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Original Article

Design of Optimal Fuzzy Logic Load Frequency Controller for Smart Grid Under Resonance Attacks

Md Khaled Momeni[1], M. Ravindra Babu[2], K. Poorna Rajeswari[3], K. Rama Sudha[4]

[1,3,4]*Department of Electrical Engineering, AU College of Engineering, Andhra University, Andhra Pradesh, India.*
[2]*Department of Electrical and Electronics Engineering, University College of Engineering Narasaraopet, Jawaharlal Nehru Technological University Kakinada, Narasaraopet, Andhra Pradesh, India.*

[1]*Corresponding Author : mohammadkhaledmomeni@gmail.com*

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Abstract - *This has a look at investigates Load Frequency Control (LFC) in electric power systems, emphasizing the utility of Fuzzy Logic Controllers (FLC) to deal with stability worries, significantly in resonance attack situations. FLCs, known for their adaptability and integration of professional knowledge, rely upon nicely defined rule bases and membership functions for powerful management. To enhance control approach robustness, the study proposes using the Fuzzy C-means Clustering Method (FCM) for the best rule-based technology, especially beneath resonance attack situations. Generating the guideline base includes studying system dynamics and using phase-plane plots of controller inputs. Resonance attacks, in which outside manipulation objectives system stability via frequency rate modifications, are taken into consideration. Comparative evaluation among the proposed FCM-primarily based controller, traditional controllers, and unique fuzzy controllers is carried out to assess performance beneath numerous situations, along with resonance attacks and generation rate constraints. This study aims to illustrate the efficacy of superior management strategies in bolstering power system resilience in opposition to outside disturbances, thereby contributing to better balance and reliability in electric power systems.*

Keywords - *Load Frequency Control (LFC), Resonance attacks, Optimized fuzzy controller design, Fuzzy C-means Clustering Method (FCM).*

1. Introduction

Because the energy demand continues to rise, the electric power grid is present in the process of extensive expansion to fulfill these developing desires. This growth underscores the significance of maintaining stability and reliability in power delivery. In everyday operating conditions characterized by regular frequency and voltage profiles, the strength machine operates with a positive stage of reliability. However, to make certain seamless operations underneath extraordinary situations, extra management mechanisms are necessary [4]. Automatic Generation Control (AGC), or Load Frequency Control (LFC) [3, 5] monitoring, will become imperative for the powerful operation and renovation of energy systems, making sure the supply of enough, dependable, and high-quality electrical energy. Interconnected strength systems are usually segmented into managed areas, with generators forming cohesive companies within every area. The incidence of local variations in power gadget parameters, such as frequency, necessitates careful control to maintain machine integrity [15]. Frequency deviations, particularly, are essential signs of machine balance, as they can cause gadget damage, load performance degradation, and transmission line overloads, demanding situations to power system stability rise from external attacks, significant resonance assaults and cyber-attacks. Resonance attacks contain manipulating power plant inputs, in particular, concentrated on the Rate of Change of Frequency (RoCoF), to rapidly destabilize the machine. In comparison, cyber-attacks target computer networks or systems with the intention of changing, stealing, destroying, or exposing statistics; whilst both forms of attacks pose huge threats, the focus of this focuses on resonance attacks due to their direct effect on frequency stability.

The significance of maintaining stable frequency and RoCoF parameters through the years is underscored by using past incidents, which include the blackouts in Italy because of failure to stick to frequency control requirements. Addressing those demanding situations requires sturdy analysis and manipulation techniques to guard power systems against outside threats, ensuring non-stop reliability in energy supply. To beautify dynamic overall performance in Load Frequency Control (LFC) design, diverse control strategies had been hired, consisting of conventional Proportional Integral (PI) controllers [3, 17, 20-25], which might be extensively used because of their simplicity notwithstanding their tendency to supply considerable frequency variations. In assessment, nation feedback controllers based totally on Linear most useful manipulate fashions have been proposed to enhance performance through decreasing frequency versions. Regardless, literature has a famous limited exploration of Fuzzy common-sense Controllers (FLC) in LFC.

This research endeavors to cope with LFC and inter-place tie controls in a -location power device, especially focusing on the impact of resonance assaults. The unpredictable and unsure nature of strength systems has prompted the exploration of FLC by means of several authors [4, 8, 12, 15, 16, 19], as Fuzzy logic gives a rule-based, totally choice-making technique able to cope with imprecise information. A Fuzzy C-Method (FCM) clustering set of rules emerges as a treasured tool for records type, facilitating the identity of suitable fuzzy set obstacles and detecting capability outliers inside the proposed decentralized manage gadget; FCM clustering is leveraged to generate the necessary rule base for the deliberate Fuzzy Controller. By using section-aircraft plots of entering speeds and clustering cluster centers, a robust decentralized management machine has evolved. Simulation of the proposed controller for a two-place strength device, thinking about era charge constraint underneath numerous working conditions, lets in for assessment with traditional and original Fuzzy controllers. Simulation effects suggest that FCM controllers provide reliable performance across numerous running situations with reduced rule complexity. Particularly in the presence of resonance attacks, FCM-based load frequency manipulation demonstrates superior overall performance, showcasing its effectiveness in ensuring gadget stability and reliability.

2. Model of the System

Inter-connected power systems encompass a couple of control areas interconnected via tie-lines. Figure 1 illustrates the block scheme of the area reheat power system, in which all blocks usually exhibit non-linear, time-version, and/or non-minimal segment characteristics. Throughout regular operation, the burden deviation inside the strength device stays minimal, allowing traditional techniques to employ linear fashions to represent machine dynamics around the running factor. Mills within each manipulated place are expected to function cohesively as a unified group. Modifications in loads at the working point have an effect on requencies throughout all regions and the electricity flow via tie-strains connecting the areas. In the event of a load disturbance, Load Frequency Control (LFC) should swiftly regulate area angular deviations to zero and alter tie-line power deviations to gain a new equilibrium between call for and generation ability.

The kingdom area equations of the device is,

$$\dot{x} = Ax+Bu+Ld \tag{1}$$

$$y = Cx \tag{2}$$

In Figure 1, each section of the interconnected power system comprises four modules: the governor, the intermediate re-heater, the steam turbine, and the power system. In this context, T_{r1} and T_{r2} represent the re-heater time constants; T_{g1} and T_{g2} denote the governor time constants; T_{t1} and T_{t2} are the turbine time constants; K_{r1} and K_{r2} are the re-heater gains (pu); ΔPD1 and ΔPD_2 indicate load disturbances; Tp1 and T_{p2} are the time constants of the power system; K_{p1} and K_{p2} are the power system gains; R_1 and R_2 are the governor adjustment deviation coefficients; ACE1 and ACE2 are the area control errors; and u_1 and u_2 are the control outputs. The parameters for the two areas are provided in Table 1.

The primary reason for considering the Generation Rate Constraint (GRC) is that a rapid increase in power can lead to about immoderate steam from the boiler device, which might reason steam condensation due to adiabatic expansion. For the reason that temperature and pressure within the HP turbine are normally very excessive with some margin, it is miles expected that the steam condensation. If the boiler steam pressure itself no longer drops below a positive diploma, it will now not stand up with approximately 20% glide adjustments. For the primary tens of seconds, however, it is possible to boom energy production by as much as around 1.2, keeping with the cent of regular power. The GRC need to restrict the growth in the strength of the generator after achieving this marginal upper limit. GRC affecting massive faster-generator is typically bounded through 3%/min. To be able to keep away from immoderate manipulated movement, limiters with a limit fee of ±zero.0005 shall be carried out within the computerized Generator Controller. by means of adding limiters to the mills as proven in parent 2, those grids are considered for all regions.

2.1. Test System for Load Frequency Control

This thesis considers three different test systems for the LFC of multi-area power systems.

Test Case 1: In test case 1, the IEEE 30-bus system is considered. It is distributed into a two-area system. In Area 1, there are four generating units represented by generators at buses 1, 2, 5 and 13. In Area 2, there are two generating units represented by generators at buses 8 and 11. Details of the system data are given below. The parameters of the two area power systems are given in Table 1. In area 1, the power load (PLoad) is 161.4 MW, with a corresponding damping factor (D) of 2.421 Hz/pu. For area 2, the power load is 122 MW, and the damping factor is 1.83 Hz/pu.

The maximum Power Generation (PG) in Area 1 is 700.2 MW. Taking the load demand into account, the system is still able to cater to a maximum load demand of 538.8 MW. In Area 2, the maximum PG is 200 MW, and the system can still cater for a load of 78 MW. The reheat thermal parameters K_{ri} and T_{ri} are 0.5s and 10s, respectively. The GRC for each generator is taken as 3%.

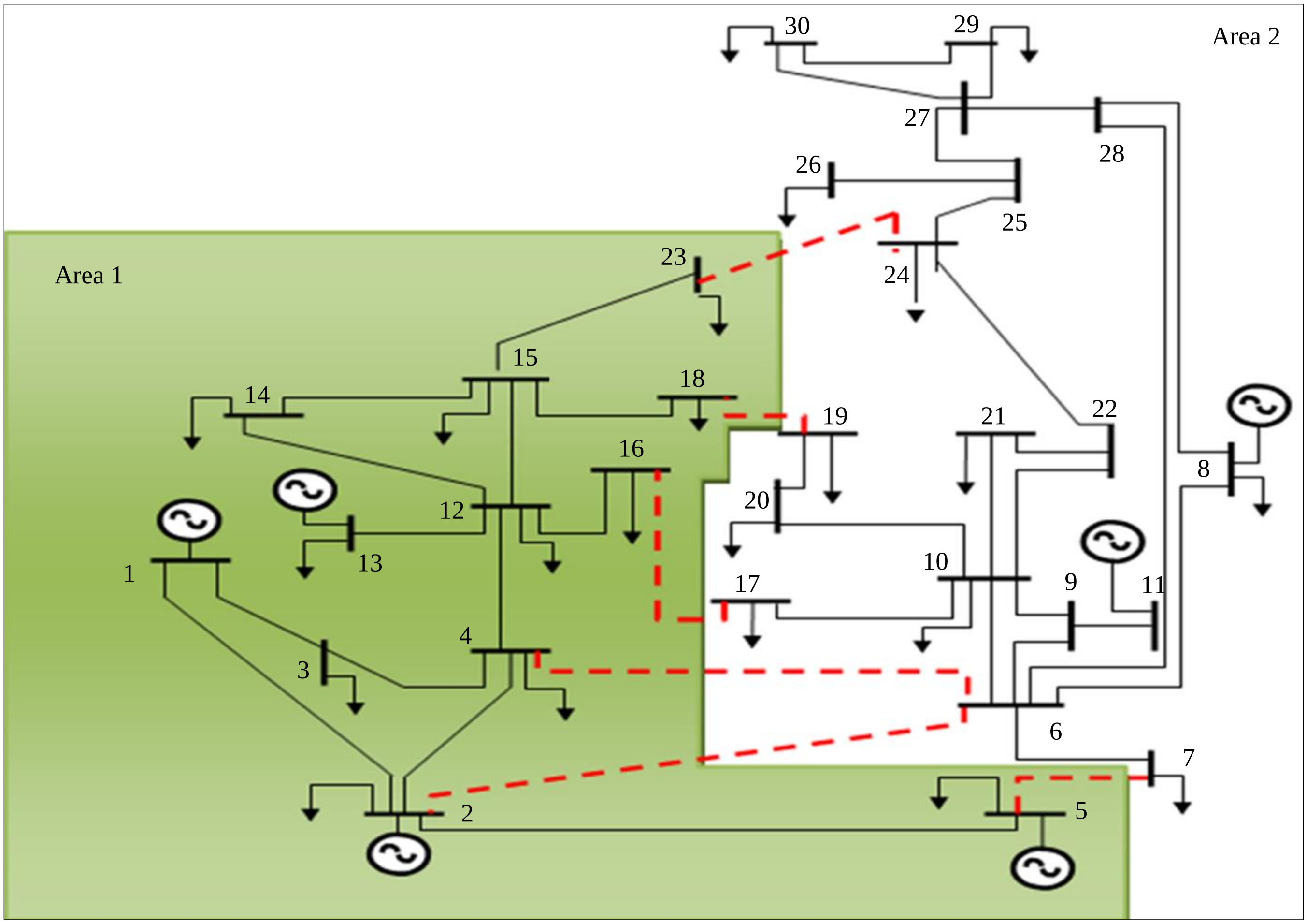

Fig. 1 IEEE 30 bus two area system

Table 1. Generating unit parameters for IEEE 30-bus test system with multiple interconnected generators

Parameters	G1	G2	G3	G4	G5	G6
T_{Ti} (sec)	0.4	0.36	0.42	0.44	0.32	0.4
T_{Hi} (sec)	0.081	0.06	0.07	0.06	0.06	0.08
R_i (Hz/pu)	3.0	3.0	3.3	2.7273	2.667	2.5
B_i (pu/Hz)	0.3483	0.3473	0.318	0.3827	0.3890	0.414
2H (sec)	7	8.05	8.05	8.05	8.05	8.05

Table 2. Generating unit parameters for IEEE 39-bus test system with multiple interconnected generators (from G1 to G6)

Parameters	G1	G2	G3	G4	G5	G6
T_{Ti} (sec)	0.44	0.36	0.05	0.36	0.05	0.05
T_{Hi} (sec)	0.06	0.06	0.06	0.06	0.06	0.06
R_i (Hz/pu)	2.7273	3	3	3	3	3
B_i (pu/Hz)	0.3827	0.3473	0.3473	0.3473	0.3473	0.3473
2H (sec)	12.102	7.2	30	7.2	7.2	30

Table 3. Generating unit parameters for IEEE 39-bus test system with multiple interconnected generators (from G7 to G10)

Parameters	G7	G8	G9	G10
T_{Ti} (sec)	0.05	0.32	0.4	0.44
T_{Hi} (sec)	0.06	0.06	0.08	0.06
R_i (Hz/pu)	3	2.667	2.8235	2.7273
B_i (pu/Hz)	0.3483	0.389	0.3692	0.3827
2H (sec)	30	9	7.482	12.102

3. Phase Plane Analysis

The fuzzy model relies on empirical information, drawing upon an operator's preference for a deep technical understanding of the system. This function offers a massive mission in developing the rule base, an essential issue of Fuzzy control systems. However, this venture can be addressed by leveraging phase-plane plots of inputs to a Fuzzy Controller [16].

Stability analysis of a fuzzy management system necessitates understanding the connection between the rule country space and the dynamic machine under manipulation. This relationship is decided by the comparative impact of every rule and the control action based on rules generated with the aid of the fuzzy inference engine.

A series of rules called a linguistic trajectory is derived by mapping the closed-loop path onto the position area. This trajectory aligns with the machine's behavior, presenting insights into using phase-plane plots for entering fuzzy controllers and determining the requisite rule base.

The closed-loop trajectory is plotted onto the location space of inputs, in which clusters are shaped using the bushy C-approach approach. Cluster centers are then recognized and marked on the section-plane plot. These cluster centers will eventually be aligned with the closed-loop trajectory, facilitating the identification of the necessary policies. Consequently, non-cooperative or unwanted rules are diagnosed and excluded from attention.

4. Clustering Analysis Fuzzy C-Means

Fuzzy modeling techniques have received significant traction in recent years, especially in complicated gadget fashions wherein traditional techniques like mathematical and model-unfastened approaches warfare because of insufficient know-how. In contrast to traditional techniques, which frequently rely on specific technical understanding, fuzzy models are empirically based totally, drawing on operators' experiential expertise.

In situations requiring huge statistics, version-unfastened techniques like neural networks provide a sturdy approach to lowering uncertainty through records-pushed mastering. Fuzzy reasoning provides a framework for expertise machine behavior with the aid of interpolating between current enter and output states, especially in scenarios where numerical records are scarce or statistics are ambiguous.

Despite their inherent imprecision, fuzzy models are adept at handling complicated structures with restrained records, offering a way to navigate uncertainty. One first-rate advantage of fuzzy systems is their capacity to generate crisp inputs and outputs at the same time as additionally presenting a non-linear useful map.

This pliability allows for efficient manipulation without the want to evaluate all feasible enter combos, as a consequence decreasing complexity even as doubtlessly enhancing manipulate best. Fuzzy C-Approach (FCM) clustering is a method that further complements the adaptability of fuzzy systems by means of permitting records to belong to a couple of clusters concurrently [6,12].

In pattern reputation, this is a common use. It's far primarily based on the reduction of the goals function as follows:

$$J_m=\Sigma_{\{i+1\}}^{N}\Sigma_{\{j=1\}}^{C}u_{ij}^{m}\left|\left|X_i - C_j\right|\right|^2,\ 1<=m<=\text{infinity} \quad (3)$$

Where m is any real number greater than 1, u_{ij} is the degree of membership of x_i in the cluster j, x_i is the i^{th} of d-dimensional measured data, c_j is the d-dimension center of the cluster, and $||*||$ is any norm expressing the similarity between any measured data and the center.

When updating membership u_{ij} and cluster centers c_j, fuzzy partitioning is performed by iterative optimization of the objective function shown below:

$$u_{ij} = \frac{1}{\left(\Sigma_{\{k=1\}}^{c}\left(\frac{\left|\left|x_i - c_j\right|\right|}{\left|\left|x_i - c_k\right|\right|}\right)^{\frac{2}{m-1}}\right)} \quad (4)$$

$$c_j = \frac{\Sigma_{\{i=1\}}^{N}u_{ij}^{m}x_i}{\Sigma_{\{i=1\}}^{N}u_{ij}^{m}} \quad (5)$$

This new release will forestall while $\max_{ij}$ {|uij(k+1)-uij(k)|}<ε where ε is a termination criterion among 0 and 1, whereas k are the iteration steps.

This process converges to a local minimal or saddle. Factor of Jm. FCM will decide the cluster centers ci and membership matrix U for the usage of the subsequent steps in a batch mode operation:

Step 1 : Set the wide variety of clusters C Initialize the membership matrix U with arbitrary values between 0 and 1 such that the summation of stages of familiarity of a records factor to all Clusters will constantly be identical to cohesion.

Step 2 : Evaluate the C Fuzzy cluster facilities, 1, c_i wherein i=1,2..........c, the usage of Equation (3).

Step 3 : If either the tolerance price or the improvement from the previous iteration falls below a specified threshold, calculate the objective function according to Equation (1). Stop.

Step 4 : Compute a new U using Equation (2). Visit Step 2.

5. The Design of Proposed Fuzzy C-Mean (FCM) Logic Controller for Optimal Control [11, 14]

1. The regular Fuzzy controller is designed heuristically with rules, as shown in Table 5. There are 4 components in its basic shape:
   - Fuzzification: Interprets inputs (actual values) to fuzzy values.
   - Deduction system: Applies a fuzzy reasoning mechanism to attain a fuzzy output.
   - Information Base: Includes a set of fuzzy guidelines and a set of club functions referred to as the database.

   The 2 normalized enter variables ΔACE and $\Delta ACE^{\cdot}$;are first fuzzified $\mu_p(\Delta ACE)$ and $\mu_N(\Delta ACE)$.The definitions of the fuzzy sets are as follows [7-9]:

$$\mu_p(\Delta ACE) = \begin{cases} 0 & (-\infty, -L1) \\ L1+\Delta(ACE))/2L1 & (-L1, L1) \\ 1 & (L1, \infty) \end{cases} \tag{6}$$

2. The fuzzy C-means controller will be tuned to the general fuzzy controllers.
3. The phase-plane analysis plot of the enter space is acquired.
4. The entrance space is split into clusters, and the cluster centers are identified.
5. As shown in Figure 2, the collection of guidelines for the unique fuzzy controller is carried out to the section-plane plot of the entrance space with cluster facilities.
6. Consequently, the vital rules have been identified, and as indicated in Table 4, non-cooperative regulations have been abolished.

With the inclusion of the Generation Rate Constraint (GRC), the effectiveness of the proposed method in regulating the frequency response of the two reheat areas and the three interconnected areas of a thermal power system has been demonstrated.

Under GRC conditions, the performance of the proposed controller will be compared to that of a conventional controller and a specialized fuzzy controller. Simultaneous changes of parameters by 40% from their nominal values lead to parametric uncertainties in the system.

6. Resonance Attack Ways

In the system, to introduce a resonance attack at the specific required place on the power grid, attackers create touch bit adjustments or imitation inputs in order for them to enter resonance with a resonance supply, usually a characteristic of the gadget output. The principal methods to create resonance attacks are [2] :

1. Changes within the tie line power (feedback) can result in versions in enter, leading to frequency fluctuations and
2. And the attacker samples the output of the goal energy grid (power frequency)
3. Keep alternating your load frequencies; this results in mismatches on the factor of connection, and resonance attacks are going on as a result of that lack.
4. The attackers occasionally, cope with the insect's input to the electricity generator structures.

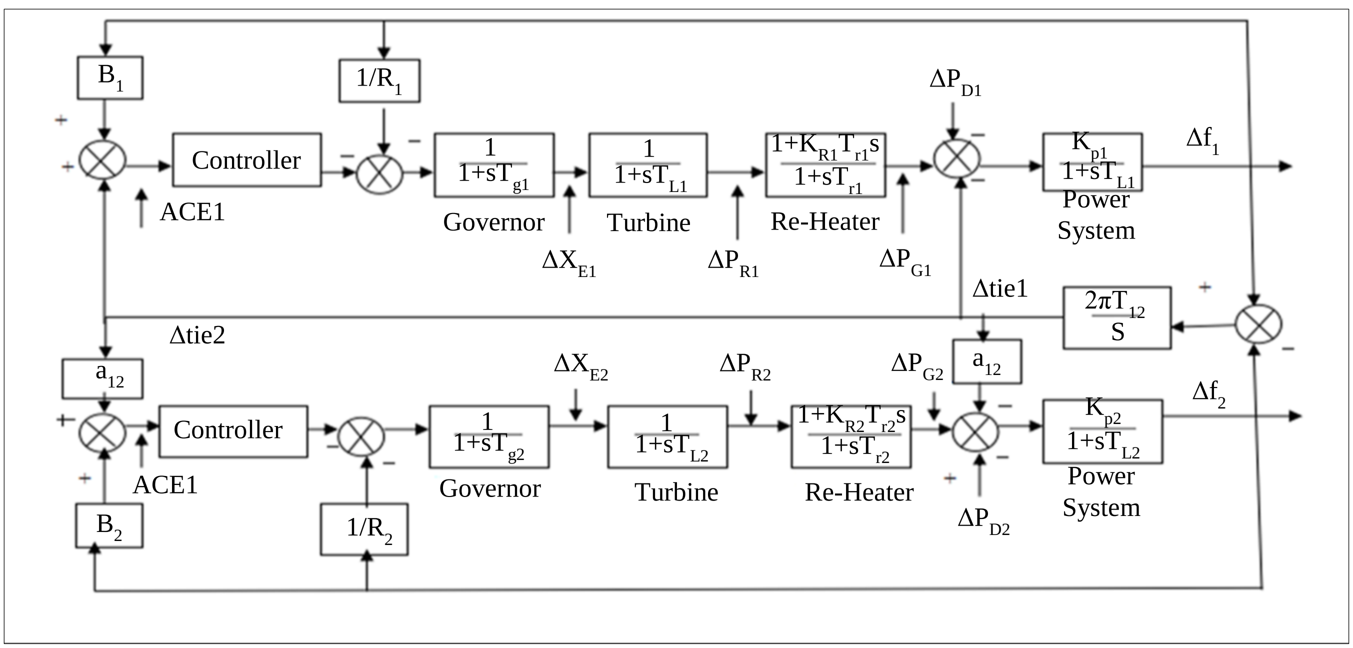

Fig. 2 Basic Block Diagram of the two area system

Table 4. Parameters of two area system

Area 1		Area 2	
T_{G1}	0.08	T_{G2}	0.08
T_{T1}	0.112	T_{T2}	0.112
T_{P1}	20.1206	T_{P2}	20.1206
R_1	3.36	R_2	3.35
B_1	18.55	B_2	18.55
K_{P1}	86.2068	K_{P2}	86.2068
T_{12}	0.763	T_{12}	0.763
K_P	0.56632	K_P	1.7853
K_I	0.71998	K_I	2.7204

Table 5. Control rules for T1 and T2 Fuzzy controller

Δ(ACE)				
Δ(ACE)'		L	Z	H
	L	H	L	L
	Z	L	H	H
	H	L	L	L

Table 6. Optimized control rules

Δ(ACE)				
Δ(ACE)'		L	Z	H
	L	H	L	-
	Z	L	H	H
	H	-	L	-

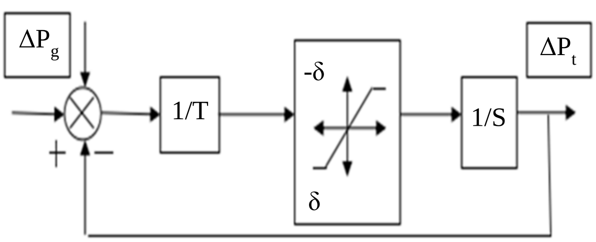

Fig. 3 Non-linear turbine model with GRC

Figure 5 is the phase-plane plot for identifying proposed rules for fuzzy C means to the load frequency control of the smart grid under resonance attacks. From these proposed rules, the 1st rule, H, is the phase plot converging point, and this point is the key rule.

The entire control system depends on the key rule; if any rule changes (means delete the rule), the control is changed, and deviation occurs at waveform slightly. However, the entire system is unstable if the key rule is deleted.

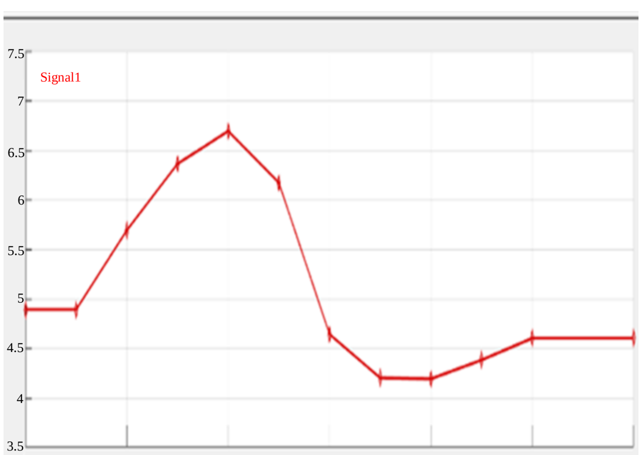

Fig. 4 Random attack signal

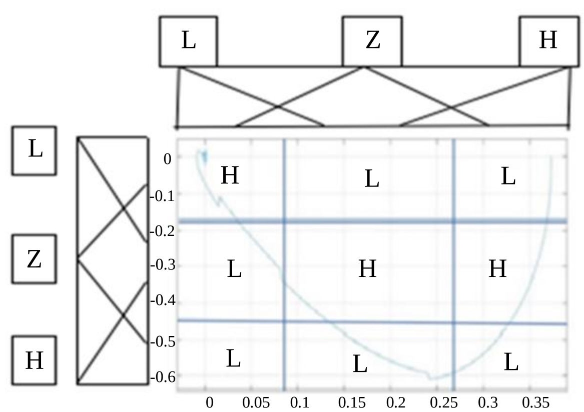

Fig. 5 Proposed rules for fuzzy

7. Results and Discussion

7.1. Simulation Observations

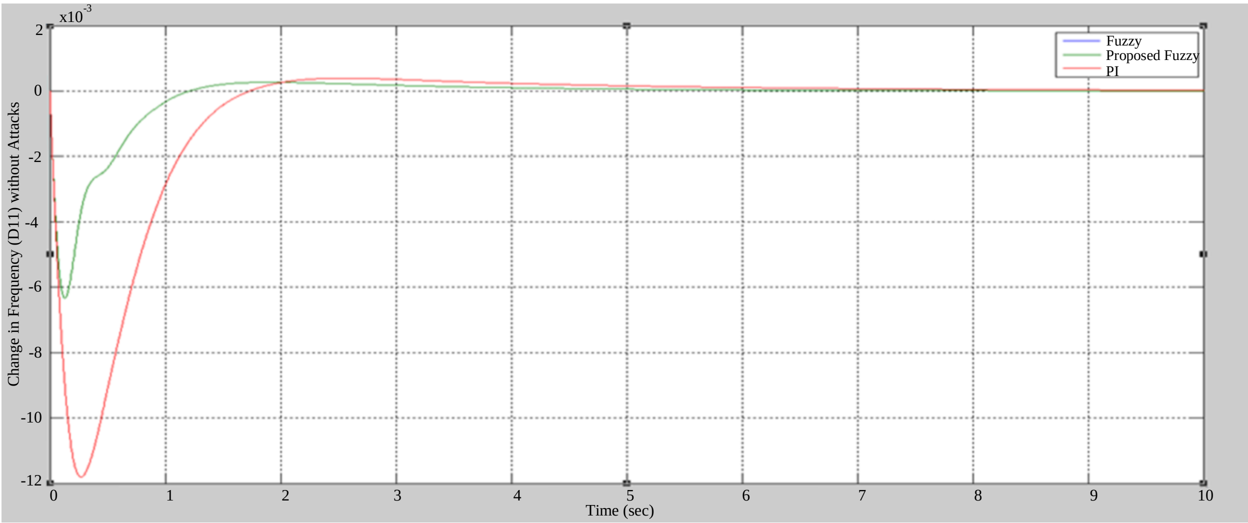

Fig. 6 Variations in frequency of area one (Δf1) without attacks

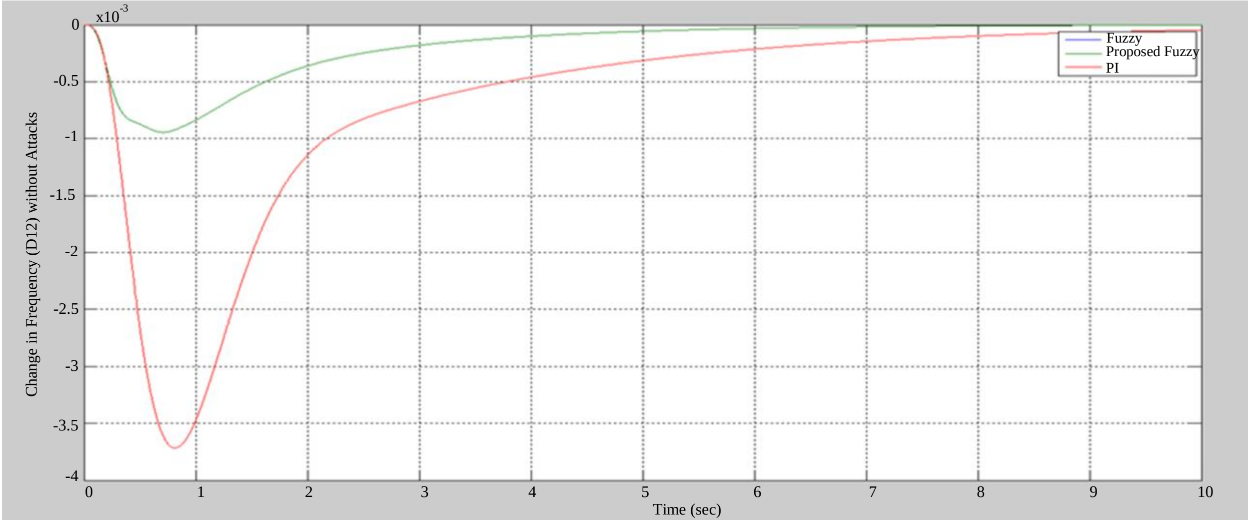

Fig. 7 Variations in frequency of area two (Δf2) without attacks

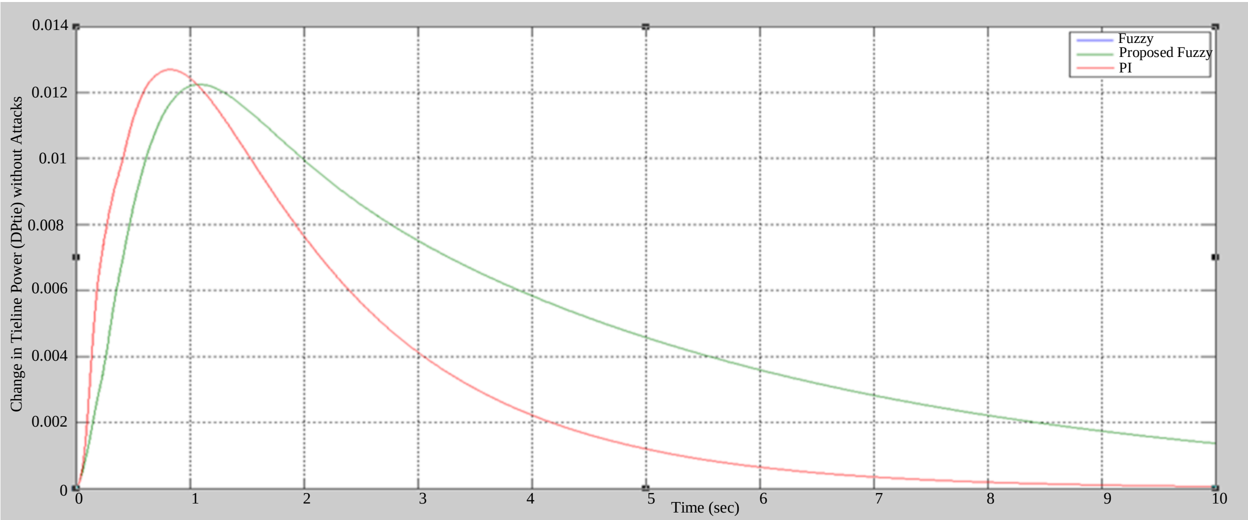

Fig. 8 Variations in tie line power (ΔPtie) without attacks

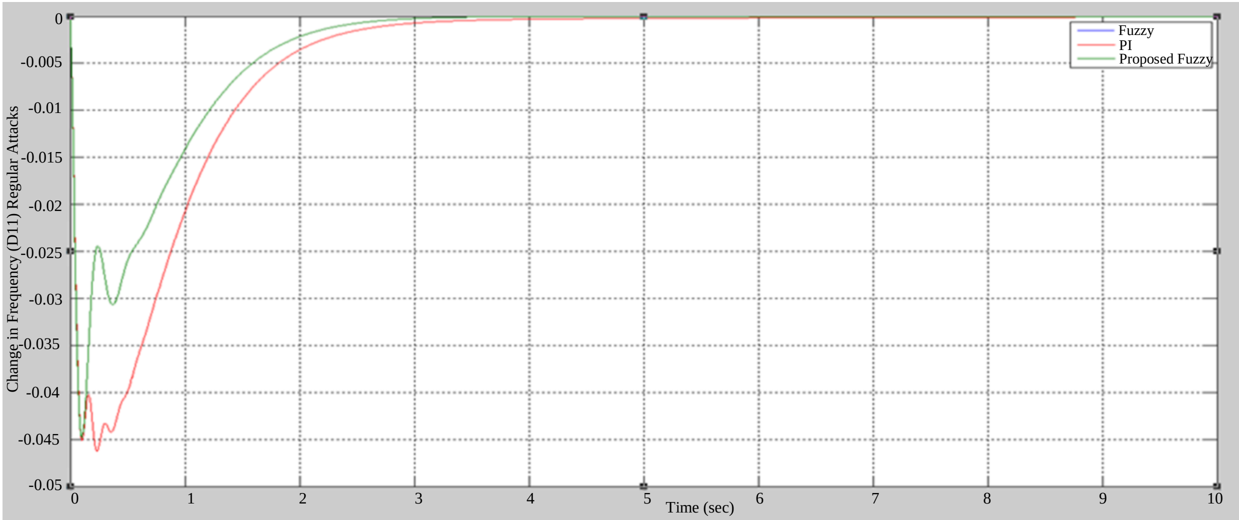

Fig. 9 Variations in frequency of area one (∆f1) with regular attacks

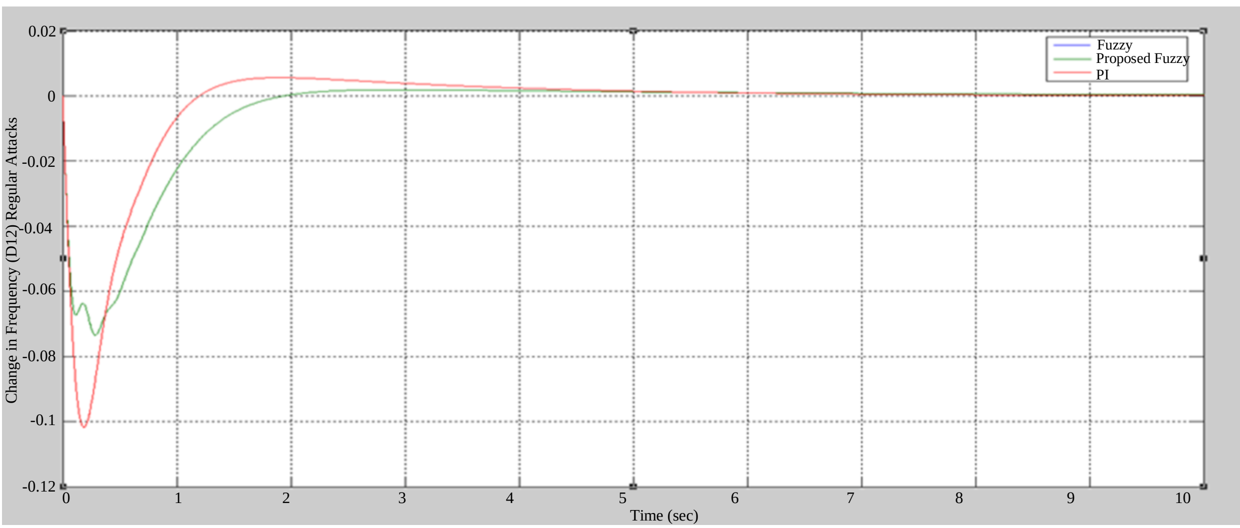

Fig. 10 Variations in frequency of area two (∆f2) with regular attacks

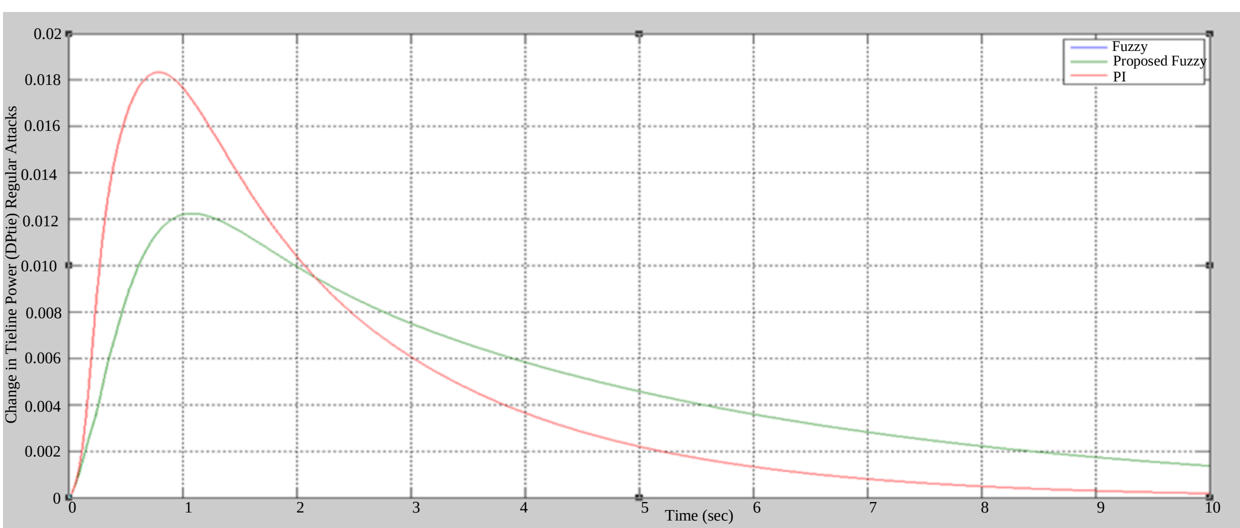

Fig. 11 Variations in tie line power (∆Ptie) with regular attacks

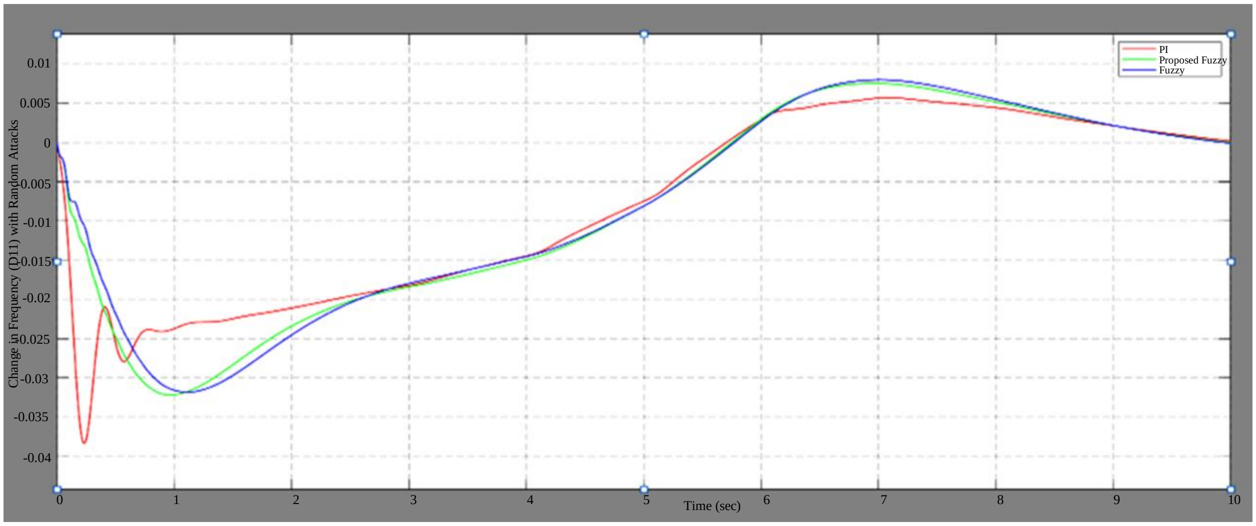

Fig. 12 Variations in frequency of area one (∆f1) with random attacks

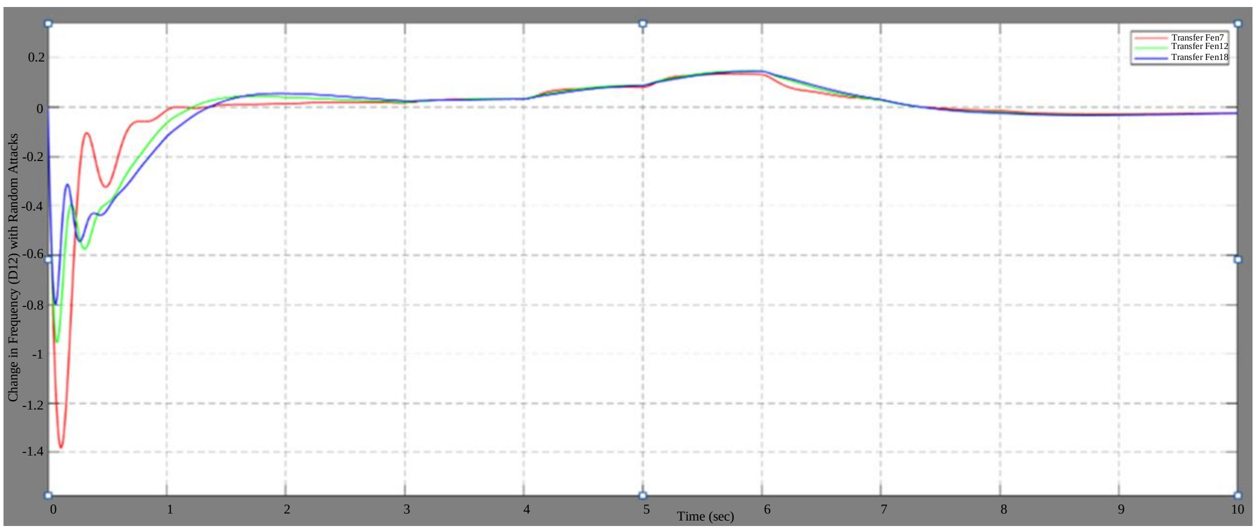

Fig. 13 Variations in frequency of area two (∆f2) with random attacks

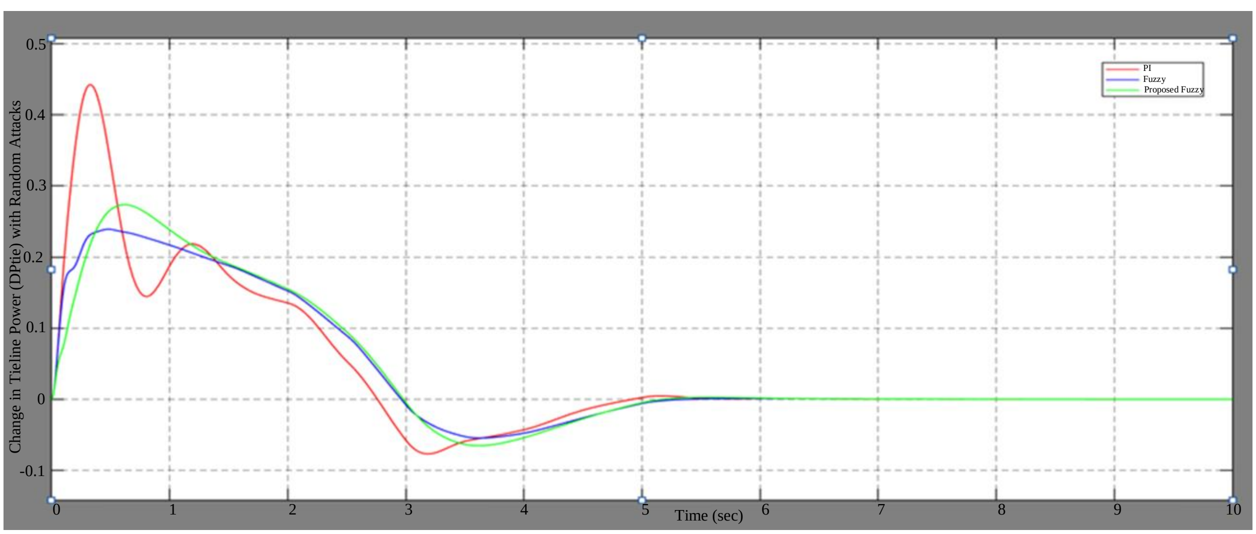

Fig. 14 Variations in tie line power (∆Ptie) with random attacks

The provided figures depict the change in frequency and tie-line powers of a two-area system under different conditions, including both with and without attacks. These attacks are classified into two types: regular attacks, represented by continuous waveforms such as sine waves, and random attacks, characterized by irregular signal shapes. In general, generators must adapt to local load variations and tie-line power fluctuations from other areas to effectively regulate local and global load balances. Figures 6, 7, and 8 illustrate the changes in load frequency for area one, area two, and tie-line power of the power system, respectively, under normal conditions, with all controllers (PI, Fuzzy, Proposed Fuzzy), in the absence of any attacks.

Figures 9, 10, and 11 showcase the impact of regular attacks on load frequency and tie-line power, with all controllers considered. Similarly, Figures 12, 13, and 14 demonstrate the effects of random attacks on load frequency and tie-line power. A comparison across various scenarios consistently shows that the proposed fuzzy logic controller provides more optimal results compared to the PI controller and the Fuzzy C controller. This highlights the superior adaptability and precision of the fuzzy logic approach in handling complex control. This trend is summarized in Table 7, highlighting the effectiveness of the proposed fuzzy logic controller across various conditions.

Table 7. Comparison of all controllers with different parameters

	PI			Fuzzy c-Means			Fuzzy Controller		
	Δf_1	Δf_2	ΔP_{tie}	Δf_1	Δf_2	ΔP_{tie}	Δf_1	Δf_2	ΔP_{tie}
Without Attacks	UP=0.0002 LP= -0.0119 ST= 6sec	UP=0 LP= -0.00375 ST= 10sec	UP=0.0125 LP=0 ST=9sec	UP=0.0001 LP=-0.0062 ST=4sec	UP=0 LP=-0.00097 ST=6sec	UP=0.0121 LP=0 ST=10sec	UP=0.0001 LP=-0.0062 ST=4sec	UP=0 LP=-0.00097 ST=6sec	UP=0.0121 LP=0 ST=10sec
With Regular Attacks	UP=0 LP= -0.0453 ST= 4sec	UP=0.005 LP= -0.12 ST= 3.5sec	UP=0.0181 LP=0 ST=10sec	UP=0 LP= -0.045 ST= 2.9sec	UP=0.002 LP= -0.073 ST= 1.9sec	UP=0.0121 LP=0 ST=10sec	UP=0 LP= -0.045 ST= 2.9sec	UP=0.002 LP= -0.073 ST= 1.9sec	UP=0.0121 LP=0 ST=10sec
With Random Attacks	UP=0.005 LP= -0.0359 ST= 10sec	UP=0.19 LP= -1.39 ST= 7.5sec	UP=0.44 LP=-.0890 ST=10.3sec	UP=0.006 LP= -0.0325 ST= 10sec	UP=0.19 LP= -0.92 ST= 7.2sec	UP=0.249 LP=-.08 ST=10.2sec	UP=0.006 LP= -0.0325 ST= 10sec	UP=0.19 LP= -0.8 ST= 7.2sec	UP=0.275 LP=-.079 ST=10.2sec

(Δf_1 : Variation in frequency of area one in the power system, Δf_2 : Variation in frequency of area two in the power system, ΔP_{tie} : Variation in tie-line power of the power system, UP : Upper peak of the waveform, LP : Lower peak of the waveform, ST : Settling time of the waveform)

8. Conclusion

A new technique for reducing fuzzy controller rules for smart grid load frequency control under resonance attack is proposed in this paper. The regulations may be derived with the aid of superimposing a segment plane plot, including clusters that have been detected with FCM on the guideline base for heuristic fuzzy controllers. A standard region interconnected reheat thermal power plants had been a problem for the proposed technique, considering the GRC with system chanciness and different resonance attacks. The simulation outcomes show that even in the presence of Fuzzy GRC, the FCM controller can make a certain balance of the overall system and preserve the equal stage of overall performance, which is huge with regard to parameter uncertainty.

The time and effort needed to improve a fuzzy controller can be considerably shortened through this technique to simplify the rules. Within the presence of approaches of resonance attack, especially load frequency is monitored with diffusion of controllers are PI, Fuzzy, Proposed Fuzzy. Finally, the proposed Fuzzy controller gives accurate results with minimum error.

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