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Dynamic Response of Load Frequency Control Using a Proportional Integral Derivative (PID) Controller

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ABSTRACT:
Load Frequency Control (LFC) plays a crucial role in maintaining power system stability by regulating frequency deviations and tie-line power flows following load disturbances. In this study, the performance of a Proportional–Integral–Derivative (PID) controller is evaluated and compared with other classical controllers (P and PI) in thermal–thermal, thermal–hydro, and multi-area interconnected systems. The analysis focuses on key performance indices, namely overshoot, rise time, and settling time. Results show that the PID controller generally enhances dynamic response by reducing settling time and improving damping characteristics, particularly in hydro and hybrid systems where settling time is minimized to 27.93 s and tie-line power deviations are significantly reduced compared to the uncontrolled case. However, in thermal–thermal systems, PID control sometimes amplifies overshoot (e.g., 0.06205 pu compared to 0.005524 pu without control), highlighting its sensitivity to tuning. Comparatively, PI controllers offer more balanced improvements in both frequency and tie-line power stabilization, while proportional control excels in reducing rise time but may worsen settling performance in certain cases. These findings align with previous studies that emphasize the superior performance of PID controllers in complex and hybrid networks due to their combined proportional, integral, and derivative actions, but also confirm observations in literature that improper tuning can degrade performance in purely thermal systems. The comparative analysis underscores the importance of controller design and parameter optimization in LFC applications and demonstrates that while PID offers the most versatile performance, PI control remains a reliable alternative for ensuring consistent stability.

KEYWORDS: Load Frequency Control (LFC), Dynamic Response, Power System Stability, Proportional-Integral-Derivative (PID) Controller, Frequency Deviation, Power System Control
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I. INTRODUCTION

Load Frequency Control (LFC) is essential for maintaining the balance between power supply and demand, ensuring system stability and reliability in power systems. However, the application of Proportional-Integral-Derivative (PID) controllers in LFC faces several challenges. The increasing integration of renewable energy sources introduces nonlinearity into the power system, complicating the LFC task. PID controllers struggle to manage these nonlinearities effectively, leading to frequency deviations and instability (Bevrani et al., 2010). Modern power systems are characterized by high penetration of intermittent renewable energy sources and more complex grid dynamics. Conventional PID-based LFC systems often fail to adapt to these changes, necessitating more advanced control strategies (Bevrani 2009; Kundur 1994). Achieving precise frequency regulation and set point tracking is challenging due to the inherent uncertainties and disturbances in power systems. PID controllers, with their fixed parameters, may not respond adequately to these variations, resulting in frequency oscillations and deviations (Zhao et al., 2015).

Traditional Proportional- Integral-Derivative (TPID) controllers, despite their widespread use due to simplicity, clarity in functionality, and ease of use, face limitations in robustness when tuned via conventional methods. Furthermore, the integration of renewable energy sources introduces additional variability and non-linearity, exacerbating the challenge of frequency stabilization. The advent of advanced control strategies, including fractional-order PID controllers, two-degree freedom PID type controllers, and Internal Model Control (IMC)-based PID controllers, offers new pathways to enhance load frequency control (LFC). However, these strategies must be scrutinized for their ability to handle the inherent non-linearity of the system, parametric uncertainties, and the effects of communication delays. This study aims to address the gap in current LFC mechanisms by developing, testing, and validating a PID controller design that ensures robust frequency stabilization across varying load conditions and system nonlinearities. By leveraging the latest advancements in PID controller design, this research will contribute to the development of a more resilient, efficient, and sustainable power system. (Bevrani 2009; Tan 2009; Li, C., & Zhang, Y. 2011).

Load frequency control using PID controllers has been a topic of interest for researchers in past decades. Modeling and simulation of such has been caried out by the researchers. PID, It has been widely used in power system to Maintaining power system stability and reliability and to compensate for load variations and disturbances. This paper explores the role of PID controllers in LFC, analyzing their effectiveness in reducing steady-state errors and improving transient response. Md.Al-Amin Sarker and A.K.M Kamrul Hasan (2016) presented load frequency in power systems. The paper presented a decentralized control scheme for Load Frequency Control in a multi-area Power System by appreciating the performance of the methods in a single-area power system. Several modern control techniques are adopted to implement a reliable stabilizing controller. An attempt was made aiming at investigating the load frequency control problem in a power system consisting of two power generation units and the dynamic performance of Load Frequency Control (LFC) in a three-area interconnected hydrothermal reheat power system by the use of Artificial intelligence. In this proposed scheme, control methodology was developed using a conventional controller, for a three-area interconnected hydro-thermal reheat power system. In this research, area-1 and area-2 consist of thermal reheat plants whereas area-3 consists of hydropower plants. Further in this scheme, the combination of the most complicated systems like a hydro plant and thermal plant with a reheat turbine were interconnected. The performance of the controllers is simulated using MATLAB/SIMULINK package. The robustness and reliability of the various control schemes are examined through simulation.

Enes Yalçin; Ertuğrul Çam; and Murat Lüy(2010) discussed Load frequency control in four-area power systems using PID controller. In this paper, load frequency control (LFC) which is one of the most important issues in interconnected power systems is affected by using PID controller, which is used in many sectors, and also investigated its performance. Four-area power system is preferred for LFC problem in multi area power systems are more complex and important than one area power system. In this paper, LFC problem is defined firstly, and then mathematical models of power systems are explained. Finally, PID controller are described shortly and power system is modelled by using MATLAB-Simulink platform.

Surya Prakash and S.K. Sinha (2011) presented a paper on Load frequency control of three area interconnected hydro-thermal reheat power system using artificial intelligence and PI controllers. In the proposed scheme, control methodology developed using a conventional PI controller, Artificial Neural Network (ANN) and Fuzzy Logic controller (FLC) for three area interconnected hydro-thermal reheat power system. In this paper area-1 and area-2 consists of thermal reheat power plants whereas area-3 consists of hydropower plants. In this proposed scheme, the combination of the most complicated systems like hydro plant and thermal plant with reheat turbines are interconnected which increases the nonlinearity of the system. The performances of the controllers are simulated using MATLAB/SIMULINK package. A comparison of PI controller, Fuzzy controller and ANN controller-based approaches shows the superiority of the proposed ANN-based approach over Fuzzy and PI for the same conditions. To enhance the performance of PI, Fuzzy and neural controller sliding surface are included. The simulation results are also tabulated as a comparative performance because of settling time and peak overshoot.

II. METHOD

In dynamic modelling and simulation of response on load frequency control using Proportional Integral Derivative (PID), we will use MATLAB software to model and understand load frequency control using a PID controller. This is to ascertain the rise time, overshoot, and settling time of a three-area interconnected hydro-thermal reheat power system using Proportional, Integral, and Derivative controllers.

In an isolated control area case, the incremental power (ΔP_G-ΔP_D) accounted for by the rate of stored kinetic energy and the increase in area load caused by frequency. The transfer function of the different blocks used in power system models is presented in equation numbering.

Transfer function (T/F) of hydraulic Turbine is $\frac{-T\omega .s+1}{0.5\ T\omega .s+1}$ (1)

T/F of hydraulic Governor is

$$\frac{Kd.s^2+Kp.s+Ki}{Kd.s^2+(Kp+f/R_2)s+Ki} \quad (2)$$

T/F of the governor (thermal plant) is

$$\frac{1}{Tg.s+1} \quad (3)$$

T/F steam turbine

$$\frac{Kr.Tr.s+1}{Tr.s+1} \quad (4)$$

T/F of Re-heater is

$$\frac{1}{Tt.s+1} \quad (5)$$

And the transfer function of the Generator

$$\frac{Kp}{Tp.s+1} \quad (6)$$

2.1 MODELING OF THE TIE-LINE

The power transfer equation through tie line is

$P_{12} = \frac{|v_1|\,|v_2|}{x}\sin(\delta_1 - \delta_2)$ (7)

Considering area 1 has surplus power and transfer to area 2

P_{12} = power transferred from area 1 to 2 through tie line.

$P_{12}\frac{|v_1|\,|v_2|}{x_{12}}.\sin(\delta_1 - \delta_2)$ (8)

Where

δ_1, δ_2 and δ_3 = power angles of end voltages V_1,V_2 and V_3 of equivalent machine of the three respectively.

X_{12} = reactance of the tie line.

The order of the subscript indicates that the tie line power is defined as positive in direction 1 to 2. For a small deviation in the angles and the tie line power changes with the amount. i.e small deviation in δ_1, δ_2 and δ_3 changes by $\Delta\delta 1$, $\Delta\delta 2$ and $\Delta\delta 3$ respectively.

Power P_{12} changes to $P_{12}+\Delta P_{12}$

Therefore, power transferred from Area 1 to Area 2 as given

$\Delta P_{12}(s) = \frac{2\pi T°}{S}(\Delta f_1(s) - \Delta f_2(s))$ (9)

T° = Torque produced

2.2 TIE LINE CONTROL

In normal operation the power on the tie-line follows from the equation

$[\Delta P_{TI}(s) - \Delta P_{12}(s)] = \frac{2H_1}{f_0}s\Delta f_1 + B_1\Delta f_1(s)$

(10)

$= \frac{2H^1}{f_0}\Delta f_1(S)B_1[\frac{1}{B_1}S + 1]$ (11)

If $\frac{2H_1B_1}{f_0} = \frac{1}{Kp_1}$ (12)

$\frac{1}{B_1} = T_{p1}$. (13)

Equation (3.10) can be given as

$\Delta f_1(s) - G_{pI}(S)[\Delta P_{TI}(s) - \Delta P_{EI}(s) - \Delta P_{12}(S)]$.(14)

$G_{PI}(s) = \frac{Kp_1}{1+sTp_1}$ (15)

$\Delta P_{12} = \Delta P_{21} = \Delta P_{31}$ (16)

Where ΔP_E is the real load change.

Due to the action of the turbine controllers, the generator increases its output by the amount ΔP_T.

The net surplus power $\Delta P_T - \Delta P_E$ will be absorbed by the system.

Tie-line bias control is used to eliminate steady-state error in frequency in tie-line power flow. This states that each control area must contribute its share to frequency control in addition to taking care of its own net interchange.

Let ACE_1 = area control error of area 1
ACE_2 = area control error of area 2
ACE_3 = area control error of area 3

In this control, ACE_1, ACE_2, and ACE_3 are made linear combination of frequency ant tie line power error (parkash S et al, 2009).

$ACE_1 = \Delta P_{12} + b_1\Delta f_1$ (17)
$ACE_2 = \Delta P_{21} + b_2\Delta f_2$ (18)
$ACE_3 = \Delta P_{31} + b_3\Delta f_3$ (19)

Where the constants b_1, b_2, and b_3 are called area frequency bias area 2 and 3 respectively.

Now ΔPR_1, ΔPR_2, and ΔPR_3 are model integrals of ACE_1, ACE_2, and ACE_3 respectively.

$\Delta PR_1 = -K_{i1}\int_0^1(\Delta P_{12} + b_1\Delta f_1)\,dt$ (20)

$\Delta PR_2 = -K_{i2}\int_0^1(\Delta P_{21} + b_2\Delta f_2)\,dt$ (21)

$\Delta PR_2 = -K_{i3}\int_0^1(\Delta P_{13} + b_3\Delta f_3)\,dt$ (22)

$\Delta P_{12} = \Delta P_{tie,1}$, $\Delta P_{21} = \Delta P_{tie,2}$, and $\Delta P_{31} = \Delta P_{tie,3}$ (23)

Therefor $\frac{\Delta Ptie_{,1}}{\Delta Ptie_{,2}} = -\frac{T_{12}}{T_{21}}$ = constant (24)

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Hence = $\Delta P_{tie,1} = \Delta P_{tie,2} = = \Delta P_{tie,3} = 0$ (25)
$\Delta PR_1 = \Delta PR_2 = \Delta PR_3$ (25)
And $\Delta f_1 = \Delta f_2 = \Delta f_3 = 0$ (26)

Thus, under steady conditions change the tie-line power frequency of each area is zero. This has been achieved by integration of ACEs in the feedback loops of each area (Kothari D P et al, 2003). The control methodology used (P, PI, and PID) is mentioned in the preceding sections.

2.3 CONTROL METHODOLOGY

Each of these controllers has a different control methodology, influencing system performance in terms of stability, accuracy, and transient response.

MODEL OF A PROPORTIONAL(P) CONTROLLER

A P controller is the simplest form of a controller, where the control output is proportional to the error signal.

Time-Domain Representation

The control law for a P controller is given by:

$U(t) = K_p e(t)$ (29)

Where:

- u(t) is the control output (e.g. input to a governor in a power system).
- e(t) = r(t) – y(t) is the error signal (difference between reference r(t) and output y(t)
- K_p is the proportional gain, which determines the control response

Laplace Transform (Transfer Function Form)

Taking Laplace Transform:

$U(s) = K_p E(s)$ (30)

The transfer function of the P controller is:

$G_p(s) = \frac{U(s)}{E(s)} = K_p$ (31)

Were

- $G_p(s)$ is the transfer function of the P controller
- S is the Laplace variable

Closed-Loop System with a P controller

Is a P controller is applied to a general system with plant transfer function G(s), the closed-loop transfer function is:

$T(s) = \frac{\left(K + \frac{K_i}{s}\right)G(s)}{1+\left(K + \frac{K_i}{s}\right)G(s)}$ (32)

2.4 MODEL OF A PROPORTIONAL INTEGRAL (PI) CONTROLLER

A Proportional-Integral (PI) controller combines proportional control and integral control to improve system performance by eliminating steady-state error.

The time PI control law is:

$U(t) = K_p e(t) + K_i \int e(t)dt$ (33)

Where:

- U(t) is the control output.
- e(t) = r(t) - y(t) is the error signal (difference between reference r(t) and output y(t)
- K_p is the proportional gain, which reacts to the current error
- K_i is the integral gain, which eliminates steady-state error by integrating past errors.

Laplace Transform (Transfer function form)

$U(s) = K_p E(s) + K_i \frac{E(s)}{s}$ (34)

The transfer function of the PI controller is

$G_{PI}(s) = \frac{U(s)}{E(s)} = K + \frac{K_i}{s}$ (35)

Closed-Loop system with a PI Controller

If a PI controller is applied to a system with plants transfer function G(s), the closed-loop transfer function is:

$T(s) = \frac{\left(K + \frac{K_i}{s}\right)G(s)}{1+\left(K + \frac{K_i}{s}\right)G(s)}$ (36)

III. MODEL OF A PROPORTIONAL INTEGRAL DERIVATIVE (PID) CONTROLLER

PID combines Proportional Control and Integral Derivative control to improve system performance by eliminating steady-state error is mathematically expressed as

$U(t)=K_p e(t)+K_i \int e(t)dt+ K_d \frac{de(t)}{dt}$ (37)

Where;

- u(t) is the control output (e.g., valve position in a power system)
- e(t) = r(t) – y(t) is the error signal (difference between reference t (t) and output y(t).
- $K_p$is the Proportional gain, which controls the reaction to the present error.
- K_i is the integral gain, which eliminates steady state error by integrating past errors
- $K_d$is the derivative gain, which predicts future error based on its rate of change

Transfer Function Representation

Taking the Laplace transform (assuming zero initial conditions)

$U(s) = K_p E(s) + K_i \frac{E(s)}{s} + K_d sE(s)$ (38)

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$$U(s) = (k_i + \frac{K_i}{s} + K_d s)\, E(s) \quad (39)$$

$$G_{PID} = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} K_d s \quad (40)$$

Where:

- $G_{PID}(s)$ is the transfer function of the PID controller
- S is the Laplace variable

Discrete-time PID controller

For digital implementation (e.g. in microcontrollers), the discrete PID equations is

$$U(k) = K_p e(k) + K_i \sum_{i=0}^{k} e(i)\,\Delta t + K_d \frac{e(k)-e(k)-1)}{\Delta t} \quad (41)$$

Where k represents discrete times steps and Δt is the sampling

This model is widely used in Load Frequency Control (LFC) application in power systems to regulate frequency deviation in thermal, hydro, and renewable energy systems

IV. RESULTS AND DISCUSSION

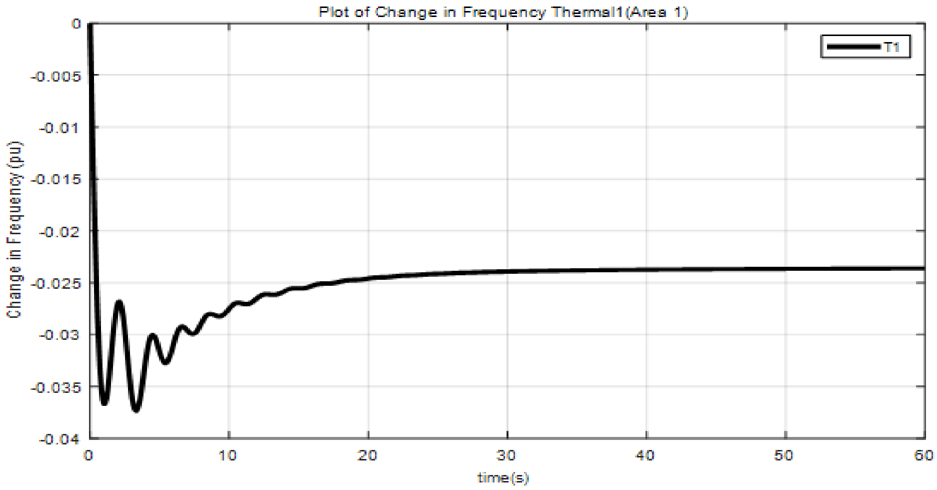

Figure 1: Plot of change in Area 1 Thermal Plant frequency without a controller

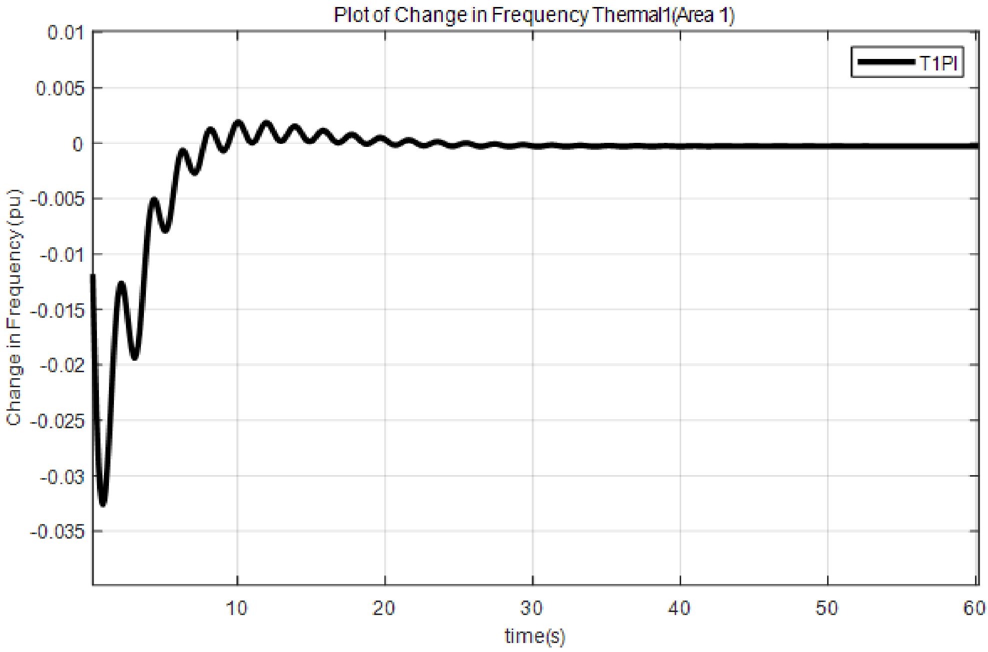

Figure 2: Plot ofchange Area 1 Thermal Plant frequency with P controller

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Figure 1 and 2 shows that without a controller, Area 1 in a thermal power plant experiences oscillatory, underdamped frequency behavior, slow settling, and a negative steady-state error. This indicates the need for a controller to enhance damping, speed up settling, and eliminate steady-state errors

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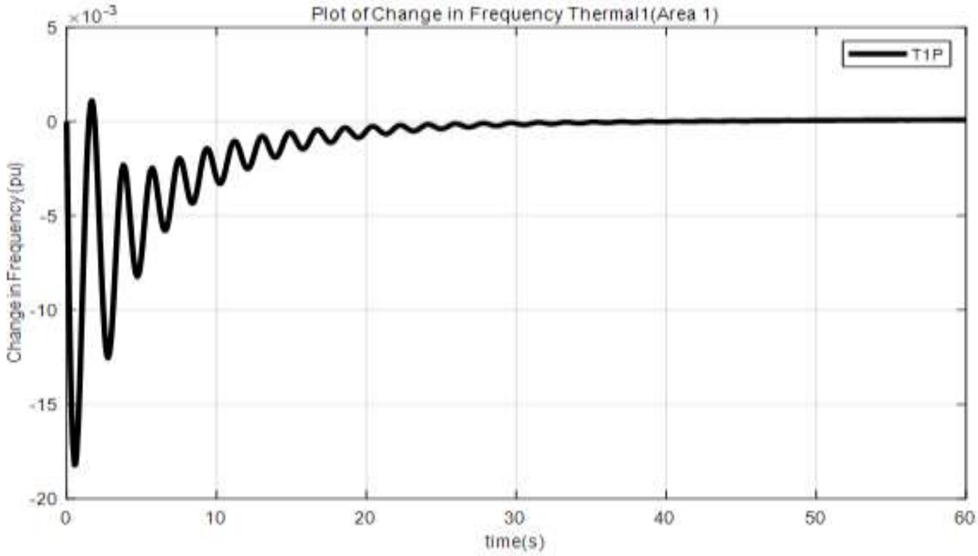

Figure 3: Plot of change in Area 1 Thermal Plant frequency with PI controller

Figure 3 shows that with a proportional controller, Area 1's frequency response shows reduced oscillations, faster settling, and improved transient stability. However, a small steady-state error remains, indicating the possible need for additional control like integral action. Figure 4 shows that with a proportional controller, Area 1's frequency response shows reduced oscillations, faster settling, and improved transient stability. However, a small steady-state error remains, indicating the possible need for additional control like integral action.

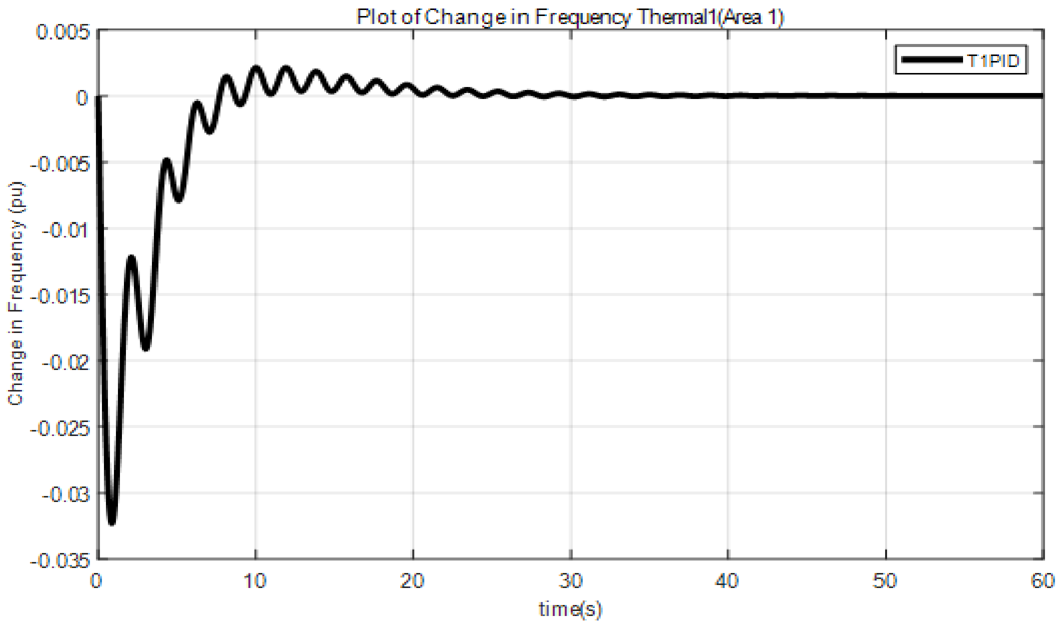

Figure 4: Plot of change in Area 1 Thermal Plant frequency with PID controller

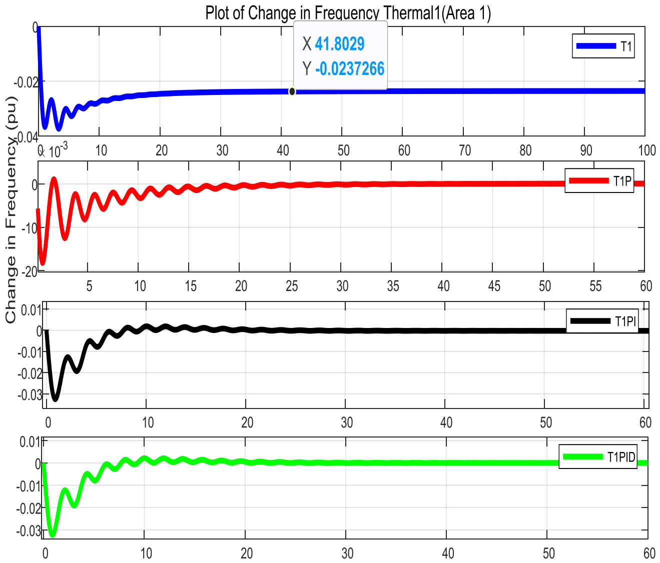

Figure 5: Plot of change in Area 1 Thermal Plant frequency for all models

Figure 5 shows that the application of a PID controller in Area 1 of the thermal power plant significantly improves the frequency response. The system experiences minimal overshoot and reduced oscillations, indicating enhanced stability and smoother transient behaviour compared to other control methods.

The comparison of the frequency responses demonstrates that the implementation and increasing complexity of control strategies lead to progressive and significant improvements in both the frequency stability and dynamic response of Area 1 in the thermal power plant. Starting from an uncontrolled system, which exhibits poor performance characterized by large oscillations, slow settling times, and persistent steady-state errors, the system gradually improves as more sophisticated controllers are introduced. The basic proportional (P) controller brings a noticeable enhancement by reducing the magnitude of oscillations and accelerating the damping process. This leads to a quicker stabilization of the frequency compared to the uncontrolled case. However, despite these improvements in transient response, the P-controller alone cannot fully eliminate the steady-state frequency error. This limitation arises because the proportional action reacts only to the current error and cannot compensate for persistent discrepancies that arise due to system disturbances or load changes. Building upon the P-controller, the proportional-integral (PI) controller introduces integral action, which accumulates the error over time and effectively eliminates the steady-state frequency deviation. This addition not only ensures that the frequency settles exactly at its nominal value but also enhances the transient response by further reducing oscillations and speeding up the settling time. The integral component thus plays a critical role in improving the accuracy and reliability of frequency regulation in the thermal plant, making the system more robust against steady-state disturbances. Finally, the proportional-integral-derivative (PID) controller offers the most advanced level of control, delivering superior overall performance. The inclusion of the derivative term allows the controller to anticipate future errors based on the rate of change of the frequency deviation. As a result, the PID controller minimizes overshoot and oscillations to the greatest extent, leading to a smooth and stable transient response. It also achieves the fastest settling time among all tested controllers, quickly bringing the frequency back to its desired value after a disturbance. Additionally, the PID controller maintains zero steady-state error, ensuring precise frequency regulation at all times. This progression from no control to P, then PI, and finally PID control highlights the critical importance of advanced control techniques in modern power system operations. Effective frequency control is essential for maintaining system stability, preventing equipment damage, and ensuring the efficient and reliable delivery of power. The results clearly show that more sophisticated controllers not only improve transient response characteristics but also ensure long-term accuracy and stability, ultimately enabling the thermal power plant to operate more safely and efficiently under varying load conditions and disturbances.

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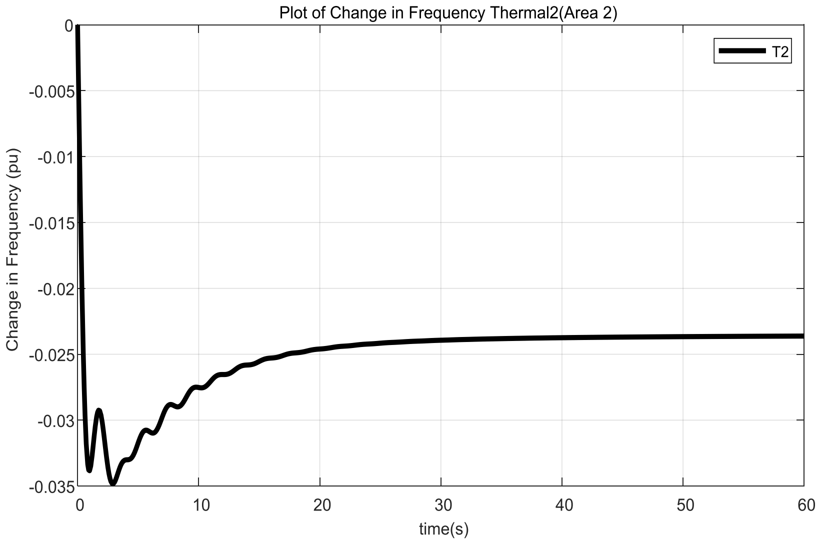

Figure 6:Plot of change in Area 2 thermal Plant frequency without controller

Figure 6 illustrates the frequency response of Area 2 in a thermal power plant operating without the aid of any control mechanisms. At the onset, the system experiences significant frequency deviations characterized by large oscillations. These oscillations indicate that the system is underdamped and lacks sufficient inherent damping to quickly stabilize after a disturbance. As time progresses, the amplitude of these oscillations gradually decreases, but the rate of damping is slow, resulting in a prolonged settling time before the frequency approaches a steady state. Importantly, the frequency does not fully return to its nominal or desired reference value, which reveals the presence of a steady-state frequency error. This offset indicates that without any form of control, the system cannot adequately correct persistent deviations in frequency caused by load changes or disturbances.

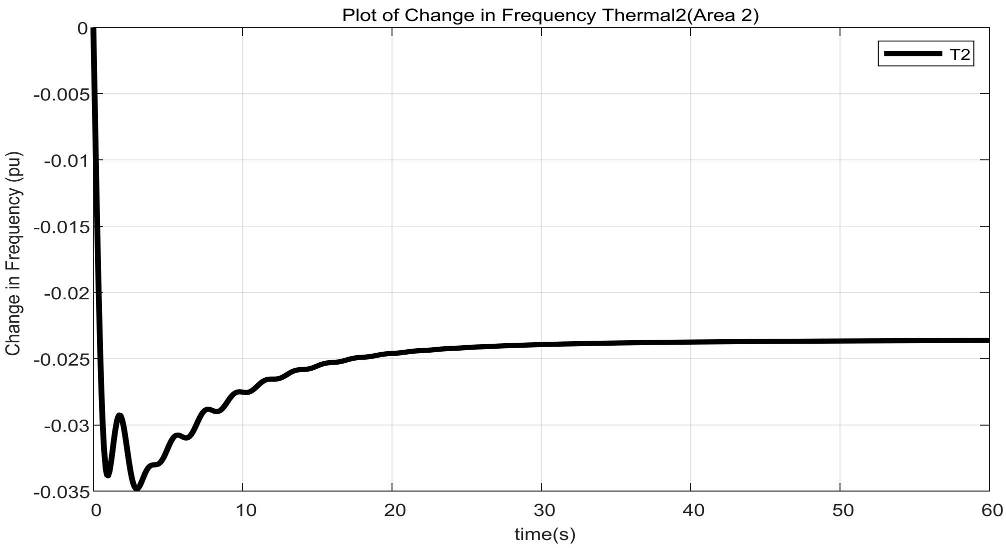

Figure 6 Plot of change in Area 2 Thermal Plant frequency without controller

Figure 6 illustrates the frequency response of Area 2 in a thermal power plant operating without the aid of any control mechanisms. At the onset, the system experiences significant frequency deviations characterized by large oscillations. These oscillations indicate that the system is underdamped and lacks sufficient inherent damping to quickly stabilize after a disturbance. As time progresses, the

amplitude of these oscillations gradually decreases, but the rate of damping is slow, resulting in a prolonged settling time before the frequency approaches a steady state. Importantly, the frequency does not fully return to its nominal or desired reference value, which reveals the presence of a steady-state frequency error. This offset indicates that without any form of control, the system cannot adequately correct persistent deviations in frequency caused by load changes or disturbances.

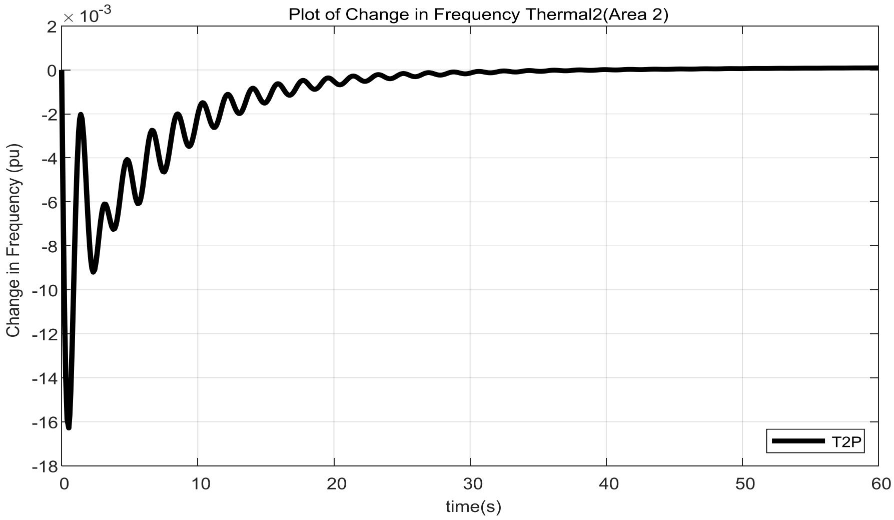

Figure 7 Plot of change in Area 2 Thermal Plant frequency with P controller

Figure 7 shows how the frequency in Area 2 of a two-area thermal power system responds over time to a disturbance when using a proportional controller. Initially, the frequency oscillates, but the system gradually stabilizes. However, it doesn't return exactly to the nominal frequency, indicating a steady-state error. The oscillatory response is due to system dynamics, and the lack of integral action means error correction is incomplete.

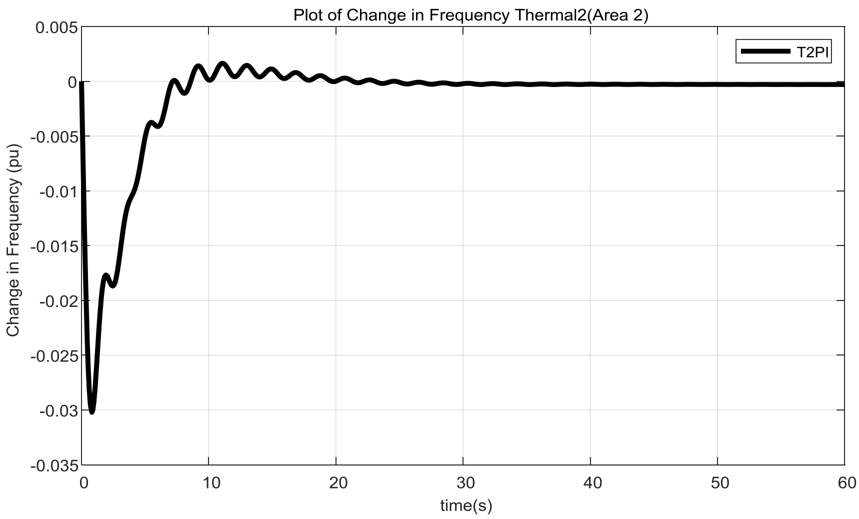

Figure 8:Plot of change in Area 2 Thermal Plant frequency with PI controller

Figure 8 depicts the frequency response of Area 2 in the thermal power plant when controlled by a proportional-integral (PI) controller. Compared to an uncontrolled system, the PI controller significantly improves the system's dynamic behavior. Initially, the frequency experiences some oscillations after a disturbance, but these oscillations are much smaller and more rapidly damped than in the uncontrolled scenario. The controller effectively reduces overshoot and mitigates fluctuations,

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leading to a smoother transition toward the desired nominal frequency.

One of the key benefits of the PI controller, as evident in this graph, is its ability to eliminate steady-state frequency error. This means the system frequency settles exactly at the target value without any persistent deviation, ensuring reliable and accurate frequency regulation. Furthermore, the settling time—the duration for the frequency to stabilize within a certain range of the nominal value—is considerably shorter with the PI controller, indicating a faster system response.

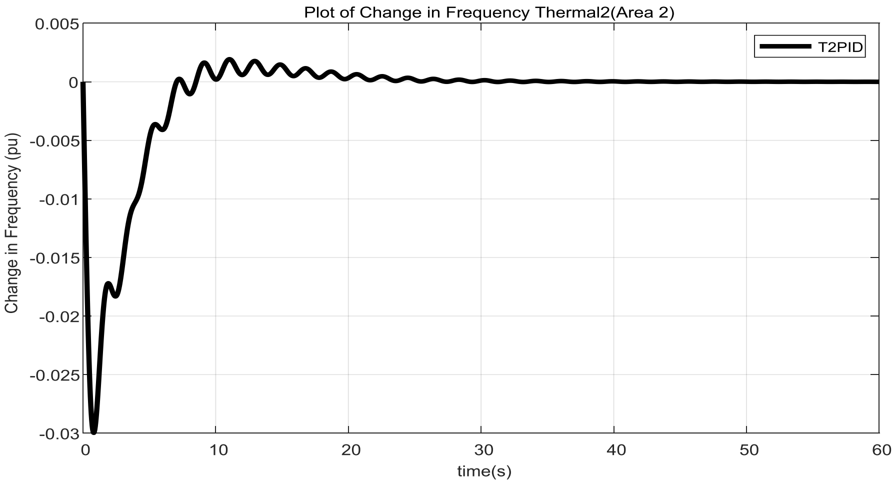

Figure 9:Plot of change in Area 2 Thermal Plant frequency with PID controller

Figure 9 illustrates the frequency response of Area 2 in the thermal power plant when regulated by a proportional-integral-derivative (PID) controller. The introduction of the PID controller markedly enhances the system's dynamic behavior compared to other control approaches. Specifically, the controller effectively reduces the magnitude of oscillations that occur immediately after a disturbance, providing a smoother and more controlled response. Additionally, the PID controller minimizes overshoot, preventing the frequency from exceeding its desired value by a large margin, which is critical for maintaining system reliability and avoiding stress on equipment. Moreover, the PID controller successfully eliminates the steady-state frequency error, ensuring that the system frequency returns exactly to its nominal reference value without any persistent deviations. This precise regulation is essential for maintaining power quality and operational efficiency within the thermal plant.

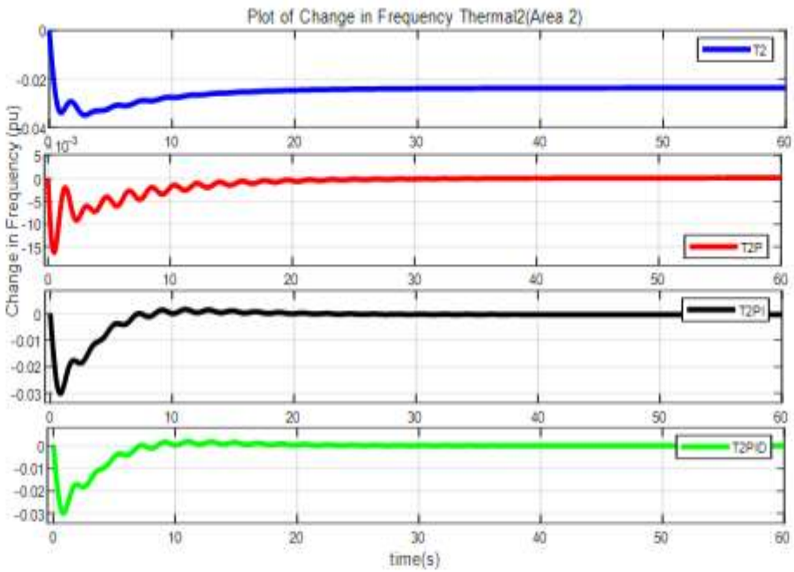

Figure 10: Plot of change in Area 2 Thermal Plant frequency for all the models

The comparison Without any controller, the system experiences significant challenges in maintaining stable operation. It exhibits large oscillations in frequency, which means the system's response swings widely before beginning to settle. This results in a long settling time, indicating that the system takes a considerable amount of time to stabilize after a disturbance. Moreover, there is a noticeable steady-state error, where the frequency does not return fully to its desired nominal value, highlighting poor accuracy and overall system stability in the absence of control. Introducing a Proportional (P) controller improves the situation by reducing the magnitude of oscillations, thereby making the system less erratic. The system also settles faster compared to the uncontrolled case. However, while the P controller enhances transient response, it still cannot fully eliminate the steady-state error. This means that even after the system stabilizes, there remains a persistent deviation from the target frequency, which compromises the system's precision. To address this issue, an Integral component is added, forming a Proportional-Integral (PI) controller. The inclusion of the integral action effectively removes the steady-state error by continuously adjusting the control input based on accumulated past errors. This leads to a more accurate steady-state response where the frequency fully returns to its nominal value. Additionally, the PI controller further dampens oscillations, leading to smoother system behavior and improved stability overall. Finally, the Proportional-Integral-Derivative (PID) controller combines the benefits of proportional, integral, and derivative actions to achieve the best performance among the three. The derivative component helps predict system behavior, thereby minimizing overshoot and oscillations more effectively than the other controllers. As a result, the PID controller provides the fastest settling time, with the system stabilizing quickly after disturbances. It also ensures zero steady-state error, delivering highly accurate frequency regulation. Overall, the PID controller significantly enhances both transient and steady

V. CONCLUSSION

Load Frequency Control (LFC) is essential for ensuring stable and reliable power system operation, especially in interconnected grids where frequency deviations can affect system stability and power quality. PID controllers have been widely used in LFC due to their simple structure, ease of implementation, and satisfactory performance in handling small-signal frequency deviations. However, the growing complexity of modern power systems characterized by high renewable energy penetration, demand-side management, deregulation, and cyber-physical interactionshas highlighted the limitations of conventional PID controllers. These limitations include fixed parameters, slow adaptability, and sensitivity to system nonlinearities and disturbances.Advanced tuning and hybrid approaches, such as Fuzzy-PID, Artificial Neural Networks (ANN)-PID, Particle Swarm Optimization (PSO)-PID, and Adaptive PID, have demonstrated superior dynamic responses, robustness, and adaptability in handling these complexities.Moreover, integrating demand response and smart grid technologies into LFC strategies necessitates more intelligent and self-learning control mechanisms to cope with varying loads, distributed energy resources (DERs), and cyber-physical vulnerabilities

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