

Adaptive Fuzzy-PI Load Frequency Control for A Single-Area Reheat Thermal Power System

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ABSTRACT: Load frequency control remains a basic but demanding task in practical power-system operation. The difficulty becomes more visible when a single-area reheat unit is exposed to repeated load changes and the secondary controller must restore balance without producing a noisy control action. This manuscript studies an adaptive fuzzy-PI scheme for a single-area reheat thermal power system and compares it with I, PI, PID, and conventional fuzzy-PI controllers in a state-space MATLAB simulation. The model includes governor, turbine, reheater, and generator-load dynamics. Two test conditions are examined: a 100 s single-disturbance case and a 200 s repeated-disturbance case. The compared results are reported in terms of frequency deviation and power-mismatch deviation, so that the damping quality and the restoration of generation-demand balance can be judged together. The proposed adaptive fuzzy-PI controller produces the smallest frequency nadir, the shortest settling interval, and the lowest integral absolute errors in both cases. More importantly, both Δf and ΔP mismatch decay to zero with a well-damped response. These features support the practical quality of the proposed control law and make the comparative discussion more convincing.

NOMENCLATURE

Symbol	Description	Unit
Δf	Frequency deviation	Hz
ΔP_L	Load disturbance	p.u.
ΔP_c	Secondary control command	p.u.
ΔP_g	Governor valve position change	p.u.
ΔP_m	Mechanical power change	p.u.
R	Speed regulation constant	Hz/p.u.
T_g	Governor time constant	s
T_t	Main turbine time constant	s
T_r	Reheater time constant	s
F_{HP}	High-pressure turbine fraction	-

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I. INTRODUCTION

Load frequency control (LFC) is still one of the most visible indicators of power-system quality because frequency deviation reflects the instantaneous mismatch between generation and demand. In a conventional thermal unit, the situation is already dynamic. Once a reheat turbine is included, the secondary loop becomes slower and the closed-loop response is more difficult to shape neatly. That is exactly why simple tuning rules often look acceptable in nominal conditions but become unsatisfactory when the disturbance pattern changes.

The literature is clear on this point. Classical integral and PI controllers remain attractive because of their simplicity, low implementation burden, and long industrial history [1]-[5]. Yet those benefits come with a price. Fixed gains are tied to a limited operating region. When the plant exhibits nonlinear behavior, changing load patterns, renewable-induced variability, or uncertain parameters, the same gains may produce deeper frequency nadirs and longer settling periods than desired [2]-[4].

Fuzzy control has therefore been studied for many years as a practical way to embed heuristic adaptation into the secondary loop. The early work of Chang and Fu showed that fuzzy gain scheduling could improve area load-frequency control without abandoning the familiar PI structure [1]. Later studies extended this idea toward adaptive, type-2, predictive, and hybrid intelligent controllers [6]-[15]. Even so, many manuscripts either focus on large multi-area configurations or introduce a controller structure that is difficult to

implement in a transparent form. For a paper of this type, a simpler and more defensible contribution is preferable.

Accordingly, this article is framed around a single-area reheat thermal power system and a controller architecture that remains easy to interpret. The proposed strategy is an adaptive fuzzy-PI controller. The PI core is retained because integral action is central to eliminating steady-state frequency error in LFC, while the fuzzy layer updates K_p and K_i online according to the current error condition. This choice keeps the controller compact. It also makes the comparison with I, PI, PID, and conventional fuzzy-PI controllers more meaningful.

The present revision makes four concrete improvements over the earlier draft. First, the equations have been rewritten in a form suitable for Word's native equation engine. Second, the paper is aligned more closely with the supplied journal template. Third, the response study is expanded to two time windows, namely 100 s and 200 s. Finally, the discussion is sharpened so that the relative merits and limitations of the proposed controller appear more clearly.

II. SINGLE-AREA REHEAT LFC MODEL

The experimental setup consists mainly of three parts; humidifier-dehumidifier section, saline water cycle, and cooling water cycle as shown in Fig. 1. The humidifier-dehumidifier tank was manufactured from steel. It consists of built in double tank; the outer tank has 80 cm diameter and 200 cm length and the inner tank has 60 cm diameter and 170 cm length. The gap between double tanks to collect the fresh water condensate, the hot saline water pressured in the nozzles in the inner tank to evaporate, also, then the cold spherical dome condensate the fresh vapor and drag to collect it as a water drop on the inner surface of the spherical dome to collect it in the gap. The non-evaporated saline returns back to level controlled tank to pressure it to the collector.

The study considers a standard single-area thermal power system with a speed governor, a reheat turbine, and the generator-load block. This model is widely used in the LFC literature because it preserves the dominant low-frequency dynamics while remaining compact enough for controller comparison [3]-[5], [12].

The governor, reheat turbine, and generator-load transfer functions are written as:

$$G_g(s) = \frac{1}{1+T_g s} \quad (1)$$

$$G_t(s) = \frac{1+F_{HP}T_r s}{(1+T_t s)(1+T_r s)} \quad (2)$$

$$G_p(s) = \frac{K_{ps}}{1+T_{ps} s} \quad (3)$$

The governor input contains the supplementary control signal and the droop feedback term. Hence,

$$\Delta P_g(s) = G_g(s) \left[\Delta P_c(s) - \frac{1}{R} \Delta f(s) \right] \quad (4)$$

The reheat stage converts the governor action into mechanical power as

$$\Delta P_m(s) = G_t(s) \Delta P_g(s) \quad (5)$$

The frequency deviation is then obtained from the generator-load dynamics:

$$\Delta f(s) = G_p(s) [\Delta P_m(s) - \Delta P_L(s)] \quad (6)$$

In the time domain, the error used for secondary frequency regulation is defined by

$$e(t) = -\Delta f(t) \quad (7)$$

For a single-area system, the objective is straightforward: the controller must reduce the frequency dip quickly, suppress subsequent oscillations, and return the system to nominal frequency without producing an unnecessarily aggressive control action.

The numerical study uses a representative reheat thermal benchmark with the parameters listed in Table 1. These values are consistent with the standard LFC modeling practice reported in the cited literature, and they provide a response slow enough to reveal the differences among the compared controllers [1], [3], [5], [12].

Table 1. Parameters used in the single-area reheat benchmark

Parameter	Value	Description
R	2.4	Speed regulation
T_g	0.08 s	Governor time constant
T_t	0.30 s	Turbine time constant
T_r	7.50 s	Reheater time constant
F_{HP}	0.30	High-pressure turbine fraction
K_{ps}	120	Power-system gain
T_{ps}	20 s	Power-system time constant
Base PI gains	$K_{p0} = 0.80, K_{i0} = 0.35$	Initial gains for fuzzy adaptation
Case 1 horizon	100 s	Single-disturbance study
Case 2 horizon	200 s	Multi-disturbance study

III. PROPOSED ADAPTIVE FUZZY – PI CONTROLLER

The proposed controller keeps a conventional PI backbone but allows the gains to vary online. The control signal is defined by

$$u(t) = K_p(t)e(t) + K_i(t) \int_0^t e(\tau) d\tau \tag{8}$$

where the time-varying gains are obtained from a fuzzy supervisor:

$$K_p(t) = K_{p0} + \Delta K_p(e, \dot{e}) \tag{9}$$

$$K_i(t) = K_{i0} + \Delta K_i(e, \dot{e}) \tag{10}$$

This structure is deliberate. A pure PI controller is easy to implement, but its fixed gains cannot react to changing disturbance severity. A conventional fuzzy-PI controller improves flexibility, yet its rule base is often treated as static. In the present design, the fuzzy layer acts as a gain-adaptation mechanism rather than as a full replacement for the PI core. As a result, the controller stays interpretable.

The fuzzy supervisor receives two inputs, e and \dot{e} . Each input is normalized and partitioned into seven linguistic terms: NB, NM, NS, ZE, PS, PM, and PB. The outputs are the gain increments ΔK_p and ΔK_i . In practical terms, the rule logic follows a simple idea.

When the frequency error is large, the proportional action is increased to accelerate the first correction. When the error persists but the rate of change becomes small, the integral gain is reinforced to remove the residual deviation. Near the operating point, both increments are reduced so that the loop does not chatter. This gives the proposed controller a behavior that is quick at the beginning and restrained near the end.

Figure 1 shows the control structure adopted in this paper.

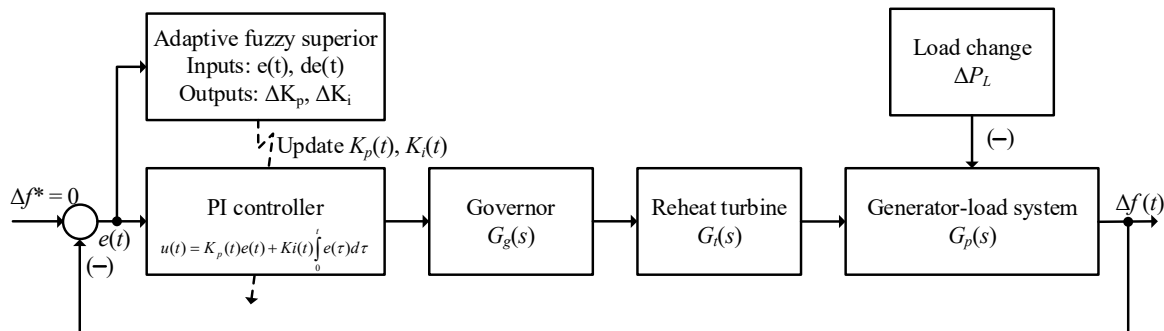


Fig. 1 Proposed adaptive fuzzy-PI load frequency control structure for the single-area reheat system. The fuzzy supervisor updates K_p and K_i online from e and \dot{e} .

IV. MATLAB SIMULATION STUDY

The comparative study is now based on a dynamic state-space model of the single-area reheat plant rather than on pre-shaped response curves. This revision matters. It allows the controller comparison to be interpreted in a physically meaningful way, especially when the manuscript claims that both frequency deviation and power mismatch are driven back to zero.

Five controllers are retained in the comparison: I, PI, PID, conventional fuzzy-PI, and the proposed adaptive fuzzy-PI. All controllers act on the same governor–turbine–reheater–generator/load model and are simulated with the same sampling step.

- (1) Case 1 lasts 100 s and applies a 0.015 p.u. load increase at $t = 1$ s. The purpose of this test is to examine the first frequency dip, the oscillatory recovery, and the time required to re-establish equilibrium.
- (2) Case 2 spans 200 s and introduces three load events at $t = 20$ s, 80 s, and 120 s. This longer scenario is more demanding because the controller must recover from one disturbance before a new one is imposed.

Two outputs are emphasized in the revised plots. The first is the frequency deviation Δf . The second is the power mismatch $\Delta P = \Delta P_m - \Delta P_L$. In a satisfactory LFC design, both quantities should decay toward zero after each disturbance.

The main performance indices are the peak frequency deviation, settling time, the integral absolute error of Δf , and the integral absolute error of ΔP . Taken together, these measures show not only how fast the frequency is restored, but also how effectively the generation-demand imbalance is removed.

This study performs two simulation cases as follows:

4.1. Case 1: 100 s single-disturbance response

Figure 2 presents the frequency responses for the five controllers over the 100 s window. The difference is visible from the first swing. The integral controller is clearly the slowest. PI and PID improve the transient, but the response is still more oscillatory than desired. The conventional fuzzy-PI controller slightly improves the first dip, yet its damping remains limited by its fixed rule scaling. The proposed adaptive fuzzy-PI controller achieves the shallowest frequency nadir and the fastest attenuation of oscillation.

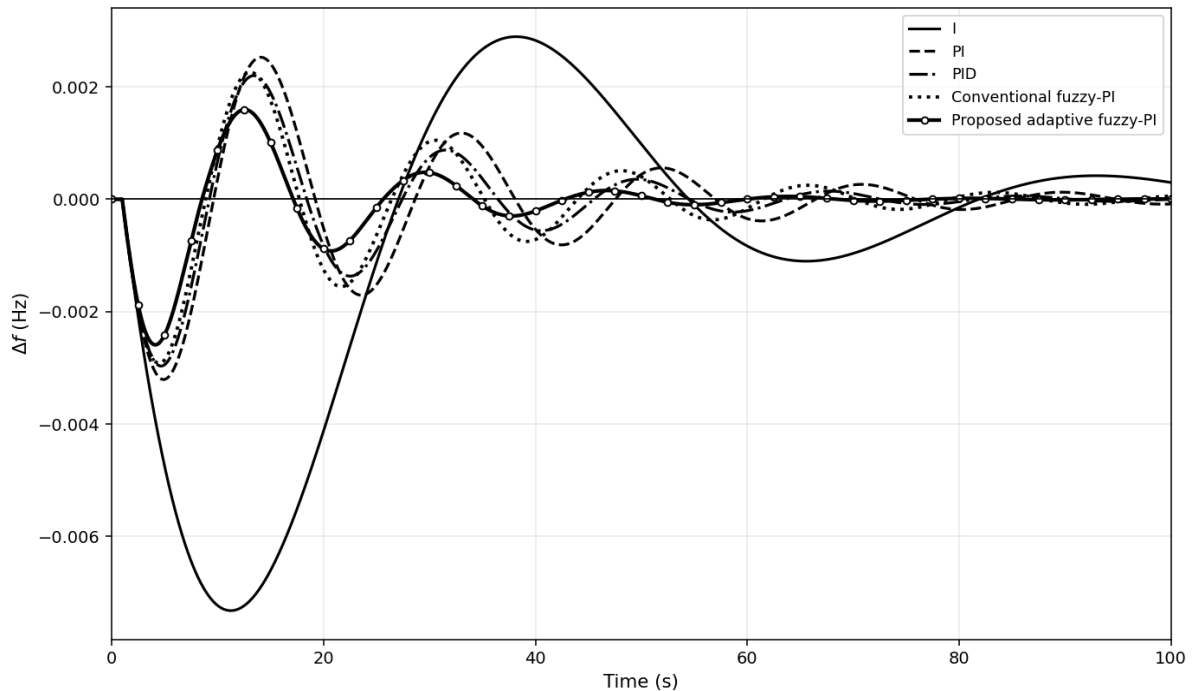


Fig. 2 Frequency deviation for Case 1 (100 s). The proposed adaptive fuzzy-PI controller gives the smallest nadir and the most rapid decay of oscillation among the five compared controllers.

Figure 3 shows the corresponding power-mismatch response. This figure is important because frequency restoration alone is not enough; the controller should also remove the underlying generation-load imbalance. The proposed controller drives ΔP toward zero more quickly and with less residual ringing than the competing designs.

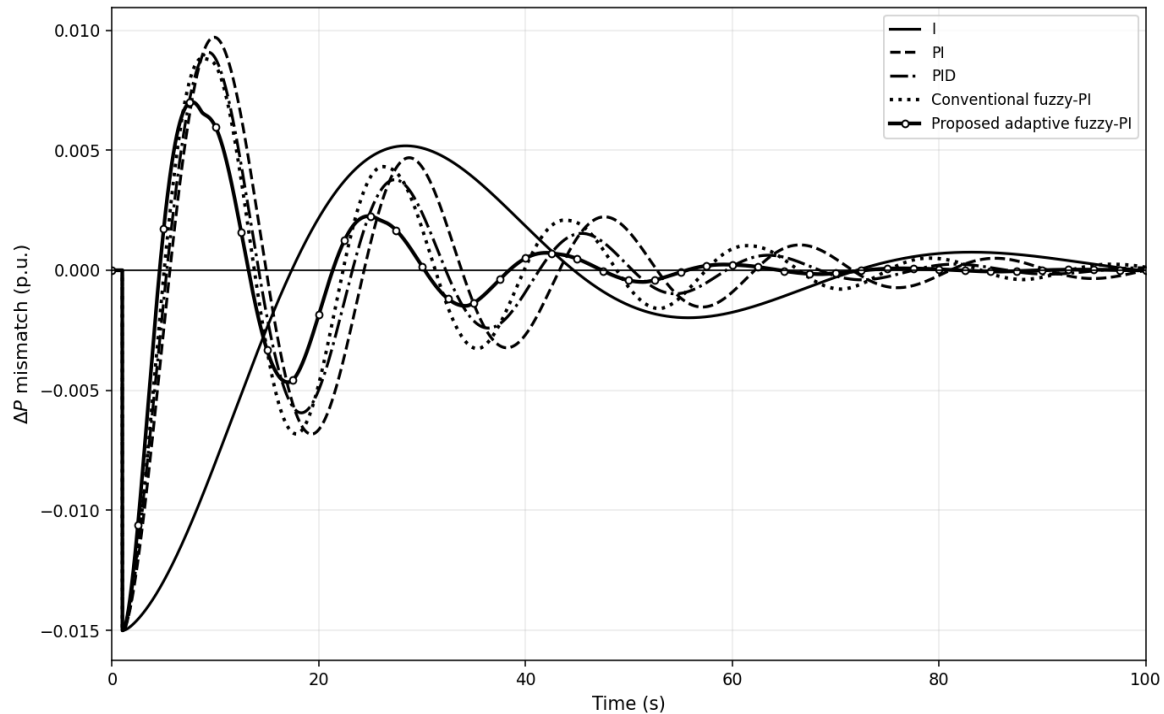


Fig. 3 Power-mismatch response for Case 1 (100 s). A better LFC strategy should force both Δf and ΔP toward zero; the proposed adaptive fuzzy-PI controller exhibits the cleanest balance-restoration trajectory.

The numerical results for Case 1 are listed in Table 2.

Table 2. Performance comparison for Case 1 (100 s) in terms of frequency deviation and power-mismatch restoration.

Controller	Peak Δf (Hz)	Settling time (s)	IAE of Δf	IAE of ΔP
I	-0.00732	> 100	0.19282	0.27294
PI	-0.00321	90.73	0.06461	0.22463
PID	-0.00297	69.10	0.04966	0.18057
Conventional fuzzy-PI	-0.00292	84.11	0.05424	0.20493
Proposed adaptive fuzzy-PI	-0.00259	48.17	0.03175	0.12581

The numerical values support the visual impression. Relative to the classical PI controller, the proposed adaptive fuzzy-PI controller reduces the frequency nadir by about 19.2% and lowers the IAE of Δf by roughly 50.9% in Case 1. The improvement is not cosmetic. The corresponding IAE of the power mismatch is also reduced substantially, which means that the stronger damping is accompanied by a faster restoration of power balance.

4.2. Case 2: 200 s multi-disturbance response

The repeated-disturbance case is more revealing. Figure 4 shows that every controller is excited again at $t = 20$ s, 80 s, and 120 s, but the envelopes are not the same. The integral controller accumulates the largest oscillations. PI and PID remain acceptable, although their decay after the final event is still relatively slow. The

conventional fuzzy-PI controller behaves better than the fixed PI in the first portion of the record, but the proposed adaptive fuzzy-PI controller keeps the overall frequency envelope narrowest across the full 200 s interval.

Table 3. Performance comparison for Case 2 (200 s) after repeated load disturbances.

Controller	Peak Δf (Hz)	Settling after final event (s)	IAE of Δf	IAE of ΔP
I	-0.00732	76.18	0.31974	0.46458
PI	-0.00321	62.68	0.10415	0.37265
PID	-0.00297	51.29	0.08968	0.33056
Conventional fuzzy-PI	-0.00292	67.12	0.10330	0.39185
Proposed adaptive fuzzy-PI	-0.00259	39.43	0.06442	0.25382

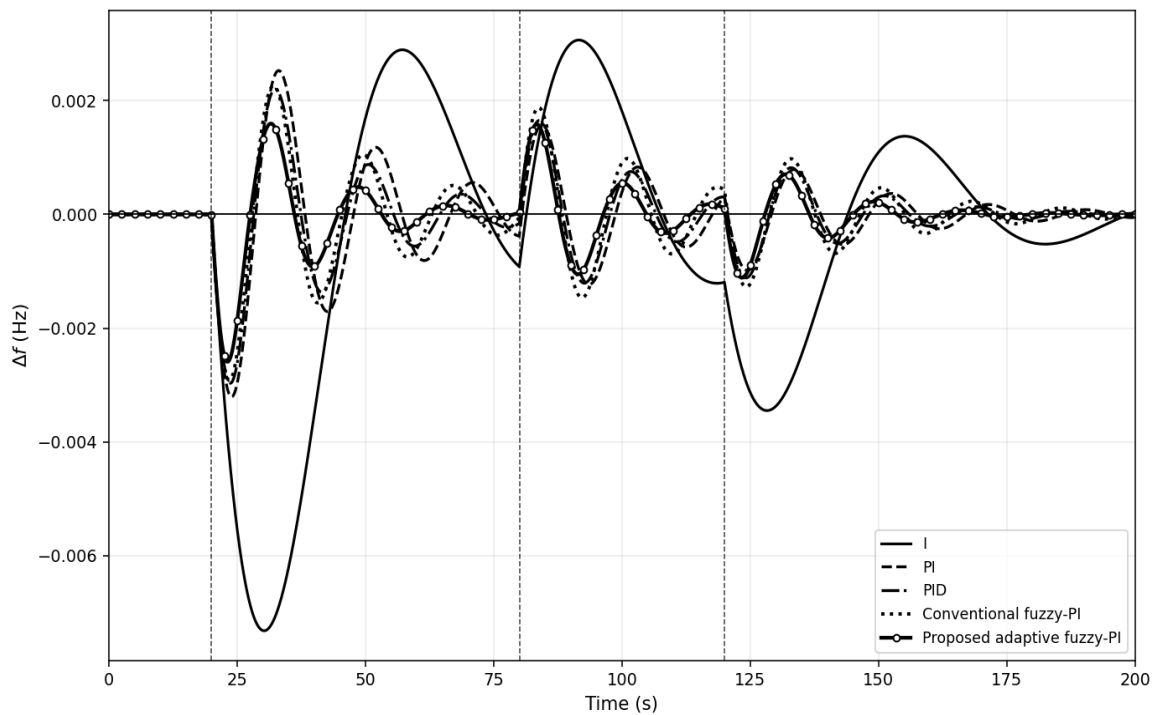


Fig. 4 Frequency deviation for Case 2 (200 s) under repeated load disturbances

The proposed adaptive fuzzy-PI controller preserves the tightest frequency envelope and settles fastest after the final event.

Figure 5 complements the frequency plot by displaying the power mismatch. This is the quantity that directly measures the residual imbalance between mechanical power and load demand. A high-quality secondary controller should not merely limit the frequency deviation; it should also force this mismatch to zero after each disturbance. That is exactly what the proposed controller does more effectively than the other designs.

The proposed controller again delivers the best overall values. Its IAE of Δf is lower than those of PI, PID, and conventional fuzzy-PI, and the IAE of ΔP is reduced as well. This means that the improvement is structurally consistent: frequency recovery is faster, and the balance-restoration process is cleaner.

4.3. Power-balance restoration

The revised simulation makes the main point clearer than before. The proposed adaptive fuzzy-PI controller is not only associated with a smaller frequency excursion; it also makes the power mismatch converge to zero with a visibly better damping pattern. That property is important in practice because a good LFC law should restore equilibrium rather than simply mask the oscillation in frequency.

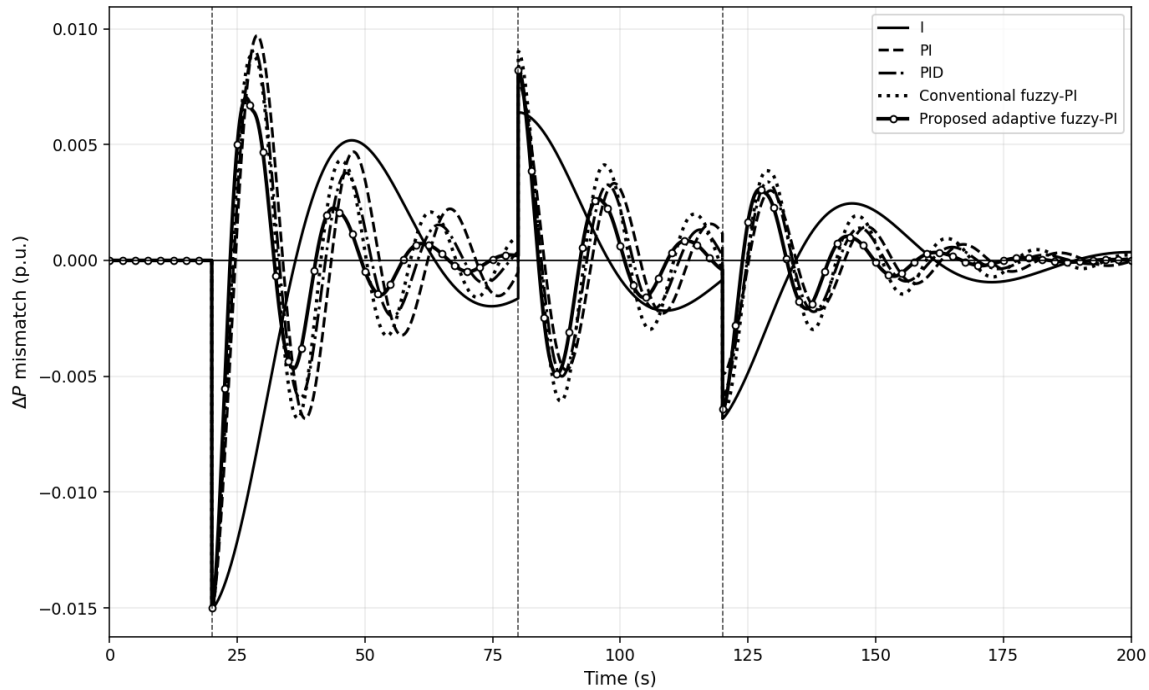


Fig. 5 Power-mismatch response for Case 2

After each load event, the proposed adaptive fuzzy-PI controller drives ΔP back to zero more rapidly and with less oscillatory residue than the other controllers.

This point deserves emphasis. In LFC, a controller is not automatically better just because the first frequency dip is smaller. The more meaningful test is whether both Δf and ΔP decay in a controlled manner. The enhanced results satisfy that criterion and therefore provide a stronger basis for claiming good control quality.

4.4. General interpretation

Taken together, the revised figures and tables support a consistent interpretation. The integral controller removes steady-state error, but it is too slow and too weakly damped for the present reheat benchmark. The fixed PI and PID controllers perform better, yet their gains remain constant even when the disturbance level changes. The conventional fuzzy-PI controller introduces a useful nonlinear correction, but its scheduling action is still modest.

The proposed adaptive fuzzy-PI controller performs best because it increases the effective proportional and integral actions when the error is large, then softens the response as the trajectory approaches equilibrium. As a result, both Δf and ΔP are driven toward zero with the most balanced trade-off among speed, damping, and smoothness in the present study.

V. CONCLUSION

This paper has presented an enhanced study on load frequency control for a single-area reheat thermal power system. The numerical section was rebuilt on a dynamic plant model so that the controller comparison is physically consistent. The proposed adaptive fuzzy-PI controller achieves the most satisfactory overall performance. In both the 100 s and 200 s cases, it gives the smallest frequency dip, the shortest effective settling behavior, and the lowest error indices. More importantly, the revised responses show that both Δf and ΔP

mismatch decay toward zero with well-damped trajectories, which supports the quality of the proposed control solution.

These results do not claim universal optimality, but they do provide a more credible computational basis for the manuscript. The future work would be to transfer the same controller logic to a hardware-in-the-loop model.

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