International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 13, Issue 5 [May. 2024] PP: 90-99

Modeling and Control of a Large-Scale Three-Area Hybrid Interconnected Power System

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Abstract: *Large-scale power systems represent interconnected electric grids comprising power plants linked by transmission lines. These networks typically integrate various types of generating stations, including hydro, non-reheat, and reheat (steam) facilities. Load-frequency control (LFC) constitutes a critical control scheme within these interconnected systems, aimed at maintaining grid stability amidst continuous and stochastic load fluctuations. As an essential component of automatic generation control (AGC), LFC within large-scale power grids aims to maintain the network frequency at its designated value (50 Hz or 60 Hz) despite variations in load. Conventional LFC regulators, such as proportional-integral-derivative (PID) controllers, might struggle to meet increasingly stringent performance demands due to inherent limitations. Intelligent alternatives employing modern fuzzy logic controller (LFC) and artificial neural network (ANN) techniques emerge as promising remedies. This study concentrates on mathematically modeling a typical three-area interconnected power system featuring diverse turbine types in generating stations, subjected to random load fluctuations. The current work contrasts the performance of traditional PID controllers with intelligent FLC in addressing the LFC challenge within this three-area hybrid power system. The superior control performance exhibited by the FLC strategy underscores its efficacy in effectively tackling LFC issues.*

Keywords: *Large-scale power system, subsystem, modelling, LFC, PID, FLC.*

Date of Submission: 02-05-2024 Date of acceptance: 12-05-2024

I. INTRODUCTION

Electric power grids within a nation are regarded as expansive systems due to their intricate features, which include dispersed generation units, extensive transmission networks, and numerous interconnected control areas. These control areas, typically consisting of a multitude of substations, act as miniature versions of the larger grid, managing the balance between supply and demand within their respective domains. The connection between these areas is established through tie-lines, synonymous with transmission lines, enabling the exchange of power and bolstering the overall reliability of the system [1-5].

Nevertheless, the dynamic nature of power demand poses a significant challenge. Unlike a perfectly predictable and static load, real-world consumption fluctuates continuously. This variability, influenced by the behavior of individual consumers, residential areas, industries, and other factors, disrupts the delicate equilibrium between power demand and consumption within the grid. Consequently, deviations from the nominal network frequency occur, which not only compromise the reliability of power delivery to end-users but also adversely affect tie-line power exchange, leading to deviations from planned values.

Hence, ensuring grid stability requires the implementation of an effective control strategy. Load-frequency control (LFC) emerges as a crucial element of automatic generation control (AGC), specifically addressing these frequency discrepancies. Through continuous monitoring and adjustment of real-time generator power output, LFC aims to keep the grid frequency within acceptable limits, thereby ensuring smooth operation of interconnected control areas and facilitating dependable power exchange via tie-lines [6-12].

The realm of LFC control strategies is remarkably diverse, encompassing a vast array of techniques that have been explored and implemented across theoretical and practical applications. Beyond the well-established and widely used traditional regulators, such as integral (I) and proportional-integral-derivative (PID) controllers, a burgeoning landscape of advanced control methodologies has emerged. These advanced techniques delve into the realm of computational intelligence, incorporating fuzzy logic and artificial neural network (ANN) controllers [1, 13-15].

The efficacy of these various LFC strategies has been rigorously evaluated using established quality criteria. Control results across these diverse methodologies have been demonstrably successful in achieving grid stability and maintaining frequency within acceptable tolerances. However, the selection of the optimal LFC strategy hinges on a multitude of factors specific to each power grid's unique characteristics. These factors encompass system size and complexity, the nature of the power source generation mix, and the dynamics of consumer demand profiles. Furthermore, ongoing research and development efforts continually push the boundaries of LFC strategy effectiveness. Novel control algorithms, incorporating elements of machine learning and adaptive control, are being explored to address the ever-evolving challenges posed by the growing integration of renewable energy sources and distributed generation into power grids. The pursuit of optimal LFC strategies remains an active area of research, driven by the unwavering commitment to ensuring the stability, reliability, and efficiency of modern power systems [16-20].

This paper presents a mathematical model of three-area hybrid power system. This power plant is a large-scale includes three subsystems: a hydroelectric power plant, a thermal power station using reheat turbines and a thermal power one employing non-reheat turbines. Such a power system can be considered a typical interconnected network which is highly suitable for practical electric power grids. Load-frequency control strategies using intelligent fuzzy logic controllers will be selected in this study. Simulation results demonstrate the applicability of the proposed control strategy.

II. MODELLING OF A LARGE-SCALE ELECTRIC POWER GRID

Large-scale power networks or interconnected electric power grids, spanning vast regions, constitute the backbone of modern power delivery systems. These intricate networks seamlessly integrate geographically dispersed power generation units with numerous consumers through a web of high-voltage transmission lines. By interconnecting control areas, each managing supply and demand within its boundaries, these grids leverage the concept of collective strength. This enables efficient power exchange, enhancing overall system reliability and facilitating the integration of diverse energy sources, such as renewables. However, maintaining grid stability in the face of fluctuating demand and geographically separated generation necessitates sophisticated control strategies.

In this section, a three-area hybrid electric power grid is studied. This network includes three sub-power stations: one hydropower plant and two steam power plants (one uses non-reheat turbines and the other employs re-heat turbines). The illustration of this power network is depicted in Fig. 1. The mathematical equations describing this model are presented below [1]:

- **Area 1: Non-reheat thermal power plant**

$$\Delta f_1 = \frac{K_1}{1+s.T_1}.\Delta P_{m1}(s) = \frac{K_1}{1+s.T_1}.\left(\Delta P_{T1}(s) - \Delta P_{L1}(s) - \Delta P_{tie1}(s)\right) \tag{1}$$

$$\Delta P_{T1}(s) = \frac{1}{1+s.T_{t1}}.\Delta P_{v1}(s) \tag{2}$$

$$\Delta P_{V1}(s) = \frac{1}{1+s.T_{g1}}.\Delta P_{e1}(s) = \frac{1}{1+s.T_{g1}}.\left(\Delta P_{ref1}(s) - \frac{1}{R_1}.\Delta f_1(s)\right) \tag{3}$$

$$\Delta Ptie1(s) = \frac{2\pi}{s}.\left(T_{12}.\left(\Delta f_1(s) - \Delta f_2(s)\right) + T_{13}.\left(\Delta f_1(s) - \Delta f_3(s)\right)\right) \tag{4}$$

$$ACE_1(s) = B_1.\Delta f_1(s) + \Delta P_{tie1} \tag{5}$$

- **Area 2: Hydropower plant**

$$\Delta f_2 = \frac{K_2}{1+s.T_2}.\Delta P_{m2}(s) = \frac{K_2}{1+s.T_2}.\left(\Delta P_{HT2}(s) - \Delta P_{L2}(s) - \Delta P_{tie2}(s)\right) \tag{6}$$

$$\Delta P_{HT2}(s) = \frac{1-s.T_W}{1+0.5s.T_W}.\Delta P_{HV2}(s) \tag{7}$$

$$\Delta P_{HV2}(s) = \frac{1-s.T_{R2}}{1+s.T_{H2}}.\Delta P_{Hg2}(s) \tag{8}$$

$$\Delta P_{Hg2}(s) = \frac{1}{1+s.T_{g2}}.\Delta P_{e2}(s) = \frac{1}{1+s.T_{g2}}.\left(\Delta P_{ref2}(s) - \frac{1}{R_2}.\Delta f_2(s)\right) \tag{9}$$

$$\Delta P_{tie2}(s) = \frac{2\pi}{s}.\left(T_{21}.\left(\Delta f_2(s) - \Delta f_1(s)\right) + T_{23}.\left(\Delta f_2(s) - \Delta f_3(s)\right)\right) \tag{10}$$

$$ACE_2(s) = B_2.\Delta f_2(s) + \Delta P_{tie2} \tag{11}$$

- **Area 3: Reheat thermal power plant**

$$\Delta f_3(s) = \frac{K_3}{1+s.T_3}.\Delta P_{m3}(s) = \frac{K_3}{1+s.T_3}.\left(\Delta P_{T3}(s) - \Delta P_{L3}(s) - \Delta P_{tie3}(s)\right) \quad (12)$$

$$\Delta P_{T3}(s) = \frac{1+s.K_{r1}.T_{r1}}{(1+s.T_{r1}).(1+s.T_{t1})}.\Delta P_{v3}(s) \quad (13)$$

$$\Delta P_{V3}(s) = \frac{1}{1+s.T_{g3}}.\Delta P_{e3}(s) = \frac{1}{1+s.T_{g3}}.\left(\Delta P_{ref3}(s) - \frac{1}{R_2}.\Delta f_3(s)\right) \quad (14)$$

$$\Delta P_{tie3}(s) = \frac{2\pi}{s}.\left(T_{31}.\left(\Delta f_3(s) - \Delta f_1(s)\right) + T_{32}.\left(\Delta f_3(s) - \Delta f_2(s)\right)\right) \quad (15)$$

$$ACE_3(s) = B_3.\Delta f_3(s) + \Delta P_{tie3} \quad (16)$$

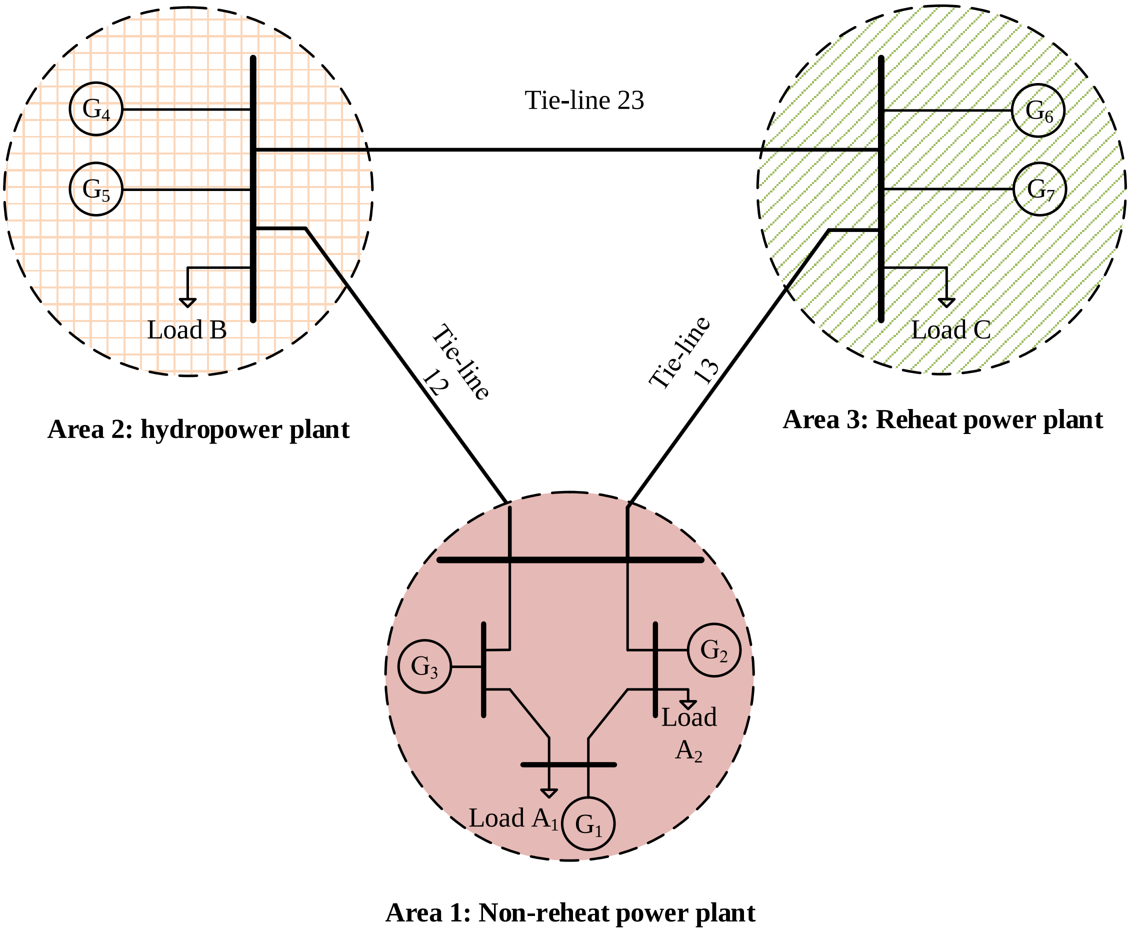


Fig. 1 A typical three-area hybrid electric power grid model

All simulation parameters for the typical hybrid electric power plant can be found in [1].

III. INTELLIGENT FUZZY LOGIC-BASED LFC

While traditional I, PI, and PID controllers have served as the workhorses of Load-Frequency Control (LFC) for decades, their reliance on precise mathematical models can render them less effective in handling the inherent complexities of modern power grids. These complexities include:

- Non-linearities: Power system dynamics exhibit non-linear behavior, particularly under transient conditions or disturbances.
- Parameter uncertainties: System parameters can vary due to factors like aging infrastructure or fluctuating loads.

- Multi-objective optimization: LFC needs to balance multiple objectives such as frequency regulation, tie-line power exchange, and minimizing control effort.

Fuzzy Logic Controllers (FLCs) offer a compelling alternative by mimicking human decision-making processes. FLCs can effectively handle non-linear system behavior and tolerate parameter uncertainties. They rely on a set of linguistic rules defined by human experts, translating operational experience into control actions.

The effectiveness of FLCs for LFC has been extensively documented in research and real-world applications. As depicted in Fig. 2, a typical FLC with two inputs (ACE and dACE) and one output (control signal) can be implemented in each control area. The ability of FLCs to handle complex system dynamics and achieve multiple objectives makes them a promising choice for LFC, particularly in modern grids with various generating power sources. Table 1 also presents a set of fuzzy logic rules used for the proposed FLC. The illustration in 3D of such a fuzzy set is depicted in Fig. 3.

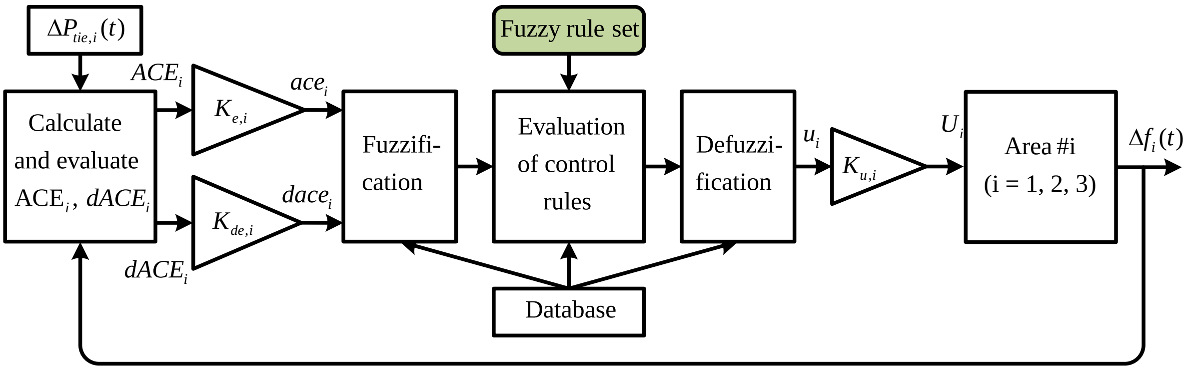


Fig. 2 Typical fuzzy logic – based control scheme for the load-frequency control problem

Table 1. A set of fuzzy logic rules used for the FLC

DACE \ ACE	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

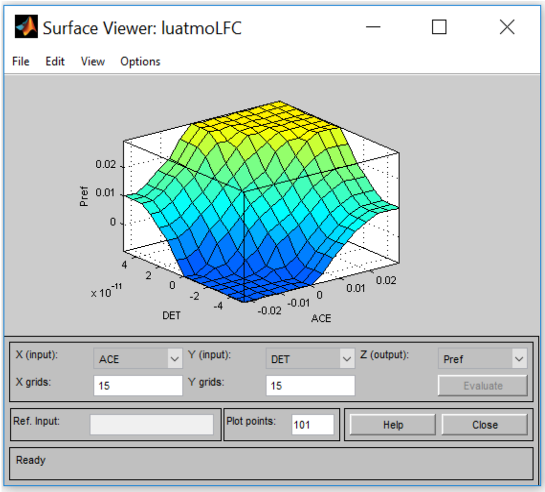
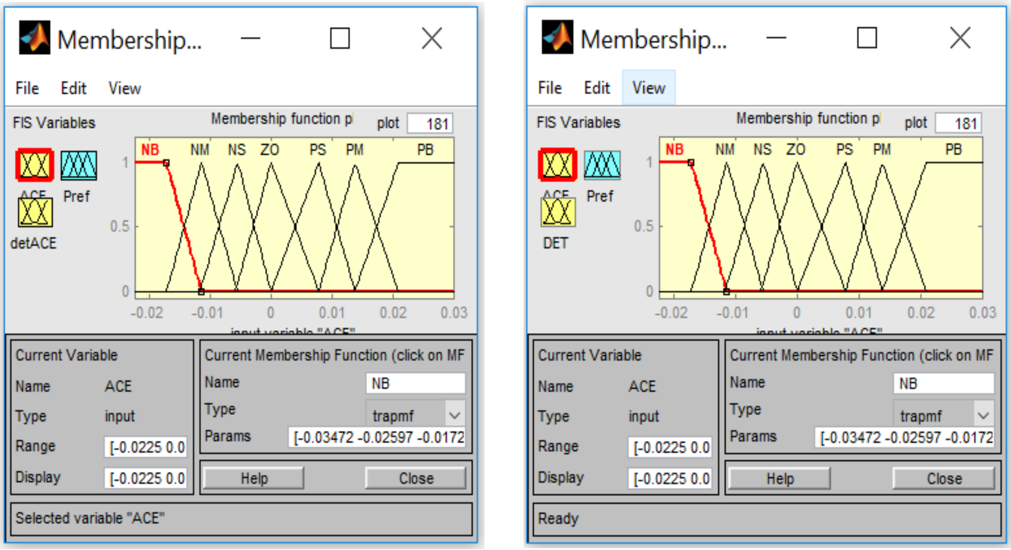
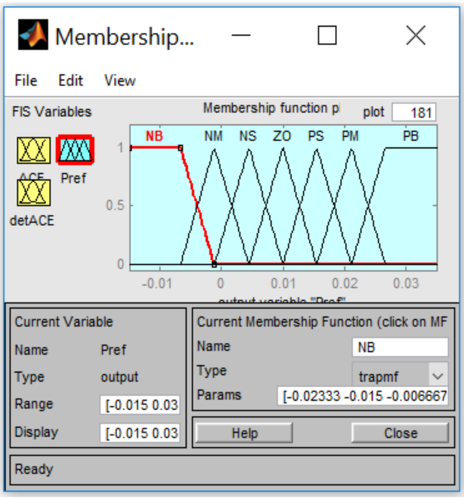


Fig. 3 A 3D-illustration of the 49-fuzzy logic rules



(a) Two inputs



(b) One output

Fig. 4 Input/output of the fuzzy logic model

The successful implementation of a fuzzy logic controller (FLC) hinges on the meticulous design of its rule base, which relies on expert knowledge. Theoretically, well-defined and optimized rules lead to superior control performance. Conversely, overly complex or poorly designed rules can significantly hinder controller efficacy and potentially compromise real-time execution speed, ultimately impacting control quality. This paper proposes a 49-rule base for the FLC, achieved through a robust optimization method – Particle Swarm Optimization (PSO). Two exemplary rules are presented:

- Rule 1: When the area control error (ACE) exhibits a significant decrease, and its derivative (dACE) experiences a substantial increase, the control output (u) must be aggressively increased.
- Rule 2: If both ACE and dACE remain unchanged, the control output (u) should be maintained at its current value.

By adhering to these meticulously crafted rules, the proposed FLC is expected to achieve desirable control performance metrics. The subsequent section will showcase the application of this FLC to a three-area interconnected power network, demonstrating its effectiveness in a practical scenario.

IV. SIMULATION RESULTS AND DISCUSSIONS

This section delves into a case study exploring a three-area interconnected power system, as depicted in Fig. 1 with mathematical equations given in (1) – (16). For this specific scenario, it is reasonable to evaluate the performance of two LFC strategies: the proposed fuzzy logic controller (FLC) introduced earlier and the conventional PID controller, widely used for comparison. The PID controller has the following representation:

This section presents a case study that investigates the performance of load-frequency control (LFC) strategies within a three-area interconnected power system. The system under consideration is depicted in Figure 1, and its mathematical modeling is established through equations (1) to (16).

To comprehensively evaluate the effectiveness of different LFC approaches in this specific scenario, we will compare the performance of two prominent control methods:

Proposed Fuzzy Logic Controller (FLC): This controller, introduced in a previous section, leverages the principles of fuzzy logic to handle complex system dynamics and achieve optimal control performance.

Conventional Proportional-Integral-Derivative (PID) Controller: This widely used controller represents a well-established benchmark for LFC applications. Its mathematical representation is provided below:

$$\begin{aligned} u_i(t) &= K_{P,i} ACE_i(t) + K_{I,i}\int_0^t ACE_i(\tau)d\tau + K_{D,i}\frac{d}{dt}ACE_i(t) \\ &= K_{P,i}\left(ACE_i(t) + \frac{1}{T_{Ii}}\int_0^t ACE_i(\tau)d\tau + T_{D,i}\frac{d}{dt}ACE_i(t)\right) \end{aligned} \tag{17}$$

$$U_i(s) = K_{P,i}\left(1 + \frac{1}{sT_{I,i}} + sT_{D,i}\right) ACE_i(s) \tag{18}$$

Using the above PID controllers, the model of three-area power system built in MATLAB/Simulink is presented in Fig. 5. It should be noted that each area employs one PID regulator for the control aim to maintain the network frequency agains load changes.

Similarly, the control system for such a three – area hybrid electric power grid using the proposed fuzzy logic controllers is illustrated in Fig. 6. Then, comparative simulations will be implemented.

Through this comparative analysis, we aim to identify the LFC strategy that demonstrably offers superior control performance within the three-area interconnected power system. The chosen control approach should effectively maintain grid stability and ensure the desired frequency regulation despite load variations.

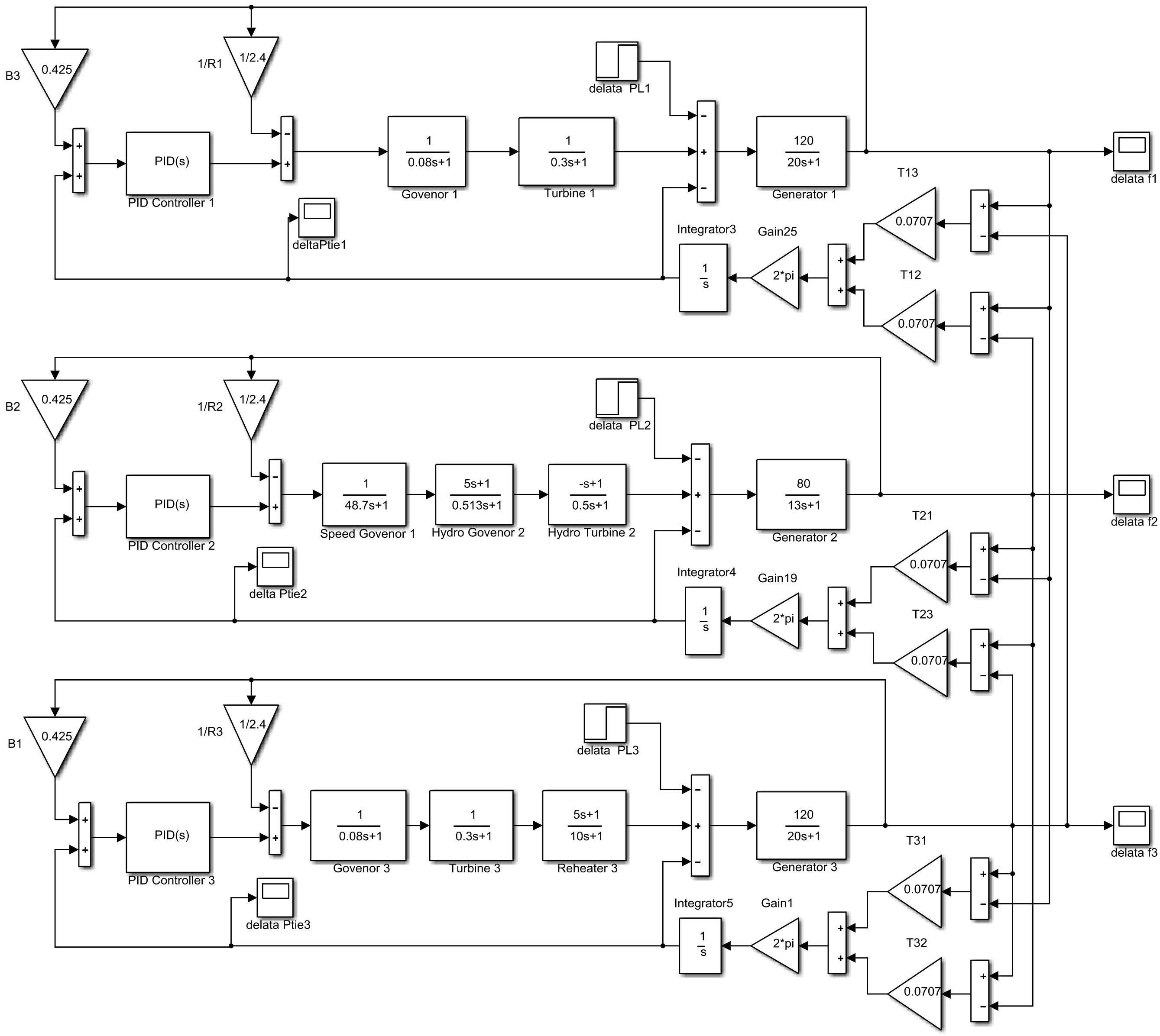


Fig. 5 Three-area interconnected power system with conventional PID-based LFC

Table 2. Three factors of the PID controller

	K_P	K_I	K_D	N
Area 1	0	-0.439552444	0	0
Area 2	-0.7870819146	-0.0368139678	23.3575756045	0.03369707233
Area 3	0	-0.2258644524	0	0

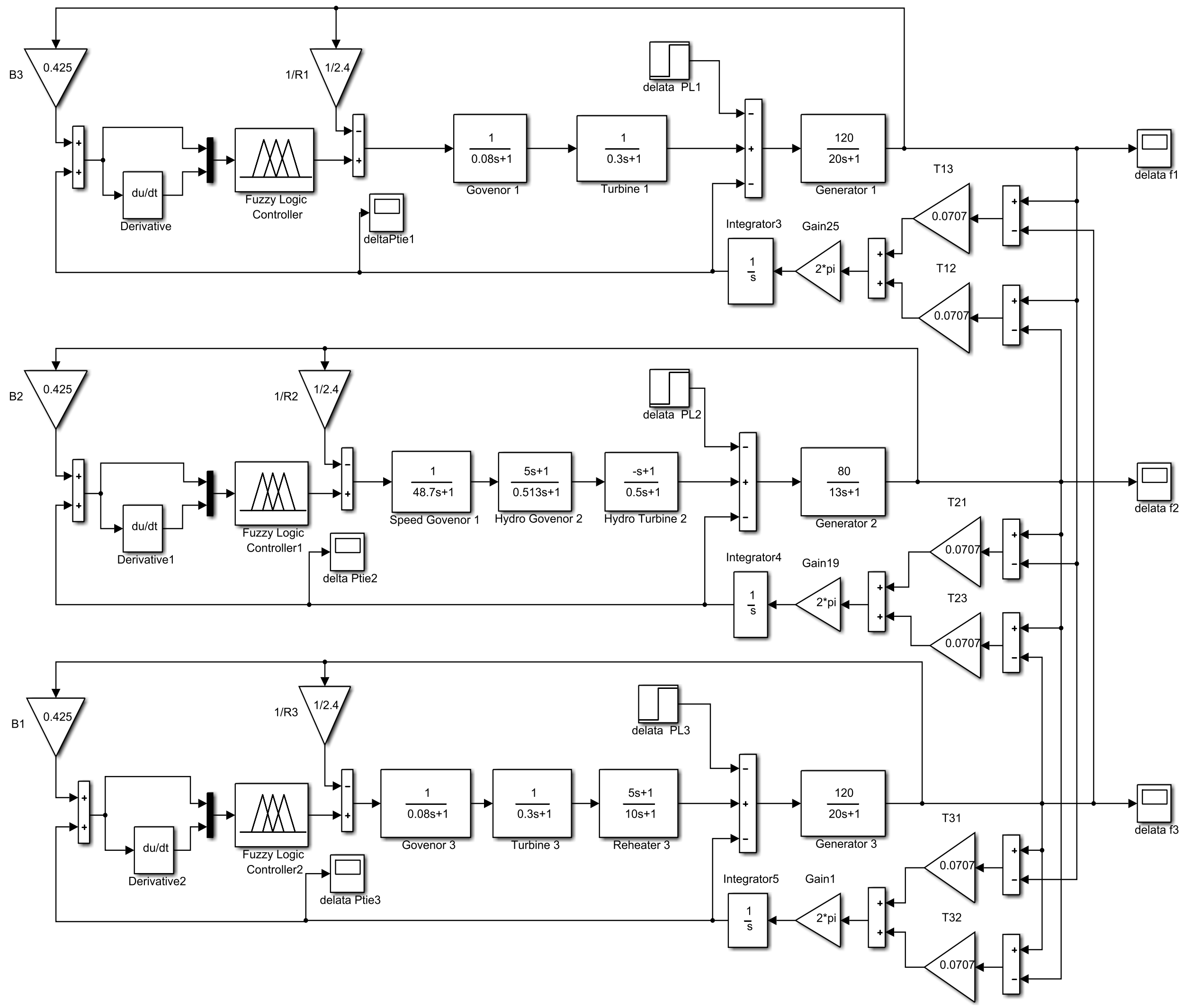


Fig. 6 The three-area interconnected power system with intelligent FLC-based LFC

Table 3 presents the numerical simulation results obtained by implementing both LFC controllers – the traditional PID controller and the proposed fuzzy logic controller (FLC). For comparison purposes, the table also includes a scenario without any LFC implemented. This highlights the effectiveness of both control strategies in maintaining grid stability against load changes.

As evident from Table 3, the FLC demonstrably outperforms the PID controller in terms of key performance metrics. These metrics likely include rise time, undershoot, steady-state error and POT (percentage overshoot) (%).

The superior performance of the FLC can be attributed to its inherent capabilities. Unlike PID controllers, which rely on predefined mathematical models, FLCs can effectively handle non-linearities and uncertainties present in real-world power systems. FLCs leverage a set of fuzzy rules based on expert knowledge, enabling them to adapt to changing system dynamics and achieve superior control performance.

The findings from Table 3 strongly advocate for the adoption of FLCs as a preferred choice for LFC applications. Their ability to handle complex system behavior and achieve better control performance makes them a valuable tool for ensuring grid stability, particularly in modern power systems with increasing complexity.

Table 3. Numerical simulation results

	Control criteria	**Without controller**	**PID – based LFC**	**Fuzzy logic – based LFC**
Δf_1	Rise time (s)	80	115	120
	Undershoot (Hz)	-0.033	-0.0479	-0.031
	Steady-state error (Hz)	-0.005	0	0
	POT (%)	6.6	9.6	6.2
Δf_2	Rise time (s)	80	115	120
	Undershoot (Hz)	-0.0367	-0.044	-0.03
	Steady-state error (Hz)	-0.005	0	0
	POT (%)	7.3	8.8	6.0
Δf_3	Rise time (s)	80	114	120
	Undershoot (Hz)	-0.0331	-0.044	-0.031
	Steady-state error (Hz)	-0.005	0	0
	POT (%)	6.6	8.8	6.2

V. CONCLUSIONAND FUTURE WORKS

This paper has successfully investigated and modelled a complex power system comprising three interconnected subsystems: a hydroelectric power plant, a thermal power plant with non-reheat turbines, and a thermal power plant with reheat turbines. A mathematical model of the power system has been established to facilitate the design of intelligent fuzzy logic controllers for load-frequency control strategies. Simulation results obtained using MATLAB/Simulink software have been compared with those achieved using a PID controller, demonstrating the superior performance of the proposed fuzzy logic-based control solution. Future research will focus on exploring the application of artificial neural network (ANN) controllers for LFC problems. Additionally, the extension of the considered power system to include multiple generators and adapt to the specific characteristics of each country is another promising research direction.

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