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Adaptive PID control with disturbance compensation for a gas turbine unit

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Abstract:

Gas turbine units operate under variable load and ambient conditions, which may significantly affect the quality of temperature regulation when a conventional fixed-gain proportional–integral–derivative controller is used. This paper proposes an adaptive PID control approach with model-based feedforward disturbance compensation for the gas temperature control loop of a gas turbine unit. The controller retains the conventional PID structure while introducing bounded online adjustment of the proportional, integral, and derivative gains according to the current tracking error, its low-frequency component, and its filtered rate of change. A separate feedforward channel compensates for measurable variations in mechanical load and ambient temperature. The proposed approach is evaluated using a coupled temperature–speed dynamic model of a gas turbine compressor unit. Two simulation scenarios are considered: simultaneous setpoint and operating-condition changes, and a sharp partial load-shedding event with constant temperature reference. A component-wise ablation study is additionally performed to distinguish the effects of adaptive gain adjustment and disturbance compensation. In the first scenario, the proposed controller reduces the integral time absolute error from 23188.24 to 17299.56 and decreases the temperature overshoot from 8.90% to 1.90% compared with the conventional PID controller. Under sharp load variation, the integral absolute error is reduced by 47.86%, while the maximum gas-temperature deviation is reduced by approximately 52.76%. The component analysis shows that adaptive gain adjustment primarily improves transient performance following setpoint changes, whereas feedforward compensation provides the dominant contribution to load-disturbance rejection. The results demonstrate that combining bounded PID adaptation with explicit disturbance compensation can improve gas turbine temperature regulation without replacing the conventional feedback control structure.

Keywords:

gas turbine unit, adaptive PID control, feedforward compensation, disturbance rejection, temperature regulation, load shedding, gain adaptation

1. Introduction

Gas turbine units are widely used in power-generation systems and industrial drive applications because of their high power density and operational flexibility. However, changes in load, temperature reference, and ambient conditions can significantly affect gas-temperature regulation and may increase thermal stresses during transient operation. Recent studies therefore continue to consider transient performance and disturbance rejection as important problems in gas turbine control [1].

Conventional proportional–integral–derivative (PID) controllers remain attractive for industrial applications because of their simple structure, low computational requirements, and ease of implementation. Nevertheless, fixed PID parameters represent a compromise between reference tracking, overshoot suppression, and disturbance rejection. When operating conditions change, parameters tuned for a nominal regime may no longer provide the same control quality. For this reason, different extensions of conventional PID control, as well as robust, predictive, and adaptive strategies, have been investigated for gas turbine systems [2]–[6].

In particular, adaptive model predictive control has been applied to simultaneous gas turbine speed and temperature regulation under load variations [5], while active disturbance rejection control has been proposed to improve robustness against external disturbances and operating-point changes [7], [9], [11]. Recent studies have also addressed gas-turbine frequency-control dynamics and the influence of control-

system delays under transient operating conditions [8], [10]. Although these approaches can improve control performance, they may also increase model requirements, computational complexity, and tuning effort. Therefore, control structures that retain the conventional PID architecture while introducing only the necessary adaptive and compensating mechanisms remain of practical interest.

Reference tracking and disturbance rejection represent different control tasks. Adaptive gain adjustment can improve the feedback response during transient operation, whereas measurable disturbances can be compensated through a feedforward channel before their full effect appears in the controlled variable [12]. In the present study, these functions are intentionally separated: bounded online adjustment of the PID gains is used to improve transient tracking, while model-based feedforward compensation accounts for measurable changes in mechanical load and ambient temperature.

The present work differs from the author's previous study, where multilayer perceptron and gated recurrent unit neural networks were used as adaptive control structures for a nonlinear thermal process [14]. Here, no neural network directly generates the control action. Instead, the conventional PID controller is retained as the main feedback element and is extended by bounded gain adaptation and disturbance compensation.

The aim of this study is to evaluate the effectiveness of the proposed adaptive PID control strategy for gas-temperature regulation of a gas turbine unit under varying operating conditions. Two transient scenarios are

 <https://orcid.org/0009-0007-5769-9333>



considered: combined changes in temperature reference, load, and ambient conditions, and a sharp partial load-shedding scenario at a constant temperature reference. In addition to comparison with a conventional fixed-gain PID controller, a component-wise ablation study is performed to distinguish the individual contributions of gain adaptation and feedforward disturbance compensation.

2. Research methodology

Dynamic model of the gas turbine unit

The investigation was carried out using a simplified coupled temperature–speed model of a gas turbine unit used to drive a gas compressor. Reduced-order dynamic representations are widely used in gas-turbine control studies because they provide a practical compromise between model interpretability and computational simplicity [15]. The main controlled variable is the gas temperature, denoted by T_g . The normalized rotor speed n is treated as a dynamically coupled state, while u represents the normalized fuel-control signal. The model additionally accounts for the influence of mechanical load M_L and ambient temperature T_{amb} .

The quasi-steady gas temperature is described by

$$T_{g,ss}(k) = T_{g0} + K_{Tu}[u(k) - u_0] + K_{Tn}[n(k) - n_0] + K_{Ta}[T_{amb}(k) - T_{amb0}] + K_{Tm}[M_L(k) - M_{L0}].$$

The steady-state rotor speed is calculated as

$$n_{ss}(k) = n_0 + K_{nu}[u(k) - u_0] + K_{nm}[M_L(k) - M_{L0}].$$

The transient dynamics are represented by first-order differential equations

$$\frac{dT_g}{dt} = \frac{T_{g,ss} - T_g}{\tau_T},$$

$$\frac{dn}{dt} = \frac{n_{ss} - n}{\tau_n},$$

where τ_T and τ_n are the temperature and rotor-speed time constants, respectively.

For numerical simulation, the equations were discretized using the simulation step T_s :

$$T_g(k+1) = T_g(k) + \frac{T_s}{\tau_T} [T_{g,ss}(k) - T_g(k)],$$

$$n(k+1) = n(k) + \frac{T_s}{\tau_n} [n_{ss}(k) - n(k)].$$

The nominal parameters are given in Table 1. The temperature time constant was set to 16 s, while the rotor-speed time constant was 7 s. The normalized fuel input was constrained to the interval $0.25 \leq u \leq 0.95$, and rotor speed was limited to $0.85 \leq n \leq 1.12$.

Table 1

Parameters of the gas turbine model

Parameter	Value	Description
T_{g0}	720 °C	nominal gas temperature
n_0	1.0 p.u.	nominal rotor speed
u_0	0.58	nominal fuel-control input
M_{L0}	0.75	nominal mechanical load
T_{amb0}	25 °C	nominal ambient temperature
τ_T	16 s	temperature time constant
τ_n	7 s	rotor-speed time constant
K_{Tu}	390	fuel-to-temperature gain
K_{Tn}	55	speed-to-temperature coupling
K_{Ta}	0.45	ambient-temperature gain
K_{Tm}	-35	load-to-temperature gain

Parameter	Value	Description
K_{nu}	0.28	fuel-to-speed gain
K_{nm}	-0.42	load-to-speed gain
T_s	0.1 s	simulation step

The parameters were selected as physically plausible values for the computational study and were not identified from operating measurements of a specific industrial gas turbine. Therefore, the model is used for comparative algorithm evaluation rather than for prediction of a particular commercial unit.

Baseline PID controller

A conventional PID controller was used as the reference control system. PID control was selected as the baseline because of its simple implementation and well-established tuning methodology [13]. The temperature error is defined as

$$e(k) = T_{ref}(k) - T_g(k),$$

and the discrete derivative is

$$\dot{e}(k) = \frac{e(k) - e(k-1)}{T_s}.$$

The unsaturated fuel-control command is calculated as

$$u_{PID}^*(k) = u_0 + K_p e(k) + K_i I(k) + K_d \dot{e}(k),$$

where $I(k)$ denotes the accumulated integral error.

The nominal controller coefficients are

$$K_p = 0.0105, \quad K_i = 0.00125, \quad K_d = 0.018.$$

The final actuator command is restricted by

$$u(k) = \text{sat}(u_{PID}^*(k), u_{\min}, u_{\max}).$$

For the baseline PID controller, the integral state is updated when saturation does not reinforce the control error,

$$I(k+1) = I(k) + T_s e(k),$$

and is otherwise frozen. This anti-windup rule prevents further accumulation of the integral term when the actuator is already saturated in the same direction as the control error.

Adaptive PID control with disturbance compensation

The proposed controller preserves the conventional PID structure but introduces two additional mechanisms: bounded online adaptation of the PID gains and feedforward compensation of measurable disturbances.

The raw error derivative is first filtered to reduce excessive sensitivity to rapid numerical changes:

$$\dot{e}_f(k) = \beta_d \dot{e}_f(k-1) + (1 - \beta_d) \dot{e}(k),$$

where

$$\beta_d = 0.75.$$

A low-frequency error component is calculated as

$$e_{lf}(k) = \beta_l e_{lf}(k-1) + (1 - \beta_l) e(k),$$

with

$$\beta_l = 0.99.$$

The normalized adaptation variables are defined as

$$q_p(k) = \min\left(\frac{|e(k)|}{60}, 1\right),$$

$$q_i(k) = \min\left(\frac{|e_{lf}(k)|}{40}, 1\right),$$

$$q_d(k) = \min\left(\frac{|\dot{e}_f(k)|}{80}, 1\right).$$

The adaptive controller coefficients are then calculated as

$$K_p^{ad}(k) = K_p [1 + \alpha_p q_p(k)],$$

$$K_i^{ad}(k) = K_i [1 + \alpha_i q_i(k)],$$

$$K_d^{ad}(k) = K_d [1 + \alpha_d q_d(k)],$$

where the adaptation intensities are



$$\alpha_p = 0.80, \quad \alpha_i = 1.20, \quad \alpha_d = 0.10.$$

To prevent excessive gain variation, the adapted coefficients are bounded:

$$0.90K_p \leq K_p^{ad}(k) \leq 1.50K_p,$$

$$0.75K_i \leq K_i^{ad}(k) \leq 1.70K_i,$$

$$0.90K_d \leq K_d^{ad}(k) \leq 1.20K_d.$$

The second mechanism is a model-based feedforward compensation term. Because both load and ambient temperature explicitly influence the steady-state temperature equation, their measured deviations can be converted into an equivalent fuel-control correction:

$$\Delta u_{ff}^{raw}(k) = -\gamma \frac{K_{Ta}[T_{amb}(k) - T_{amb0}] + K_{Tm}[M_L(k) - M_{L0}]}{K_{Tu}},$$

where

$$\gamma = 0.75.$$

A value below unity was deliberately selected so that the feedforward channel compensates only part of the calculated steady-state disturbance instead of attempting exact cancellation.

To prevent abrupt changes in the fuel-control command, the correction is filtered:

$$\Delta u_{ff}(k) = \beta_f \Delta u_{ff}(k-1) + (1 - \beta_f) \Delta u_{ff}^{raw}(k),$$

where

$$\beta_f = 0.95.$$

The complete control law is

$$u^*(k) = u_0 + K_p^{ad}(k)e(k) + K_i^{ad}(k)I(k) + K_d^{ad}(k)\dot{e}_f(k) + \Delta u_{ff}(k),$$

followed by actuator saturation:

$$u(k) = \text{sat}[u^*(k), u_{\min}, u_{\max}].$$

When saturation occurs, mild back-calculation is applied to the integral state:

$$I(k+1) = I(k) + 0.03 \frac{u(k) - u^*(k)}{\max(K_i^{ad}(k), 10^{-6})} T_s.$$

Thus, adaptation modifies the feedback response, whereas the feedforward term acts directly on measured external disturbances.

Simulation scenarios

The simulations were performed over a 250 s interval with a fixed step of $T_s = 0.1$ s.

In the first scenario, the initial gas-temperature reference was 720 °C. At $t = 40$ s, the reference increased to 780 °C. The load initially had a value of 0.75 p.u., increased to 0.92 p.u. at $t = 100$ s, and subsequently decreased to 0.80 p.u. at $t = 170$ s. Ambient temperature increased from 25 °C to 35 °C at $t = 140$ s. Therefore, this scenario simultaneously evaluates reference tracking and rejection of operating-condition disturbances.

The second scenario was designed specifically to evaluate load-disturbance rejection. The temperature reference was held constant at 780 °C, while the mechanical load changed abruptly from 0.90 to 0.60 p.u. at $t = 40$ s and returned to 0.90 p.u. at $t = 170$ s. Ambient temperature remained constant at 30 °C. The system was initialized at steady state to eliminate an unrelated initial transient. For this isolated disturbance test, the nominal operating point was set to $T_{g0} = 780$ °C, $u_0 = 0.74$, $M_{L0} = 0.90$, and $T_{amb0} = 30$ °C, while the dynamic gains and time constants were retained unchanged.

The two scenarios serve different purposes. The first contains both setpoint changes and external disturbances and therefore evaluates overall closed-loop behavior. The second

removes the setpoint transition and isolates the controller response to a sudden load disturbance.

Performance indices and ablation methodology

Controller performance was evaluated using standard integral error criteria. The integral absolute error is defined as

$$IAE = \int_0^{T_f} |e(t)| dt,$$

the integral squared error as

$$ISE = \int_0^{T_f} e^2(t) dt,$$

and the integral time absolute error as

$$ITAE = \int_0^{T_f} t |e(t)| dt.$$

The maximum absolute temperature error is

$$\Delta T_{\max} = \max_t |e(t)|.$$

For the first scenario, temperature overshoot after the reference step is calculated as

$$\sigma = \frac{T_{g,\max} - T_{ref,f}}{T_{ref,f} - T_{ref,0}} \cdot 100\%.$$

For the load-shedding scenario, the maximum deviation from the constant reference is used instead of percentage overshoot because no reference step occurs.

For each performance criterion J , the relative improvement with respect to the conventional PID controller is calculated as

$$\eta_J = \frac{J_{PID} - J}{J_{PID}} \cdot 100\%.$$

In addition to the direct comparison between the conventional PID controller and the complete proposed controller, a component-wise ablation study was performed. Five configurations were evaluated under identical plant parameters and disturbance profiles: the original conventional PID controller; a fixed-gain filtered PID core; the filtered PID structure with adaptive gains but without feedforward compensation; the fixed-gain structure with feedforward compensation but without gain adaptation; and the complete adaptive PID controller with disturbance compensation.

The fixed-gain filtered core retains derivative filtering and the same anti-windup structure used by the proposed controller, but disables both gain adaptation and feedforward compensation. This configuration provides a consistent reference for separating the contribution of the two added mechanisms.

The ablation decomposition was introduced specifically for the present study. It allows the effect of adaptive feedback to be separated from the effect of disturbance feedforward compensation and avoids attributing the total performance improvement to the combined controller without identifying its physical source.

3. Results and discussion

Combined setpoint and operating-condition changes

The first scenario evaluates the controller under a 60 °C reference increase combined with subsequent changes in mechanical load and ambient temperature. Both the conventional PID controller and the proposed controller remained bounded and converged to practically zero steady-state error. However, substantial differences were observed in transient quality. The proposed controller reduced the temperature overshoot from 8.903% to 1.898%,



corresponding to a 78.69% reduction. The integral absolute error decreased from 395.676 to 330.606 (16.45%), while ITAE decreased from 23188.245 to 17299.562 (25.40%). The reduction in ISE was comparatively small, from 10018.164 to 9911.625 (1.06%). This is explained by the large instantaneous error introduced by the 60 °C reference step, which dominates the squared-error integral for both controllers.

The maximum absolute temperature error remained 60 °C for both controllers because this quantity is determined at the instant of the reference step, before the dynamic model can respond. Consequently, maximum absolute error is not a discriminating performance indicator for this particular setpoint-change experiment, whereas overshoot and time-weighted integral criteria provide more informative measures of closed-loop behavior.

The quantitative results are summarized in Table 2.

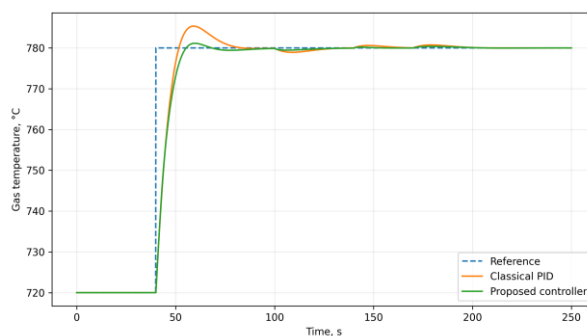


Fig. 1. Gas-temperature response in the combined setpoint and operating-condition scenario

Figure 1 shows that the principal improvement is associated with the transient after the reference change: the proposed controller reaches the new operating condition with substantially lower overshoot. Figure 2 further shows a reduction in the duration and magnitude of the error after the later load and ambient-temperature disturbances. These observations are consistent with the lower IAE and, particularly, the lower ITAE value.

Component-wise ablation analysis

To identify the source of the observed improvement, the controller was decomposed into reduced configurations. The fixed-gain filtered core retains derivative filtering and the same anti-windup logic as the proposed structure, but disables both gain adaptation and feedforward compensation. The adaptation-only configuration enables bounded gain adjustment while the feedforward path is disabled. The feedforward-only configuration retains fixed PID gains and activates only disturbance compensation. The complete controller combines both mechanisms.

Table 3
Component-wise ablation results for the first simulation scenario

Configuration	IAE	ISE	ITAE	Overshoot, %
Classical PID	395.676	10018.164	23188.245	8.903
Fixed-gain filtered core	400.224	10461.584	23256.945	7.101

Table 2
Performance comparison for the combined setpoint and disturbance scenario

Criterion	Classical PID	Proposed controller	Improvement, %
IAE	395.676	330.606	16.45
ISE	10018.164	9911.625	1.06
ITAE	23188.245	17299.562	25.40
Maximum e , °C	60.000	60.000	0.00
Overshoot, %	8.903	1.898	78.69
Steady-state error, °C	-0.000318	0.000540	≈0

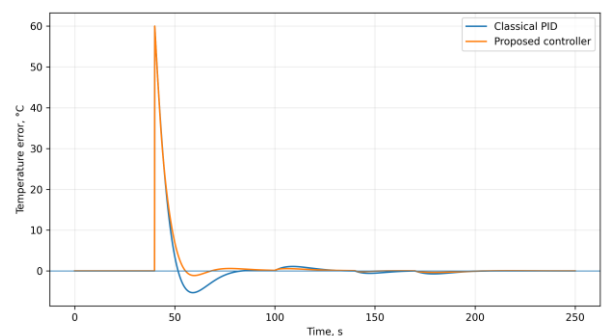


Fig. 2. Temperature-control error for the conventional PID and proposed controller

Configuration	IAE	ISE	ITAE	Overshoot, %
Adaptation only	352.820	9930.434	20599.181	1.898
Feedforward only	377.420	10440.805	19950.350	7.101
Full proposed controller	330.606	9911.625	17299.562	1.898

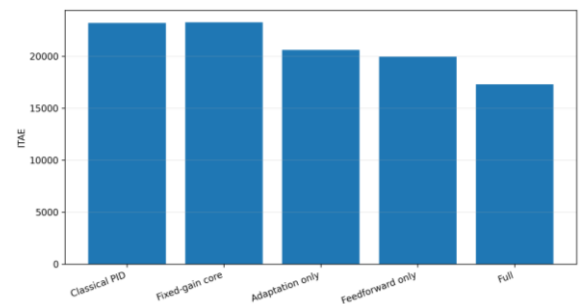


Fig. 3. ITAE comparison for the ablation configurations in the first scenario

The fixed-gain filtered core does not improve the integral criteria: its IAE and ITAE are slightly higher than those of the conventional PID controller. Its lower overshoot therefore appears to result from the modified controller core, including derivative filtering and the anti-windup implementation, rather than from improved overall error



suppression. When gain adaptation is activated, IAE, ISE, and ITAE decrease by 11.84%, 5.08%, and 11.43%, respectively, relative to the fixed-gain filtered core, while overshoot decreases by 73.28%. This indicates that bounded gain adaptation is primarily responsible for improving the setpoint-transition behavior and suppressing the temperature peak.

The feedforward-only configuration produces a different effect. Relative to the fixed-gain filtered core, ITAE decreases by 14.22%, whereas overshoot is unchanged. The compensation channel therefore contributes mainly after measurable load and ambient-temperature disturbances occur, reducing the duration of the resulting temperature deviations rather than altering the initial reference-step overshoot. The complete controller combines these effects and provides the lowest IAE and ITAE together with the low overshoot achieved by the adaptive configuration. The ablation results support the interpretation that the two mechanisms are complementary rather than redundant.

Sharp load-shedding scenario

The second scenario isolates disturbance rejection by keeping the temperature reference constant at 780 °C and applying a sharp partial load reduction from 0.90 to 0.60 p.u. at 40 s, followed by load restoration at 170 s. Because no reference step is applied, the maximum temperature deviation directly characterizes the disturbance-induced excursion. The performance indices are presented in Table 4.

Table 4

Component-wise results for the sharp load-shedding scenario

Configuration	IAE	ISE	ITAE	Max. deviation, °C
Classical PID	70.39	95.48	8350.71	1.872
Fixed-gain filtered core	7	1	7	1.858
Adaptation only	69.69	92.97	8329.65	1.867
Feedforward only	36.90	24.11	4384.29	0.882
Full proposed controller	36.70	23.88	4374.42	0.885

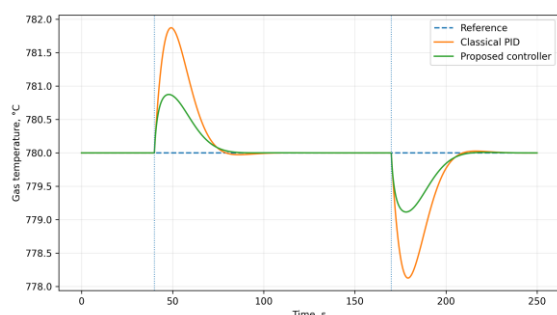


Fig. 4. Gas-temperature response during sharp partial load shedding and subsequent load restoration

Under sharp load shedding, the complete controller decreases IAE from 70.397 to 36.705, ISE from 95.481 to 23.889, and ITAE from 8350.717 to 4374.428. These changes correspond to reductions of 47.86%, 74.98%, and

47.62%, respectively. The maximum temperature deviation decreases from 1.872 °C to 0.885 °C, or by 52.76%.

The ablation results show that this improvement is produced predominantly by the feedforward channel. The feedforward-only configuration already achieves IAE = 36.905, ISE = 24.115, ITAE = 4384.298, and a maximum deviation of 0.882 °C. In contrast, gain adaptation alone produces only small changes relative to the fixed-gain filtered core. The full controller gives slightly lower integral-error criteria than feedforward compensation alone, although its peak deviation is marginally higher by approximately 0.003 °C. This small difference is not practically significant within the investigated simulation model, but it demonstrates that combining control mechanisms does not necessarily improve every individual metric simultaneously.

Discussion and limitations

The two simulation scenarios reveal a clear functional separation between the controller components. During a reference transition, bounded gain adaptation provides the dominant reduction in overshoot and improves the integral tracking criteria. During a measured load disturbance at constant reference, the model-based feedforward term provides almost the entire improvement in disturbance rejection. This behavior is physically consistent with the controller structure: feedback adaptation modifies the closed-loop response according to the tracking error, whereas the feedforward path acts directly on known disturbance channels before the full temperature deviation develops. The observed separation of control functions is consistent with the general distinction between feedback adaptation and measurable-disturbance compensation [12].

The proposed approach retains several practical advantages. In this respect, the proposed architecture retains a comparatively simple PID-centered structure relative to adaptive MPC, robust multivariable control, and observer-based ADRC approaches previously investigated for gas turbine systems [4], [5], [7], [9], [11]. It preserves a conventional PID feedback structure, does not require online neural-network inference or online plant identification, and confines parameter variation to predefined bounds. At the same time, the disturbance-compensation term requires approximate knowledge of the steady-state influence coefficients and access to measurements of load and ambient temperature. Errors in these coefficients, measurement noise, communication delay, or unmeasured disturbances may reduce the achievable improvement.

The present results are limited to a deterministic simulation model with physically plausible but non-identified parameters. No measurement noise, sensor dynamics, fuel-actuator delay, model-parameter uncertainty, or experimental gas-turbine data were included. Accordingly, the reported percentages should be interpreted as comparative results for the investigated model rather than as guaranteed performance improvements for a specific industrial unit. In addition, the study provides numerical closed-loop evidence but does not constitute a general analytical stability proof for all admissible parameter variations.

Future work should therefore include robustness testing under parametric uncertainty, measurement noise and delay, evaluation with operational or hardware-in-the-loop data, and systematic analysis of the stability margins associated with the bounded gain-adaptation law. Such studies would clarify the range of operating conditions over which the complementary behavior identified here can be preserved.



4. Conclusion

This study investigated an adaptive PID control strategy with model-based feedforward disturbance compensation for gas-temperature regulation in a gas turbine unit. The proposed structure retains the conventional PID feedback loop, introduces bounded online adjustment of the controller gains, and uses measured load and ambient-temperature deviations to generate a filtered feedforward correction.

For the combined setpoint and operating-condition scenario, the proposed controller reduced IAE by 16.45%, ITAE by 25.40%, and temperature overshoot by 78.69% compared with the conventional PID controller. Under sharp partial load shedding, IAE, ISE, ITAE, and the maximum temperature deviation were reduced by 47.86%, 74.98%, 47.62%, and 52.76%, respectively.

The component-wise ablation study provides the main methodological finding of the work. Gain adaptation was found to be primarily responsible for improved reference-transition behavior and overshoot suppression, whereas feedforward compensation provided the dominant contribution to rejection of measured load disturbances. Their combination therefore provides complementary rather than redundant control functions.

Because the investigation is based on a simplified simulation model rather than data from a specific industrial gas turbine, further validation is required before practical deployment. Future studies will focus on model uncertainty, measurement noise and delays, hardware-in-the-loop testing, and validation using operational data.

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