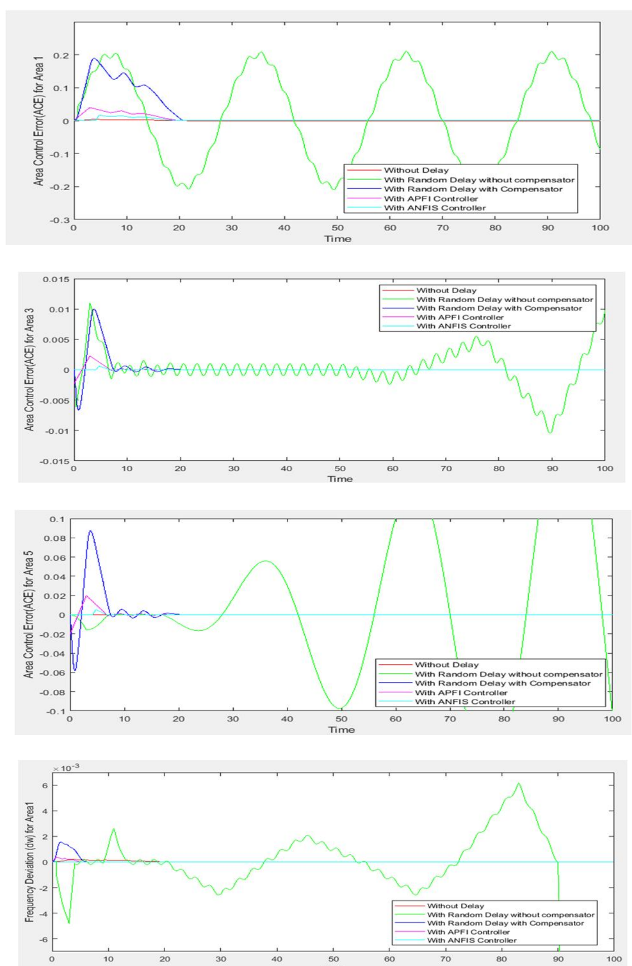


Fig.5.2.2 Proposed method in a 5 area system.
The communication delay in each area is 4 s, 5 s,
4 s, 6 s, 3 s, respectively with AFPI and ANFIS Controller

Fig.5.2.3 depicts an LFC with ten regions and changing delay. Because delays can occur at random, this simulation study employs time-varying random delays that vary within the range [max max /3,] (max = 12s). The delay compensator can be constructed for the worst-case scenario, allowing any delay less than max to be potentially alleviated. The ten-area LFC system was subjected to a separate time-varying random delay.



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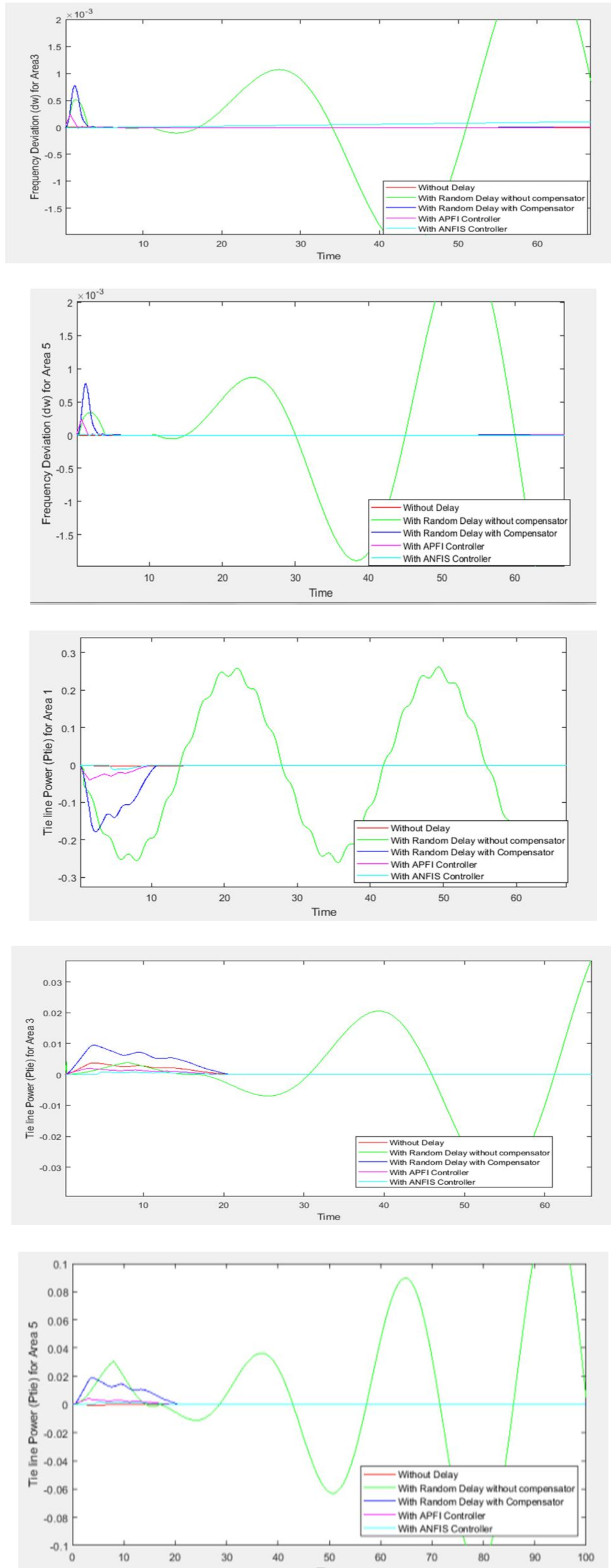

Fig.5.2.3 area system LFC with random delay (Only three areas are shown. The time varying random delays in these three areas are shown at the bottom of this figure) with AFPI and ANFIS Controller

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VI. CONCLUSION

This work proposes an alternate approach for building delay compensators for LFC schemes of big power systems with communication delays. In contrast to LMI techniques, the suggested method provides both a sufficient and a required condition (i.e., /c) for creating a delay compensator for a single-area LFC scheme. The investigation has Multi-area LFC schemes have also been expanded to span a larger region. The small gain theorem was used to construct the criterion for Adaptive Fuzzy Proportional Integral (AFPI) controller and Adaptive Neuro Fuzzy Interference System (ANFIS) are used to design controllers independently for particular areas/subsystems in a multi-area system while ensuring overall system stability. If the requirement is met, the design approach for delay compensators can be considerably simplified because each area just needs to deal with its own time delay. The suggested method's effectiveness has been proven by simulation tests for both single-area and multi-area LFC systems subject to random delays. There have been discussions on comparing this strategy to classic LMI approaches. In preparation for the deployment of the proposed approach to bulk power systems, the couplings between different control areas have been examined further.

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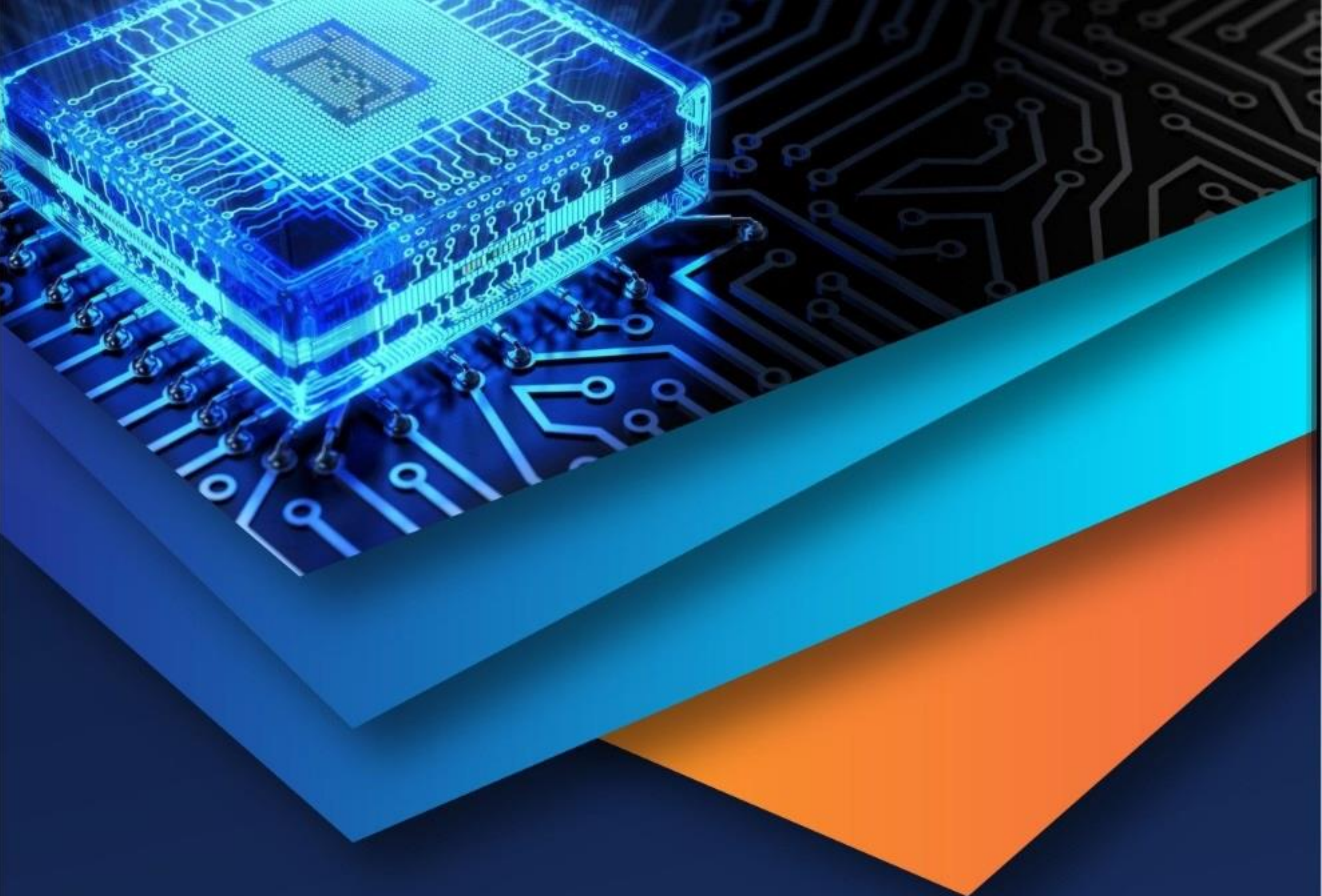

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