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## Load Frequency Control of Interconnected Power System with non-linearities using PSO-based Fuzzy PID Control Approach



**Abstract:** - Load frequency control (LFC) is vital for balancing power generation with fluctuating power demand. It ensures that the system frequency and tie-line power are maintained at their desired levels. The design of an LFC system is crucial for the automation of power systems. This article introduces a Fuzzy Proportional-Integral-Derivative (FPID) control approach for LFC in an interconnected reheat thermal power system, utilizing a Particle Swarm Optimization (PSO) method and incorporating the Generation Rate Constraint (GRC) as nonlinearities. The proposed controller offers the advantage of effectively managing system nonlinearities while being better than classical controllers. The response of the FPID controller is contrasted with both the conventional Proportional-Integral (PI) controller and the Fractional Order PID (FOPID) controller, in scenarios both including and excluding the Generation Rate Constraint (GRC). The response of the system is analyzed by considering load disturbances in each region of the integrated power network.

**Keywords:** Fuzzy PID, Fractional Order PID, Generation Rate Constraint, Load Frequency Control, Particle Swarm Optimization.

### I. INTRODUCTION

In contemporary power systems, LFC is crucial for maintaining system frequency with the power flow of tie-line at their predetermined levels, both under typical conditions and during the system experiences step load disturbance. It is widely understood that the frequency of the system is dependent on the equilibrium between the actual power produced and the instantaneous load demand [1]. The overall generation must align with the overall load demand, including any system-related losses for the efficient operation of a power system. When there is a slight change in load demand, the power flow through tie-line and system may vary from their typical values. The main objective of LFC is to keep the frequency level of the plant at a designated nominal, ensuring that the power exchange across the tie-line between various control regions remains within their predefined limits.

Various control techniques can be utilized in designing load frequency controllers (LFCs) to enhance the performance. Within the different types of LFCs, the conventional PI controller is the most commonly used [2,3]. While conventional controllers are easy to design, they tend to take more time and result in significant frequency deviations. Numerous controllers with state feedback approach, is developed to enhance the response [4,5].

Innovative methods based on intelligent approaches, including neural networks, fuzzy logic (FL), are acquiring momentum nowadays [6]. The FL method possesses the ability to handle instabilities and nonlinearities in advanced electrical structures, demonstrating that FL is an effective and versatile approach for addressing the LFC problem in sophisticated system models, including hydro-hydro configurations [7–11]. The section built upon hybrid fuzzy logic was analyzed in [7]. The effective Takagi–Sugano LFC for addressing non-linearity and parametric changes was demonstrated in reference [8]. The FL approach in interconnected LFC, along with the LFC with type-2 fuzzy that accounts for GRC, has designed in references [9, 10]. The FL approach incorporating the genetic algorithm (GA) has demonstrated in reference [11]. However, some researchers have noted limitations of the GA, such as convergence issues and the potential for getting trapped in local minima, which can affect the ability to find optimal solutions.

The use of the modern robust PSO technique has significantly minimized the challenges typically encountered with the application of GA. PSO is less likely to become trapped in local minima and generally requires less computation time to achieve comparable performance levels [12]. The advantages of the Adaptive Model Predictive Control

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(AMPC) method compared to the Model Predictive Control (MPC) method are discussed in [13]. Recently, some researchers have integrated fuzzy logic with optimization techniques. A self-regulating FPID controller for LFC in a two-region network system was utilized in reference [14]. The PSO strategy to refine the gains of PID controller for AGC based on fuzzy is employed in [15]. A Fuzzy-PSO-PID strategy for LFC in a hydro-hydro network, effectively optimized using PSO through the collective efforts of fuzzy logic and PID control, is employed in reference [16]. References [15] and [16] do not account for uncertainties. In light of the above, this paper employs an FPID control approach for LFC in a two-region interconnected reheat power plant, utilizing a PSO algorithm and considering the GRC.

The primary contributions of this article are as follows:

- The article presents a FPID control strategy for LFC in a two-area interconnected reheat thermal power plant, utilizing a PSO algorithm and accounting for the GRC.
- The responses from the FPID controller are analysed with both conventional PI and FOPID controllers, in scenarios with and without the GRC, highlighting the merits of the introduced controller in effectively managing system nonlinearities and providing faster response times.
- The system response is examined by including load perturbations in each region of the interconnected power plant, demonstrating the efficacy of the proposed FPID control strategy in maintaining system stability under varying conditions.

## II. SYSTEM MODEL

The system being studied comprises a two-area interlinked power plant of a reheat thermal system, as depicted in Fig.1. The Area Control Errors (ACEs) are the inputs to the respective controllers, while  $u_1$  and  $u_2$  are the outputs. The ACE is a summation of the frequency error and the error in tie-line. The ACEs for the system depicted in Fig.1 are defined by

$$ACE_1 = \Delta P_{12} + B_1 \Delta f_1 \tag{a}$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta f_2 \tag{b}$$

In this context,  $\Delta P_{12}$  and  $\Delta P_{21}$  represent the changes in tie-line power for areas 1 and 2, respectively;  $B_1$  and  $B_2$  are the frequency bias constants for areas 1 and 2; and  $\Delta f_1$  and  $\Delta f_2$  denote the frequency perturbations in areas 1 and 2, respectively.

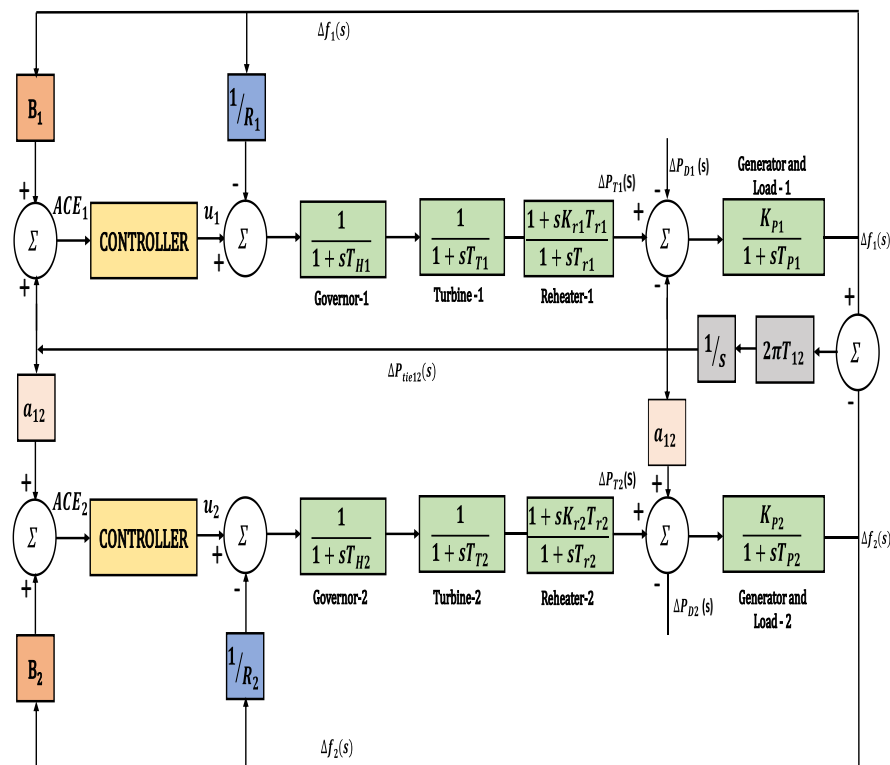


Fig.1. Block diagram representation of two area interconnected reheat thermal plant

In a power system that includes steam plants, the rate at which power production can be adjusted is restricted to a specific maximum value. As outlined, implementing limiters on the governors can constrain the rate of generation for steam plants. For thermal units, a common value for the GRC is  $3\%/min$ . [17]. The GRCs for each area are considered by incorporating limiters into the turbines, illustrated as Fig. 2.

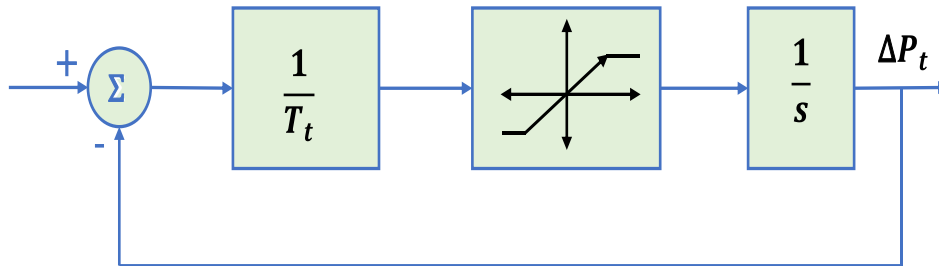


Fig. 2. Turbine system including GRC

### III. CONTROL METHODS

In traditional power systems, standard PI controllers are typically used for secondary frequency control and are usually tuned based on fixed operating conditions. However, when these conditions change, the performance of PI controllers may not meet the desired standards. Continuously adjusting the PI controller to adapt to variations in the power system is crucial for maintaining optimal performance. Fuzzy logic offers an efficient intelligent strategy for real-time optimization of the parameters of PI controller.

This portion concentrates on tuning the conventional PI controller for frequency regulation of two region interlinked reheat thermal plant, particularly considering the GRC with load variations. Subsequently, a FOPID controller is developed. The results will be analyzed using the PSO-based FPID control strategy in the following sections.

#### A. PI Controller

In the continuous time, the control signal  $u(t)$  produced by the PI controller is the sum of the proportional and integral components:

$$u_{PI}(t) = K_{p,PI}e_{PI}(t) + K_{i,PI} \int_0^t e_{PI}(\tau) d\tau \tag{2}$$

Where  $u_{PI}(t)$  is the control output,  $e_{PI}(t)$  is the error,  $K_{p,PI}$  denotes the proportional gain and  $K_{i,PI}$  represents the integral gain.

A PI controller can quickly respond to errors and gradually eliminate any steady-state error.

#### B. FOPID Controller

A FOPID control method is an expansion of the traditional PID control method that incorporates fractional analysis. The FOPID controller provides additional flexibility in tuning and can offer improved performance in various control applications. The system diagram of FOPID Controller is illustrated as Fig. 3.

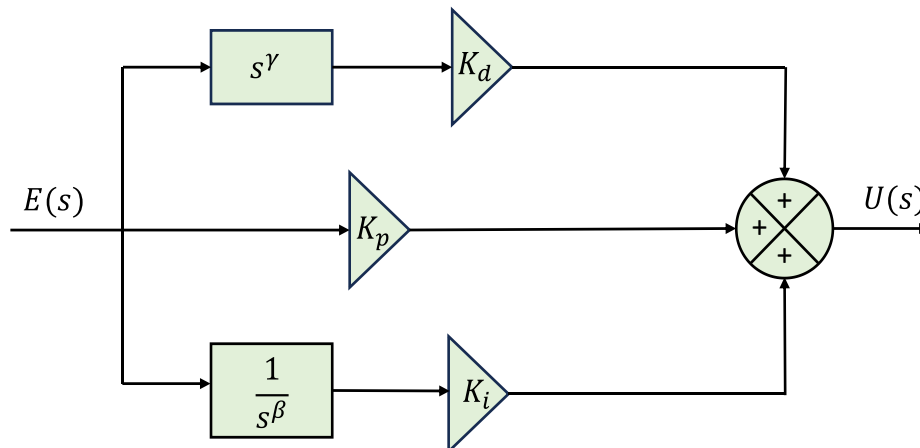


Fig.3. FOPID Controller

The FOPID controller includes three components, each with fractional orders:

**Fractional-Order Proportional (FOP):** The proportional action is modified by using a fractional order, which provides a more flexible adjustment of the control response.

**Fractional-Order Integral (FOI):** The integral action is also fractional, allowing for more precise accumulation of past errors.

**Fractional-Order Derivative (FOD):** The derivative action is fractional, which helps in adjusting the control response according to the change of error.

In the continuous-time domain, the transfer function of the FOPID control method can be presented as:

$$G_{FOPID}(s) = K_{pFOPID} \cdot s + \frac{K_{iFOPID}}{s^\beta} + K_{dFOPID} \cdot s^\gamma \tag{3}$$

Where  $K_{pFOPID}$ ,  $K_{iFOPID}$  and  $K_{dFOPID}$  are the proportional, integral, and derivative gain of FOPID,  $\beta$  and  $\gamma$  are the fractional orders for the integral, and derivative terms, respectively.

The fractional orders ( $\beta, \gamma$ ) provide greater flexibility in shaping the frequency characteristic of the controller. The FOPID control method can offer improved response compared to a classical PID control method, particularly in systems with complex dynamics and uncertainties.

*C. PSO-based Fuzzy PID Control Strategy*

The PSO-based FPID control strategy integrates a traditional PID control strategy with a fuzzy logic system to enhance its performance. The PSO algorithm functions as an optimization tool for the real-time adjustment of membership functions. The outline of proposed FPID control strategy is illustrated in Fig. 4, and the mathematical expression for the final control output of the FPID is given by:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \tag{4}$$

Here,  $K_p$ ,  $K_i$ , and  $K_d$  stands for the proportional, integral, and derivative gain of the Fuzzy PID control strategy. These gains are continuously refined based on the error  $e(t)$  and the time derivative of the error  $\dot{e}(t)$ . The errors considered here are the Area Control Errors (ACE).

In this PSO-based FPID control strategy, PSO algorithm is applied to optimize the fuzzy rules and PID variables.

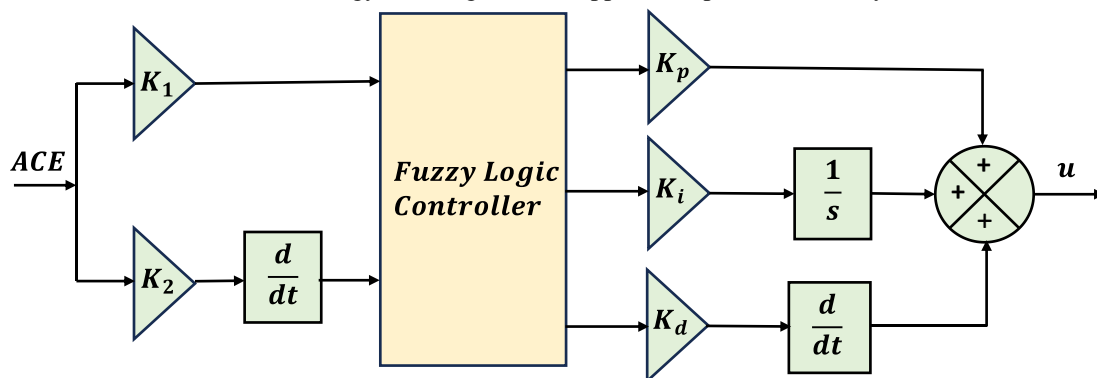


Fig.4. Structure of FPID Controller

In the proposed FPID controller shown in Fig. 4,  $K_1$  and  $K_2$  are the input scaling gains which are essential gains. Furthermore, the gains associated with the fuzzy controller's output, specifically  $K_p$ ,  $K_i$ , and  $K_d$ , are vital in dynamically shaping the system's response.

The entries to the fuzzy logic controller (FLC) are the ACE and its time derivative. The triangular membership functions, as illustrated in Fig. 5, are utilized for both the FLC's inputs and outputs. The linguistic parameters, namely Negative Small (NS), Negative Big (NB), Zero (ZE), Positive Big (PB), Positive Small (PS) are employed for the FLC inputs and outputs.

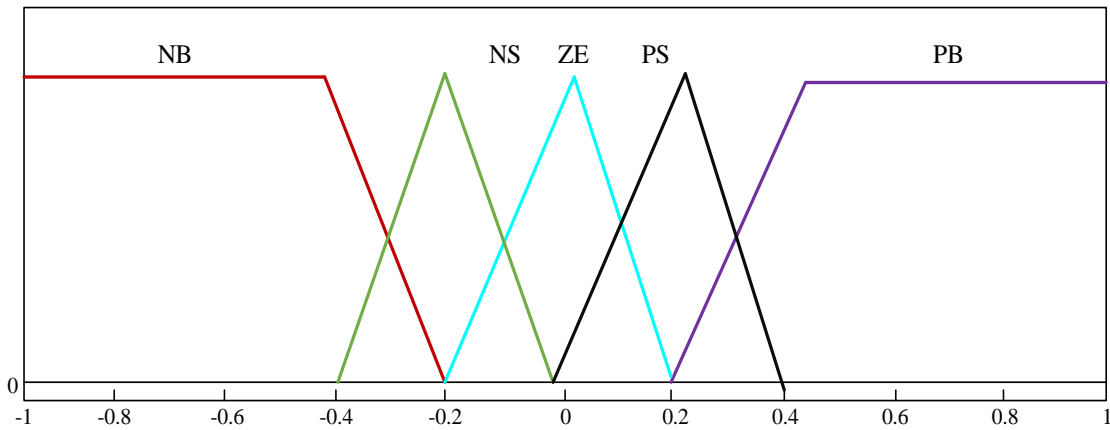


Fig.5. Input-output fuzzification functions in the FLC

Developing an appropriate rule base is crucial, as it significantly influences the effectiveness of the FLC [18]. The fuzzy rule set for the FLC's inputs and outputs is developed based on a thorough examination of the changing system behavior and is detailed in Table I. In this paper, the Mamdani inference method is chosen, and the center of gravity model is applied for defuzzification to determine the precise values of the FLC outputs.

Table I. Rule base for FLC inputs and outputs

<i>ACE</i>	<i>ACE</i>				
	NB	NS	ZE	PS	PB
NB	NB	NS	NB	NS	ZE
NS	NS	NS	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PB	PB	PB

**Objective function**

Different objective functions, including Integral Absolute Error (IAE), Integral Time Square Error (ITSE), Integral Square Error (ISE), and Integral Time Absolute Error (ITAE), are used to assess the system's performance in the time domain. In this article, the ITAE cost function is preferred for optimization because it is more effective at minimizing settling time compared to the ISE or IAE criteria [19,20]. Furthermore, optimization using the ITAE generally results in reduced peak overshoot. As a result, this study employs the ITAE objective function for tuning the controller gains. The ITAE cost function is mathematically defined as follows:

$$ITAE = \int_0^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie12}|) \cdot t \cdot dt \tag{5}$$

Where  $\Delta f$  denotes the system's frequency deviation, while  $t_{sim}$  refers to the duration of the simulation.

**PSO Algorithm**

The PSO algorithm is a probabilistic method for optimization, inspired by patterns observed in nature. This algorithm models the search operation as a flock of birds randomly exploring a particular area in search of food. Although the birds are unaware of the exact location of the food, they do know their distance from a particular spot with each movement during the search process. Each bird moves closer to the food source by tracking the adjacent bird which is closest to the target location. In this method, every bird is modelled as a particle, and a cluster or swarm is created by all the particles coming together. Every particle is defined by vectors,  $X(t)$  and  $V(t)$ , which correspond to the position and velocity of the particle at time  $t$ .

At time  $t + 1$ , the velocity and position of every particle are determined based on the equations (6) and (7). Here,  $V_{ij}$  and  $X_{ij}$  represent the  $i$ -th component of the velocity vector  $V$  and position vector  $X$  for the  $i$ -th particle, respectively [21].

$$V_{ij}(t + 1) = w \times V_{ij}(t) + c_1 \times r_1 \times (P_{best,ij}(t) - X_{ij}(t)) + c_2 \times r_2 \times (G_{best,j}(t) - X_{ij}(t)) \tag{6}$$

$$X_{ij}(t + 1) = X_{ij}(t) + V_{ij}(t + 1) \tag{7}$$

In this context,  $i$  limits from 1 to  $n$  and  $j$  limits from 1 to  $m$ , in which  $n$  denotes the total amount of particles present in the swarm, and  $m$  indicates the number of elements or dimensions for the parameters  $X_i$  and  $V_i$ .  $X_{ij}$  represents the  $j$ -th dimension of the position of the  $i$ -th particle,  $V_{ij}$  is the  $j$ -th dimension of the velocity of the  $i$ -th particle,  $P_{best,ij}$  denotes the  $j$ -th dimension of the best position found by the  $i$ -th particle up to time  $t$ , and  $G_{best,j}$  refers to the  $j$ -th dimension of the best location found by any particle up to now. The parameter  $w$  is the inertia coefficient, while  $c_1$  and  $c_2$  are two random variables within the range of  $[0, 1]$ , serving as cognitive and social factors, respectively. The variable  $t$  represents the time or iteration. The PSO strategy can generally be outlined in the subsequent steps [22-24]:

- i. The algorithm parameters, including  $N$  (population size),  $D$  (dimension of the search area),  $c_1$  and  $c_2$ , and  $w$  are chosen.
- ii. The particles' positions  $X_i$  and velocities  $V_i$  are initialized.
- iii. The  $P_{best}$  vectors for all particles to the initial values determined in Step ii are initialized.
- iv. The fuzzy system parameters are adjusted based on the position vector of particle  $X_i(t)$  and evaluating the fitness of every particle employing the objective function.
- v.  $G_{best}$  is calculated employing the cost values of all the particles.
- vi. The particle position vectors  $X_i$  and velocity vectors  $V_i$  are updated based on equations (6) and (7).
- vii. The  $P_{best}$  corresponds to each particle is updated.
- viii.  $G_{best}$  is upgraded based on the performance of  $G_{best}(t + 1)$ .
- ix. In case the stopping criteria is satisfied, the process will terminate, and the optimal values of the parameter will be obtained; otherwise, proceed back to Step vi.

#### IV. SIMULATION RESULTS AND ANALYSIS

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A PSO-based FPID control method for LFC in a two-area interlinked reheat thermal power model is developed using MATLAB/SIMULINK 2021a. The strategy is evaluated both with and without including the GRC and under a 1 percent load disturbance. The response of the introduced FPID controller is then analyzed with that of the classical PI controller and the FOPID controller. The system variables utilized in the simulation are detailed in Table II.

Table II. System variables under study

Variable	Symbol	Value
Turbine time constants	$T_T$	0.3 s
Hydraulic time constants	$T_H$	0.08 s
Reheat time constants	$T_r$	10 s
Control area time constants	$T_P$	12 s
Frequency bias constants	$B$	0.43 MW/Hz
Tie line power coefficient	$T_{12}$	0.05
Control area capacity ratio	$a_{12}$	-1
Reheat gain	$K_r$	0.5
Control area gain	$K_P$	100
Regulation Constant	$R$	2.4 Hz/MW

Fig. 6 illustrates the frequency response of Area-1, excluding the GRC. It compares the suggested FPID controller with the classical PI controller and the FOPID controller. It is clear from the results that, the proposed

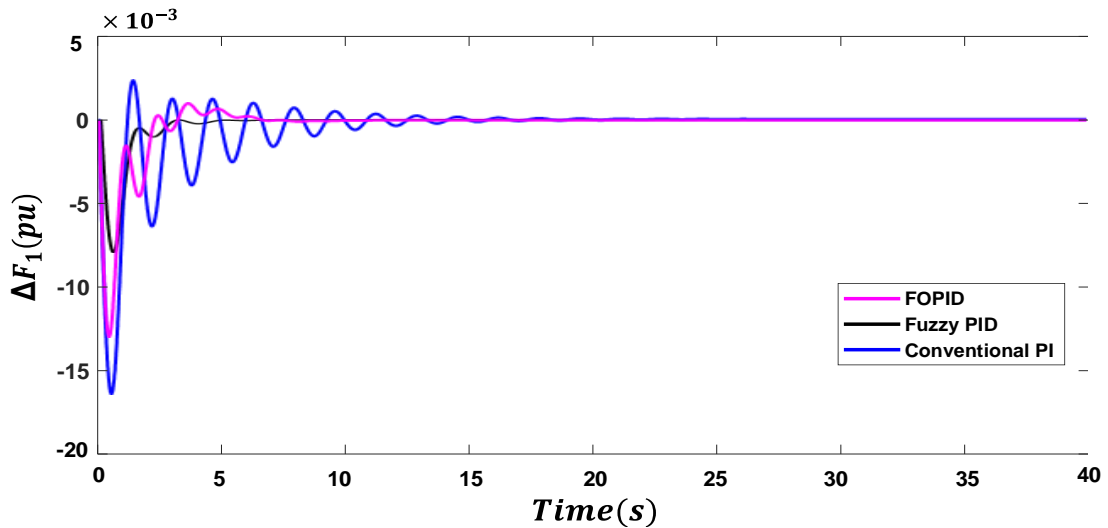


Fig.6. Frequency response in Area-1 without GRC

FPID controller demonstrates better response compared to both the PI and FOPID controller, particularly with respect to settling time, overshoot, and overall stability.

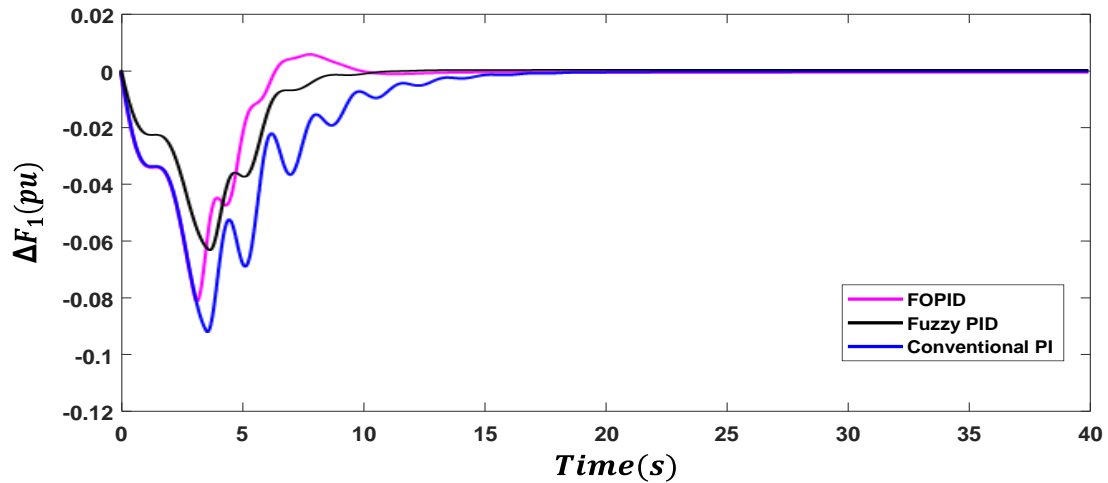


Fig.7. Frequency response in Area-1 with GRC

The frequency response of Area-1, including the GRC is depicted in Fig. 7. The results clearly reveal that the introduced FPID controller outperforms both the PI and FOPID controllers, especially with respect to settling time, overshoot, and overall stability, even with the inclusion of the GRC.

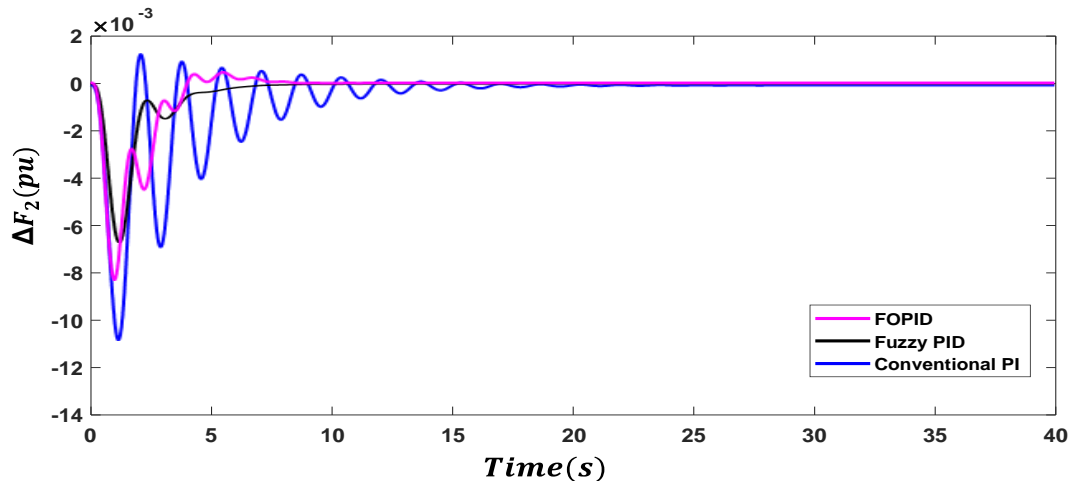


Fig.8. Frequency response in Area-2 without GRC

The frequency response of Area-2 without considering the GRC is depicted in Fig. 8. The results distinctly highlight that the FPID controller outperforms compared to both the PI and FOPID controllers.

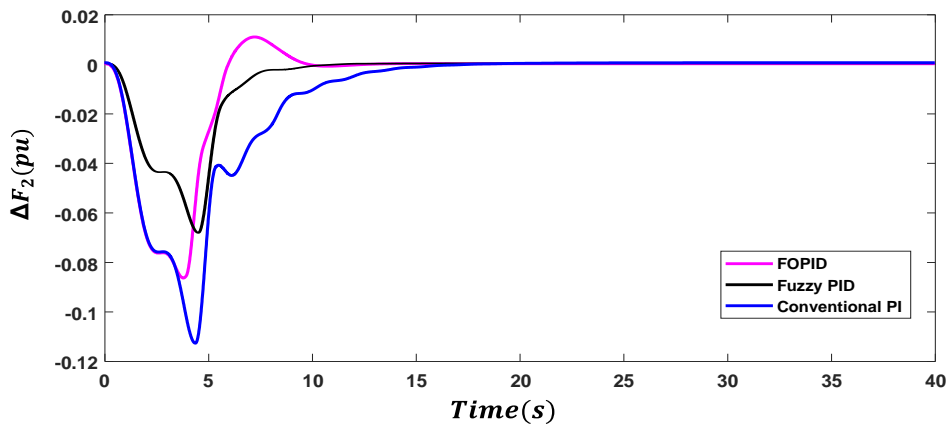


Fig.9. Frequency response in Area-2 with GRC

Similarly, Fig. 9 illustrates the frequency characteristics of Area-2 including the GRC. The results clearly show that the FPID controller shows less undershoot, less overshoot, and a shorter settling time in comparison with the PI and FOPID controllers.

Figures 10 and 11 present the simulation results showing tie-line power, with and without the GRC, respectively. The results compare the response of the FPID controller against the classical PI and FOPID controllers. The results clearly indicate that the FPID controller outperforms both the PI and FOPID controllers

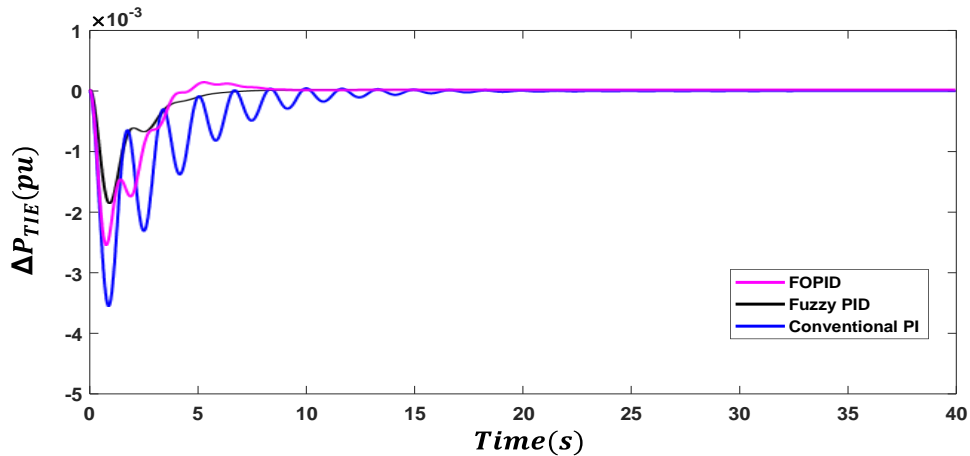


Fig.10. Tie-line power with GRC

with respect to undershoot, overshoot, settling time, and overall stability, regardless of whether the GRC is considered.

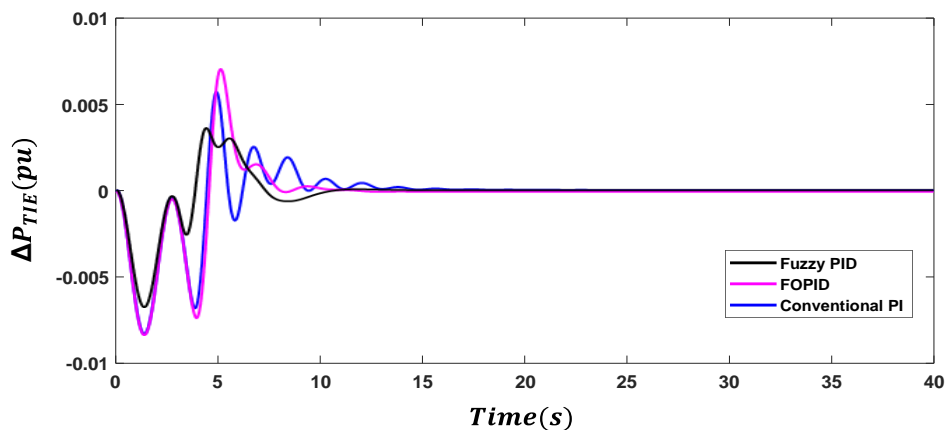


Fig.11. Tie-line power without GRC

## V. CONCLUSION

The proposed FPID controller, optimized implementing the PSO algorithm, effectively enhances LFC in a two-area interlinked reheat thermal power plant, even when considering the GRC as nonlinearities. The FPID controller demonstrates superior performance over conventional PI and FOPID controllers, particularly in managing system nonlinearities and responding more swiftly to load disturbances. This improved performance underscores the potential of the FPID controller as a robust solution for sustaining system frequency and tie-line power stability in dynamic power systems.

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