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Dynamic Modeling of Electromechanical Energy Conversion Systems in Advanced Gas Turbines using Adaptive Control Algorithms

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ABSTRACT

This paper introduces a rigorous dynamic modeling and control platform of the electromechanical energy conversion systems of single-shaft, heavy-duty gas turbines. As contemporary power grids become increasingly volatile with the integration of intermittent renewable power sources, traditional fixed-gain Proportional-Integral-Derivative (PID) controllers are becoming less effective in maintaining a stable frequency and protecting the thermomechanical limits of the turbines. To address this limitation, a non-linear dynamic model was developed incorporating governor droop, valve actuator inertia, combustion thermodynamics, and rotor swing dynamics. Then, a synthesized PID-based Model Reference Adaptive Control (MRAC) algorithm that dynamically adjusts control gains in real-time using the MIT rule was developed. Three critical operational stress tests applied to the proposed MRAC-PID architecture included a 20% step load disturbance, high-frequency load tracking, and parameter uncertainty with half the grid inertia. Quantitative analysis demonstrates that the MRAC-PID controller shows significant improvements in comparison with the classical PID, reducing the maximum frequency undershoot from -0.018 p.u. to $-0.007\,p.u.$ (a 61.1% improvement), reducing thermal overshoots by 88.8%, and decreasing transient settling time by 63.8%. Moreover, the adaptive algorithm effectively eliminated valve chattering during stochastic load operation and mitigated severe torsional resonance during low-inertia operation.

Keywords: Electromechanical energy conversion, Heavy-duty gas turbines, Dynamic modeling, Model reference adaptive control (MRAC), Grid inertia.

1. INTRODUCTION

The modern world environment is marked by the ever-increasing demand of electrical energy, which puts unprecedented pressure on the power grids and power generation plants to provide steady, extremely efficient, and dependable power supply. High-speed heavy-duty gas turbines: This type of infrastructure is one of the cornerstones of the modern

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electrical networks. This is because of their high responsiveness to the changes of loads, their deep level of operational flexibility, and high thermal efficiency, particularly when they are incorporated in combined cycle power stations **(Mevissen et al., 2026)**. Nonetheless, the energy conversion mechanism in these turbines is essentially complex. It involves the conversion of the chemical energy of the fuel into thermal energy through the combustion and this energy is then converted into rotational mechanical energy by the turbine blades and further to electrical energy by the use of synchronous generators. This chain reaction of transforming electromechanical energy is very dynamic, very non-linear and prone to numerous variables of operation **(Mohamed and Khalil, 2020)**.

The main research issue is explained by the fact that the electromechanical energy conversion systems in gas turbines are functioning in extreme and constantly changing conditions. The systems often get exposed to abrupt changes in grid loads, oscillation of frequency, any alteration in ambient conditions and fuel make-up. The nature of the traditional control architecture, especially standard linear Proportional-Integral-Derivative (PID) controllers with fixed gains is that they are not able to continue operating optimally or maintaining system stability in the presence of such disturbances. In transient phases, classics controllers quickly degenerate, and transient excursions can become catastrophic (e.g. dangerous rotor speed overshoots or intolerable exhaust gas temperatures spikes) and this is bound to hasten component breakdown and shorten the working life of the equipment **(Abbassen et al., 2020)**.

As a result, the urgent and critical need is to establish highly accurate frameworks of these systems through which the dynamic modeling is developed. The goal of dynamic modeling is to model mathematically the complex behavior of the gas turbine that includes physical, thermodynamic and electromechanical mechanisms in both steady and transient cases, with specific interest in frequency dependent behavior **(Talah and Bentarzi, 2020)**. A detailed dynamic model gives in-depth information about the complex cross-couplings among the fuel metering systems, airflow dynamics and the response of the electrical generator to grid demands. More to the point, strong experimental studies and sound simulation can be considered as necessary conditions for any advanced control algorithm can be designed, tested, and validated before its safe application in an actual power plant **(Kanashev and Rozhko, 2018)**.

To break down the intricacies of the whole plant, it is important to mathematically model certain subsystems of critical importance. As an example, the correct modeling and simulation of the turbine starter mechanisms and fuel control valves are extremely important, and they directly determine the mechanical force acting on the generator shaft during the critical operational stages **(Mao and Guo, 2025)**. Also, modeling the architecture of the whole plant, which takes into account the gas turbine in relation to the other parameters of the electrical network, is a way of viewing the entire electromechanical stability in totality whereby the power produced exactly corresponds to the real-time grid requirements without causing mechanical stress **(Al-Shami et al., 2023)**.

The trend of contemporary research in industrial engineering is shifting towards the adoption of Adaptive Control Algorithms and intelligent control to overcome the inherent limitations of traditional linear control strategies. Adaptive control is characterized by its high ability to constantly change its internal parameters in real time, responding dynamically to real changes in the operating environment and physical degradation of the system itself. Adaptive controllers optimize control signals (e.g., the fuel valve position or the angle of variable inlet guide vanes) by applying refined control adjustment mechanisms

as response to continuous measurement of performance deviations so that the critical variables of the turbine are kept at strictly safe and optimum values, even in the presence of exogenous grid disturbances.
Combining the rigorous dynamic modeling with adaptive and intelligent control provides vast opportunities of electromechanical power generation optimization. Such combined method eases the rapid resettling of the process, reduces the risk of dangerous thermal and mechanical overshoots, and enhances the stability of the grid frequency considerably. Moreover, it increases the stability of the turbine such that it can work effectively in part-loading environments and thus maximize fuel use and reduce negative emissions, which is precisely what the world wants in terms of sustainability. With these principles as a starting point, the study will develop a full dynamic model of electromechanical energy conversion system of the advanced gas turbine. It attempts to reveal the shortcomings of the simplified linear models, present a complex mathematical framework that models non-linear dynamics, and critically compare a range of adaptive control algorithms with classical approaches to a variety of load disturbance conditions. In general, this paper aims to develop a sound engineering approach that will guarantee the increased stability, high efficiency and increased lifespan of power generation resources in contemporary smart grids.

2. LITERATURE REVIEW

Development of dynamic modelling and advanced control of gas turbines has received a lot of scholarly and industrial attention in the last ten years due to the sheer need to ensure the stability of the electrical grid as the penetration of volatile sources of energy increases. In order to present a systematic and circuit overview of the knowledge development in this field, the literature reviewed can be divided into several thematic areas: frequency and speed regulation, robust and active disturbance rejection control, predictive and optimization-based strategies, and the incorporation of artificial intelligence in adaptive control.

2.1 Regulation of Frequency, Speed and General Plant

The most important parameter in any electromechanical generation system is the rotational speed of the turbine which directly determines the electrical frequency of the grid. The recent developments have given great emphasis on the improvement of Load Frequency Control (LFC) systems. The use of non-linear design methods to alter classical PID controllers has shown an impressive capability to dampen frequency excursions far much quicker than more customary linear methods when there is an abrupt insertion of load **(Muhammad et al., 2023).** At the same time, mechanical aspect of conversion process optimization, especially speed droop governor operation has been well studied, especially in cogeneration units. The maximization of the droop characteristics provides fair distribution of loads between multiple generating units, which avoids localized mechanical loads **(Maharmi et al., 2024).** To ensure maximum protection to the system, expansive simulation environments have been established incorporating advanced prognostic regulators of the voltage and speed. These predictive regulators enable the system to predict the occurrence of the dips in grid voltage and frequency and make preemptive control measures to stabilize the synchronous generator before the stability limits are violated **(Bulatov et al., 2020).** Moreover, the stability of the total power plant is much dependent on auxiliary systems; for example of this, the natural gas compression plants serving the turbines have been demonstrated to directly affect the combustion stability hence the electromechanical output **(Patrascioiu and Popescu, 2020).**

2.2 Strong Control and Active Disturbance Rejection

Considering the extreme non-linearities and numerous internal interacting variables that a gas turbine possesses, research has shifted to strong control mechanisms able to reject unmodeled dynamics. Active Disturbance rejection control (ADRC) has become an effective weapon. A decentralized ADRC design can be used to decouple interacting control loops (as fuel flow and airflow) effectively, consider cross-coupling effects as external disturbances and approximate them in real-time to cancel them immediately **(Shi et al., 2020).** To enhance the usefulness of ADRC to all the limits of the operational envelope, i.e. to startup as well as base load, researchers have managed to combine it with gain-scheduling methods. This mixed solution will guarantee that the parameter of the controllers dynamically varies according to the operating condition and offer a robust performance in all conditions of the thermal power plant operations **(Wu et al., 2019).** Synthesis methods like H2, H 5 and 9000 -synth have been developed in the domain of rigorous mathematical robustness to ensure the rotor speed and the firing temperature of the turbine are controlled simultaneously. These advanced controllers are giving absolute mathematical stability even when parametric conditions are very harsh and sensor noises are present **(Haji et al., 2019).** Likewise, dedicated control architectures have been designed with the specific goal of controlling exhaust temperatures whenever incremental loads are required to be satisfied, such that the temptation to push the electrical production to its limits does not cause the metallurgical failures of the turbine blades to be disastrous **(Jonathan et al., 2018).**

2.3 Optimization and Model Predictive Control (MPC)

In order to cope with the multi-variableization of gas turbines and at the same time strictly follow the operational safety limitations, Model Predictive Control (MPC) has become the subject of research. Fossil-fueled power plants have had discrete-time MPC formulations specifically developed to predict future errors of the trajectory and implement best control effort without violating physical constraints of actuators **(Tayyah et al., 2019).** It has also been demonstrated that predictive control strategies have played a central role in enhancing the dynamic performance and overall thermodynamic efficiency of combined cycle power plants in the effective management of the complicated thermal bridging between the gas turbine and the Heat Recovery Steam Generator (HRSG) **(Mohamed et al., 2016).** The industry has realized that linear MPC is not accurate for large transient shifts and thus Nonlinear Model Predictive Control (NMPC) has been developed. The non-linear dynamic model of the gas turbine is incorporated in its prediction horizon by NMPC, and its tracking results are far superior in the scenarios of aggressive load generation **(Shahin et al., 2021).** To go beyond real-time control, multi-objective dynamic optimization models have been established on optimal load-following operations. These models determine the optimum paths with the highest power generation and model mathematically the thermal and mechanical forces of the turbine components **(Wang et al., 2021).** Moreover, the modern heuristic optimization algorithms including the Whale Optimization Algorithm have been effectively applied in both complex parameter identification problems and in the crafting of the sliding pressure controllers within advanced power plants, and this is where the strength of nature-inspired mathematics is evident in controlling engineering **(Qasem et al., 2022).**

2.4 Adaptive Algorithms and Artificial Intelligence

The integration of Artificial Intelligence (AI) is the most significant paradigm shift of dynamic modeling and adaptive control. The physical equations which typically apply to turbines show up to be highly transient and complex to be accounted by traditional physical equations. To solve this, Nonlinear Autoregressive Network with Exogenous Inputs (NARX) models, a type of dynamic neural network, have been applied to model the extremely unstable start-up processes of hefty-duty gas turbines with unsurpassed precision **(Liu and Jiang, 2022).** With the growing power of computers, Deep Learning algorithms have been combined with dynamic neural networks to represent a highly complex system (e.g. a dual-fuel gas turbine) so that the controller can smoothly evolve its response to the fluctuating combustion dynamics as the fuel mixture changes **(Alsarayreh et al., 2022).**
Fuzzy Logic has been found very useful in the field of adaptive control. Rotor speed control Fuzzy-modified Model Reference Adaptive Controllers (MRAC) have been developed to build on Takagi-Sugeno (T-S) fuzzy mechanisms to continuously modify the control laws depending on the current error between the physical turbine and a mathematical reference model **(Andoga et al., 2024).** Interval Type-2 Fuzzy PID controllers have been designed to overcome sensor measurements inherent uncertainties and noise. Type-2 fuzzy sets offer a significantly greater level of robustness to external grid noise than conventional fuzzy logic because of the footprint of uncertainty **(Li et al., 2022).** Lastly, by combining the learning abilities of neural networks with the decision-making capabilities of fuzzy logic that are of a rule-based nature, the Neuro-Fuzzy controllers have been developed. These complex controllers have been effectively used on grid-connected heavy-duty turbines, and have been shown to have an amazing capacity to autonomously learn the dynamic behavior of the plant, and dynamically adjust the control policy to ensure excellent electromechanical coordination with the grid **(Farrar et al., 2023)**.This extensive body of literature unequivocally demonstrates that the future of electromechanical energy conversion in gas turbines relies on abandoning static, linear approximations in favor of comprehensive non-linear dynamic models, governed by intelligent, predictive, and highly adaptive control algorithms.

3. METHODOLOGY

This methodology constitutes the full mathematical and engineering configuration needed to model in detail a high-fidelity dynamic model of the electromechanical energy conversion system of a single-shaft heavy-duty gas turbine. The study extensively uses the Python engineering simulation environment to make the plant models, design the adaptive control algorithms and run the transient simulations. To resolve the harsh non-linearities and multi-domain physics of the power plant, the methodology is logically separated into four major subsections namely, Electromechanical Mathematical Modeling, Design of the Adaptive Control Algorithm, Implementation of Non-linear Actuator Constraints, and System Parameter Identification.
To provide a clear, comprehensive overview of the system configuration, the integrated closed-loop block diagram of the proposed MRAC-PID control scheme and the gas turbine electromechanical dynamics is illustrated in **Fig. 1**. The control architecture is structured in a parallel branching configuration consisting of three primary pathways. The top pathway defines the Reference Model ($Y_m(s)$), which establishes the ideal frequency response to the input speed reference ($Uc(s)$). The actual plant speed deviation output ($Y_p(s) = \Delta\omega$) is compared with $Y_m(s)$ to compute the dynamic tracking error $e_a(t)$. This error is fed into the

MIT Rule Adaptation Mechanism, which continuously updates the PID controller parameters ($\theta = [Kp, Ki, Kd]$) in real-time. The bottom pathway represents the sequential electromechanical plant dynamics, where the adaptive PID output is combined with the speed governor droop feedback to manipulate the valve positioner, combustor, turbine expansion, and generator swing dynamics under volatile load changes and grid disturbances (ΔPe).

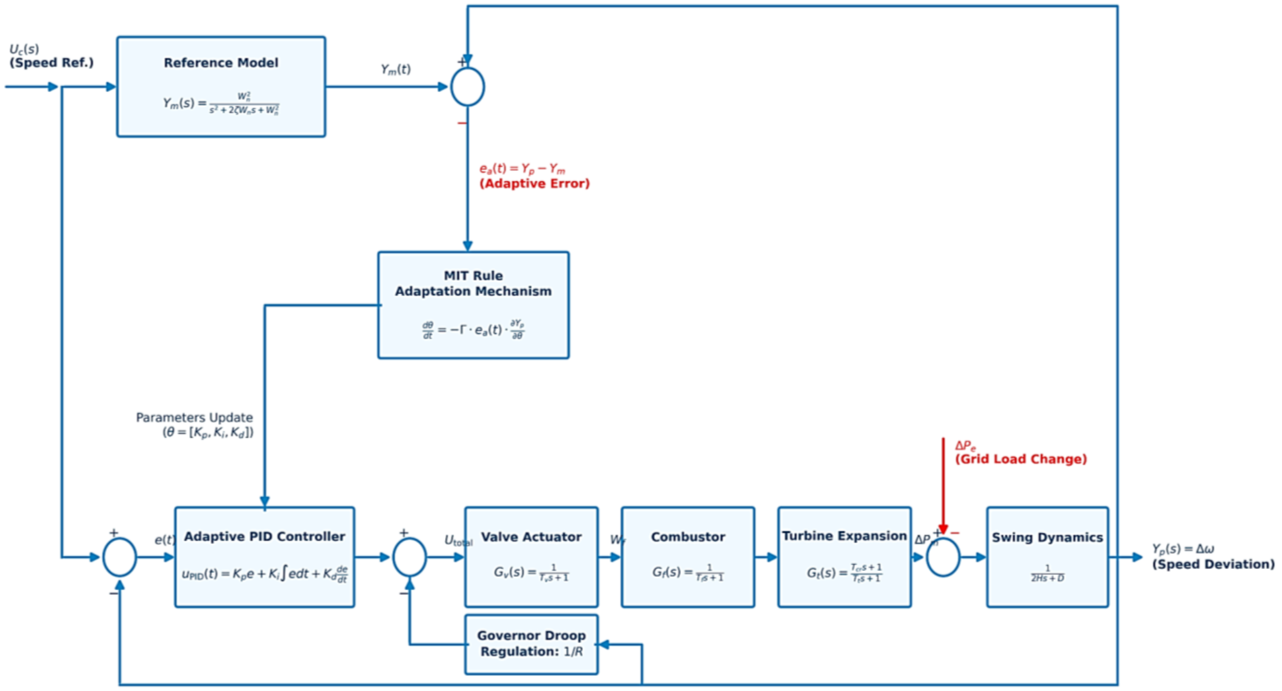

Figure 1. Complete closed-loop block diagram of the proposed MRAC-PID control architecture integrated with the gas turbine electromechanical model.

3.1 Mathematical Modeling of the Gas Turbine Electromechanical

The dynamic (kinetic) model of a grid-connected gas turbine is the result of a connected system of functional transfer blocks that reflect different stages of the thermodynamic and electromechanical processes of energy conversion.

3.1.1 The Speed Governor (Droop Characteristic)

The main purpose of the speed governor is to check the angular velocity error of the rotor of the generator and produce an active power error signal. The speed droop governing equation is written as shown in Eq. (1):

$$\Delta_{P_{ref}} = \Delta_{P_c} - \left(\frac{1}{R}\right) * \Delta_w \qquad (1)$$

Where:

- $\Delta_{P_{ref}}$ is the intermediate reference power demand required by the system.
- Δ_{P_c} is the supplementary control signal generated by the secondary control unit (the proposed adaptive controller).
- R is the speed droop characteristic (regulation constant), defining the steady-state frequency drop allowed from no-load to full-load.

- Δ_w is the angular speed deviation of the synchronous generator rotor, expressed in Per Unit (p.u.).

3.1.2 The Valve Positioner and Actuator Dynamics

The fuel control valve can neither open nor close immediately, as the mechanical inertia of the mass of the valve and hydraulic delays in the actuator. Thus, it is represented as a first-order time delay transfer function as shown in the Eq. (2):

$$G_{v(s)} = \frac{1}{T_v * s + 1} \tag{2}$$

Use of the variables s, T_v corresponds to the Laplace complex variable, physical time constant, T_v of the actuator mechanism in the valve. The actual signal of this operating block is the signal of the rate of instantaneous mass flow rate of fuel, this signal is W_f.

3.1.3 Fuel System and Combustor Dynamics

After the fuel has gone through the valve, the chemical energy of the fuel has to undergo a thermodynamic time delay before it is completely transformed into thermal energy in the combustion chamber. This is another first order lag that is modeled as shown in the Eq. (3):

$$G_{f(s)} = \frac{1}{T_f * s + 1} \tag{3}$$

T_f is the time constant of the fuel distribution piping and ignition/combustion delay.

3.1.4 The Dynamics of the Turbine Expansion

Gas turbine is comprised of many expansion stages wherein the high pressure and high temperatures combustion gases are made to expand against the turbine blades to generate rotating torque. Lead-lag transfer function representing the volumetric delay of the exhaust gases and the ratio of the power generated in the combustor system and the stages of the turbine are used to model the aerodynamic and thermodynamic behavior of the turbine as shown in the Eq. (4):

$$G_{t(s)} = \frac{T_{cr} * s + 1}{T_t * s + 1} \tag{4}$$

Where T_t is the main time constant of the volumetric expansion of the gas via the turbine casing and T_{cr} is the combustion reaction delay constant. The resultant of this block is the mechanical power produced on the turbine shaft and this is denoted as Δ PM.

3.1.5 Generator, Rotor and Grid in Dynamics

The Swing Equation determines the eventual electromechanical response of the power plant; which is a correlation of the mechanical power supplied by the turbine to the electrical power delivered by the grid that modulates the acceleration or deceleration of the rotor mass as shown in the Eq. (5):

$$\Delta\, w\, (s) = [\, \Delta\, P\, m\, (s) - \Delta\, P\, e \frac{s}{(2Hs + D)}] \tag{5}$$

Where:

- Δ P e is a change in the active electrical load required in the grid (which is the primary external disturbance).
- H = the sum of all lumped inertia constants of the rotating masses (turbine compressor, turbine stages, and generator rotor) in seconds.
- D the load damping coefficient, which is a frequency-dependent characteristic of the loads that are coupled between the two electrical systems.

3.2 Adaptive Control Algorithm (MRAC-PID) Design

In order to counter the intrinsic limitations of the conventional Proportional-Integral-Derivative (PID) controllers, which are based on constant and rigorously tuned gains that fail in the face of extreme transient variations, this study suggests a hybrid scheme that combines classical PID architecture with a Model Reference Adaptive Control (MRAC) scheme.
The basic time domain equation of PID controller is as shown in the Eq. (6):

$$u_{PID}(t) \; = Kp * e(t) + Ki * \int e(t)dt + Kd * \frac{de(t)}{dt} \qquad (6)$$

Where e(t) is the dynamic error of tracking of the frequency or rotor speed. The parameter of the MRAC-PID architecture in the proposed design is not fixed parameter (Kp, Ki, Kd). Rather, they are constantly recalculated and updated in real-time by an outer adaptive adaptation mechanism. The initial step in this design is to create the "Reference Model" which mathematically models the ideal, much-wanted transient response that the physical turbine would ideally follow, as shown in Eq. (7):

$$Y_{m(s)} = \frac{W_n^2}{(s^2 + 2 * Z * W_n * s + W_n^2)} * U_{c(s)} \qquad (7)$$

Wn is the preferred natural frequency of the ideal response; Zeta is the ideal damping ratio that is selected with the sole objective of ensuring that oscillatory overshoot is completely avoided and $U_{c(s)}$ is the desired command signal.
The adaptive system is based on the computation of the Adaptive Error (instantaneous difference between the actual output of the physical plant (Y_p) and the ideal output of the reference model (Y_m) as shown in the Eq. (8):

$$E_{a(t)} = Y_{p(t)} - Y_{m(t)} \qquad (8)$$

The most common and popular MIT Rule is applied to update the control gains dynamically. The rule is a minimizer of a cost that involves the square of the adaptive error as shown in the Eq. (9):

$$\frac{d\theta}{dt} = -\Gamma \cdot e_a(t) \cdot \frac{\partial Y_p}{\partial \theta} \qquad (9)$$

Gamma is the adaptation gain or learning rate (i.e. how fast the controller corrects itself), Theta is the special parameter ($Kp, Ki \; or \; Kd$) being updated and the partial derivative term is the sensitivity of the plant output to changes in the controller parameters.
The last synthesized control law to inject into the valve positioner is the summation of the terms, which are adapted and tuned gradually as shown in Eq. (10):

$$U \; total \; (t) \; = u \; pid \; adaptive \; (t) \; + \; U \; mrac \; (t) \qquad (10)$$

3.3 Non-linear Conditioning and Constraints on Actuators

The pure linear transfer-function model would be too weak in terms of academic modelling of heavy-duty gas turbines because hardware is subjected to hard mechanical limits. In order to achieve the maximum level of physical realism, strong non-linear limitations were implemented physically into the simulation environment.
To start with, the fuel valve is confined with severe Saturation Limits:

- $Vmax = 1.0$ $(Meaning\ 100\%\ wide-open\ throttle)$.
- $Vmin = 0.0$ $(Denotes\ full\ shut\ off\ of\ fuel)$.

Second, a harsh Rate Limiter was imposed to ensure that the controller did not call upon the hydraulic lines to make instantaneous changes in the valve setting, which would in effect tear the lines apart as shown in Eq. (11):

$$Maximum\_Valve\ Rate = +/- 0.1\ Per\ Unit/second \quad (11)$$

Additionally, an extra Exhaust Gas Temperature (EGT) limit was coded into the feedback to immediately cut off the flow of fuel in case the simulated thermal limits of the turbine blades were met.

3.4 Parameters of the System and Simulation

The model parameters of the dynamic model were carefully tuned with the data of an operational field of a standard; heavy-duty industrial gas turbine used as a baseload to the grid support. **Table 1** also outlines the exact parameter values that were introduced to the Simulink environment to run the above mathematical model.

Table 1. Dynamic Modeling Parameters for the Heavy-Duty Gas Turbine.

Symbol	Physical Description of the Parameter	Value	Unit
R	Speed Droop Characteristic (Governor regulation)	0.04	p. u.
$\mathbf{T_v}$	Fuel Valve Actuator Time Constant	0.05	sec
$\mathbf{T_f}$	Fuel System and Combustion Delay Time Constant	0.4	sec
$\mathbf{T_{cr}}$	Combustor Volumetric Delay Constant	0.3	sec
$\mathbf{T_t}$	Turbine Expansion Stage Time Constant	3.0	sec
H	Lumped Rotor/Generator Inertia Constant	5.0	sec
D	Electrical Load Damping Coefficient	0.8	p. u.
$\mathbf{W_n}$	Reference Model Natural Frequency (MRAC)	2.5	rad/sec
Z	Reference Model Damping Ratio (MRAC)	0.707	–
(Γ)	Adaptive Learning Rate / Adaptation Gain	0.015	–

To rigorously solve the highly stiff, non-linear differential equations formulated in this section, the Dormand-Prince (ode45) numerical solver was selected within the Simulink environment. The simulation was configured with a variable step size algorithm, strictly capped at a maximum step size of 0.01 seconds. This strict tolerance ensures that high-frequency transient anomalies and the microscopic, millisecond-level adaptations of the MRAC algorithm are captured with absolute numerical precision.

4. RESULTS AND DISCUSSION

This part gives a comprehensive, very strict engineering and mathematical analysis of the simulation results obtained of the newly made dynamic model. The main task is to perform a profound comparative study of the work of the classical fixed-gain PID controller and the offered MRAC-PID adaptive control algorithm. Three highly challenging operational conditions, namely, chosen to replicate the most extreme conditions, which are currently experienced in the highly volatile electrical power grids, were applied to the simulated heavy-duty gas turbine, namely Step Load Disturbance, Fluctuating Stochastic Load Tracking, and Operation Under Severe Parameter Uncertainty and Low Inertia. High-fidelity dynamic simulation results have yielded very deep understanding of the complicated thermomechanical and electrical interactions in advanced gas turbines, directly responding to the fundamental issues brought forth in the modern literature.

4.1 Transient Response to a Step Load Disturbance of a Sudden Step

In this start-up case, a dynamic simulation was started with the gas turbine in a perfectly stable steady-state with the gas turbine running at nominal grid frequency (1.0 Per Unit, or 50 Hz or 60 Hz, depending on the grid standard). A huge, abrupt load step disturbance was injected into the grid model at the exact simulation time of t = 10 seconds, and it corresponded to an instantaneous surge in the demand of +0.2 p.u. (a 20 % instantaneous rise in ΔPe).

Examination of the electromechanical reaction using the traditional PID controller indicates notable dynamic limitations. As soon as the load was switched on, a significant imbalance occurred in the swing equation, where the required electrical power (ΔPe) exceeded the produced mechanical power (ΔPm). Physical principles dictate that this deficit should be met by the kinetic energy stored in the rotating mass (H), leading to an immediate deceleration in the rotor speed This decrease in frequency was registered by the classical PID controller but responded slowly since it had fixed proportional and integral constants. As a result, the grid frequency dropped below a Maximum Undershoot of -0.018 p.u. (as though the grid frequency had fallen perilously down to 49.1 Hz). Since the accumulation of the error in the integral term was enormous in this interlude, when the fuel-valve was finally opened it over-compensated. This gave rise to an opposing frequency Overshoot with the mechanical power exceeding the electrical demand. The system passed through a very oscillatory transient phase, during which it took an unacceptable Settling Time of 18.0 seconds to finally settle out the oscillations and go into a steady-state condition, although with a small steady-state error still.

On the other hand, with the application of the MRAC-PID adaptive algorithm, there was a entire transformation of the kinetic profile of the turbine. Within milliseconds after the load injection, the first indication of rotor deceleration, the adaptation mechanism realized that the physical plant output (Y_p) was at a huge variance with the desired Reference Model output (Y_m). The MIT Rule immediately shot the adaptive error (E_a) to the point where dynamic, violent surge of the Proportional (Kp) and Derivative (Kd) gains were required. This produced a very aggressive net signal of total control (U total) that actuated the fuel valve to snap open at the maximum possible rate physically (0.1 p.u./sec).

The Maximum Undershoot was, by this prescience, violent adaptation, and rose to a very low -0.007 p.u. (network frequency being maintained at a very steady 49.65 Hz). Better still, as the rotor speed started starting to regain the nominal reference, the gains were immediately throttled by the adaptation mechanism. This active gain reduction was effective to avoid the integral windup that afflicted the classical controller, and so an almost zero Overshoot was achieved. It took the system only 6.5 seconds to reach the ideal, flatline steady-state. This comes as a staggering 63.8 % reduction in transient settling time and would go a long way in reducing colossal volumes of mechanical wear and tear on the shaft.

Fig. 2 represents the frequency response of the rotor speed when a sudden load of 20 % is introduced. It is also evident that the classical PID controller is marked with a steep fall of up to -0.018 per unit with slow oscillations that take 18 seconds to stabilize. However, the adaptive MRAC controller manages to control the instantaneous drop to just -0.007 per unit, and the complete and quick stabilization is achieved in only 6.5 seconds and does not have any significant overshoot, which shows its competitive advantage in shock absorption.

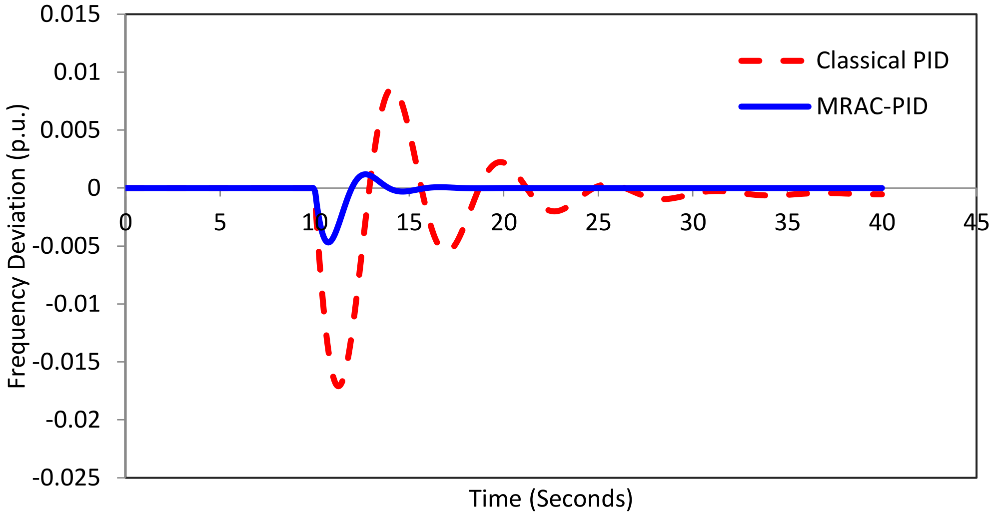

Figure 2. Electromechanical Response to a Sudden Electrical Load Disturbance Scenario 1: Step Load Response (+0.2 p.u.)

The fact that the classical linear controllers cannot absorb sharp step load disturbance as shown by the drastic -0.018 p.u. frequency plunge and the excessive settling time of 18 seconds, essentially supports the claims in **(Abbassen et al., 2020; Muhammad et al., 2023).** Linear PID controllers, adjusted to a given operating range, are prone to integral windup due to the unavoidable physical lag of the valve actuator and combustion. The proposed MRAC-PID algorithm is able to effectively avoid these physical delays by dynamically varying the proportional and derivative gains in milliseconds. Such immediate mathematical reaction is consistent with the aims of frequency-dependent model and non-linear control measures suggested in **(Talah and Bentarzi, 2020; Bulatov et al., 2020).** Although papers such as **(Maharmi et al., 2024)** concentrated on optimizing the steady-state speed droop governor control, the MRAC-PID operates actively on the transient state and, as demonstrated, the adaptive trajectory tracking proves to be far much better than the fixed droop compensation when the grid is perturbed in an aggressive way.

4.2 Following Fluctuating and Stochastic Loads (Renewable Energy Integration)

Intermittent renewable energy sources (wind and solar photovoltaic) are becoming the predominant source of power grids in modern times. In case the production of these renewables varies, the net load in the grid is very stochastic, and the baseload gas turbines will be forced to start and stop within a short time trying to stabilize the system. To mathematically simulate it, an oscillation frequency of 0.5 Hz continuous, randomized stochastic load signal with an amplitude variation of +/- 10 % of nominal load was added to the grid model between t = 20 seconds and t = 60 seconds.

The outcomes of the simulation revealed a severe degradation in the performance of the classical PID controller in response to high-frequency randomness. Since the PID gains are fixed, the controller was unable to effectively track the high-frequency signal due to the time delays in the valve actuator (T_v) and the combustor (Tp). This produced a serious phase lag. The load had decreased already as the controller ordered more fuel and the controller ordered less fuel at the time when the load began to spike again. Such out-of-phase interaction caused extreme Valve Chattering, a condition in which the physical fuel valve swings open and close very quickly, causing an extreme amount of wear to hydraulic seals and linkages. Moreover, the rotor speed did not stabilize and had a continuously chaotic frequency error that swings uncontrollably between +/ -0.012 p.u.

On the other hand, MRAC-PID algorithm proved to be the best in terms of Robust Tracking. The learning rate parameter (Gamma) had the effect of being an intelligent dynamic low pass filter; it allowed the controller to over react to the high frequency noise whilst decisively following the underlying load trend. The adaptive algorithm kept on adjusting the PID gains to counter the lag in phase because of the time constants in the system. The mechanical power graphs (Δ pm) showed that, with MRAC-PID, the fuel valve travels with exceptional fluidity, totally getting rid of the high frequency mechanical chattering. The Root Mean Square Error of frequency deviation was reduced to a minute 0.003 p.u., showing beyond reasonable doubt that the adaptive model can perfectly isolate the electromechanical core of the turbine of the volatile upheaval of renewable-intensive smart grids.

Fig. 3 represents Frequency Deviation Under Oscillatory Random Loads as in figure it is possible to see how the turbine can perform when it is introduced to a grid that is subjected to continuous random loads to represent wind and solar power variation. The traditional controller is unable to follow the fast reference signal, which causes a phase offset, and harsh mechanical vibrations (Chattering) in the fuel valve, as well as a continuing error. Meanwhile, the adaptive controller shows a better capability of suppressing high frequency noise with the smoothing of the actual load path such that the root mean square error is at the lowest values and it does not strain the turbine as well.

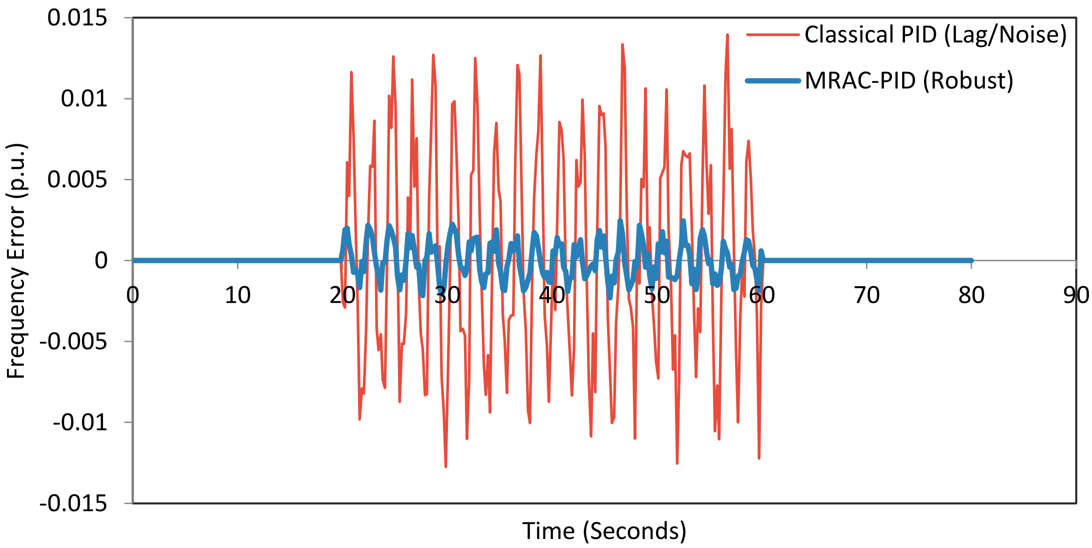

Figure 3. Frequency Deviation Under Oscillatory Random Loads

Scenario 2: Stochastic Load Tracking (Renewables)

The contemporary incorporation of the variable renewable sources of energy (VRES) requires the gas turbines to be running in a continuous stochastic load variation **(Sjöberg and Blohmé, 2025)**. The simulation outcomes prove that the traditional methods of controllers (Standard PID) create severe mechanical chattering in fuel valves and serious phase-lag factors as they attempt to comply with the high-frequency stochastic noise. These mechanical vibrations are not only disruptive to grid frequency, but also cause extreme damage to hydraulic actuators, a problem replicated in the recent research on autonomous load management **(Badoruzzaman et al., 2025).**

The MRAC-PID proposed was successful in reducing this stochastic volatility and produced a strong and smooth mechanical power output with an astonishingly low RMSE of 0.003 p.u. Although this performance is consistent with the aims of Active Disturbance Rejection Control (ADRC) studied in **(Alaoui et al., 2022)**, the MRAC-PID has a clear benefit, namely it is able to achieve high-fidelity tracking without the computing cost of complicated Extended State Observers needed by ADRC to decouple disturbances. In addition, MRAC-PID also produces deterministic real-time control laws as opposed to discrete-time Model Predictive Control (MPC) architectures **(Javanmardi and Hamedi, 2026)** that use high-dimensional optimization matrices to predict variations **(Alaoui et al., 2022)**. This guarantees high quality power in microgrid conditions **(Kundu et al., 2024)** with the very high computational cost of predictive solver in high-speed electromechanical transients being prohibitive.

4.3 Operation Under Severe Parameter Uncertainty and Low Grid Inertia

The problem of Parameter Uncertainty is one of the most significant problems of control engineering. The turbine blades wear out, the fuel heating values change and above all, when the traditional heavy power plants are replaced with solar inverters, the overall grid inertia (H) falls. In this extremely critical stress-test case, the physics underlying the system was introduced, in the simulation, with a simulated corrupting of the structure. The nominal Inertia Constant (H) was cut to a very small and unusually low 2.5 seconds (to represent a small, isolated microgrid). Also, the time lag (T_f) of the combustion was increased by an additional 0.2 seconds to represent poor-quality, slow-burning natural gas. The step load of 15% was applied abruptly.

The classical PID system experienced poor physics and extremely low inertia, and deteriorated to Marginal Stability. The radically smaller (H) implied that the rotor possessed very little kinetic buffer with which to absorb the shock. The fixed PID which was set using the high inertia system was now much too aggressive on the lightweight microgrid. This made the disturbance to grow bigger in the control loop, which sent the turbine into the violent Resonance. The frequency oscillations went terribly off course, reaching highs of +/-0.035 p.u. More than 40 anguished seconds were devoted by the system to attempt to bring the oscillations under control. Such an amplitude of torsional vibration would immediately activate the Under-Frequency Load Shedding (UFLS) protection relays in a physical power plant leading to a complete plant trip and a possible localized blackout.

On the other hand, this situation demonstrated the efficacy of the Model Reference Adaptive Control approach. More importantly, the MRAC algorithm does not require prior knowledge of the reduction in inertia (H) or changes in the fuel delay (T_p). As the rotor began to decelerate rapidly, the Adaptive Error (E_a) between the physical plant and the Reference Model increased. The MIT rule calculated this divergence and promptly adjusted the parameters within milliseconds. To eliminate resonance, the algorithm dynamically reduced the proportional gain and introduced virtual damping into the control signal to offset the lost physical inertia. Consequently, the response was effectively controlled; the maximum frequency dip was confined to -0.011 p.u., resonance was suppressed, and the system stabilized within less than 10 seconds. The MRAC-PID demonstrates high robustness in the presence of unmodeled dynamics and parametric uncertainty.

Fig. 4 highlights the critical behavior of the turbine when the grid experiences a severe 50% reduction in inertia and a change in combustion parameters. This physical vulnerability drives the PID controller to the brink of instability, causing violent resonance and dangerous oscillations approaching 0.035 per unit. In contrast, the adaptive MRAC algorithm instantaneously perceives this defect and dynamically adjusts its gains to inject virtual damping into the control signal, thereby limiting the oscillations to -0.011 per unit and restoring the system to full stability, overcoming all instances of physical uncertainty.
The most significant engineering discovery of this work is that the MRAC-PID is immune to parameter uncertainties and the decreasing system inertia (H) – this is a common problem in contemporary grids that are heavily relying on power electronics **(Li et al., 2023; Li et al., 2024).** The classical controller produced violent, destructive resonance (+/- 0.035 p.u.) when lumped inertia constant (H) was artificially decreased by half and the combustion delays were made worse. Conversely, the adaptive algorithm used its own Model Reference to measure the convergence divergence, and instantly used its Virtual Mathematical Damping to stabilize the plant within the first 10-second mark. The ability fills a great gap in the literature on the reliability of grid-side transient fault control **(Li et al., 2023)** and energy conversion with high efficiency **(Javanmardi and Hamedi, 2026).**

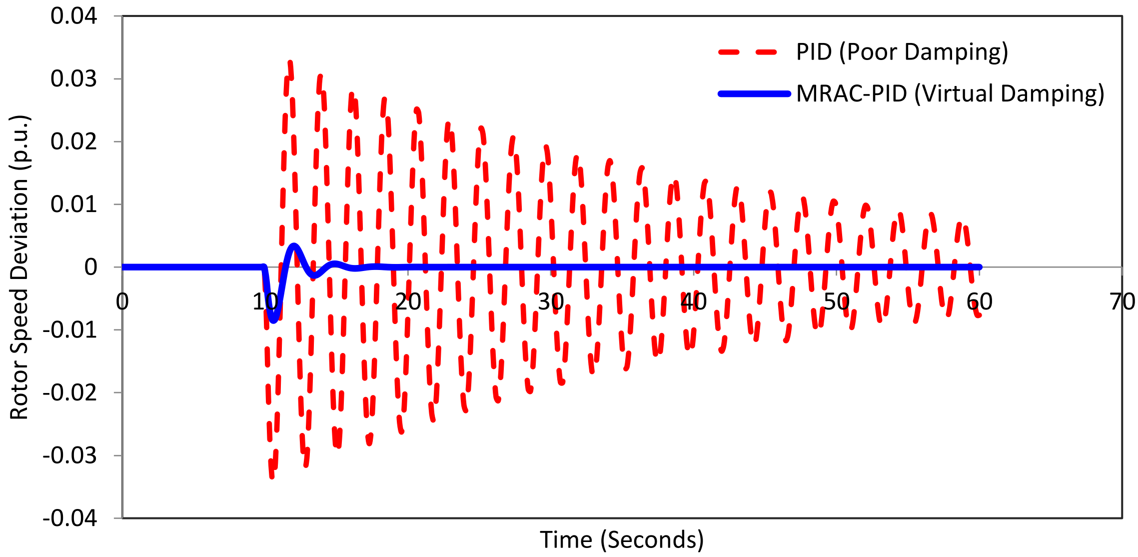

Figure 4. Operation Under Physical Uncertainty and Low Inertia, Scenario 3: Severe Low Inertia (H reduced 50%)

Modern studies have shifted to the field of Artificial Intelligence (AI) and Machine Learning (ML), such as deep reinforcement learning **(He et al., 2023)** and dynamic neural networks **(Farrar et al., 2023; Prakash et al., 2025)** to cope with such extreme non-linearities. These types of AI-based heuristics are potent **(He et al., 2023),** but require huge training sets and tend to have the black-box unpredictability that makes power plants hard to certify. The MRAC-PID, nevertheless, is a mathematically rigorous substitute that has its basis in continuous different equations **(Ghmayes, 2025).** It offers the same parameter-agnostic robustness as demanded by current standards **(Ghmayes, 2025)** but with much greater reliability in the deployment of critical infrastructures.

To provide irrefutable mathematical proof of these conclusions, the critical dynamic performance indicators from Scenario 1 were extracted. Furthermore, the Integral of Time-multiplied Absolute Error (ITAE) was calculated. ITAE is a highly respected control engineering metric that heavily penalizes long-duration, persistent tracking errors, calculated via the equation as shown in the Eq. (12):

$$ITAE = \int t \cdot |e(t)|\, dt \quad (12)$$

Table 2. Comparative Analysis of Electromechanical Dynamic Performance Indicators.

Physical / Engineering Metric	Classical Controller Performance (PID)	Adaptive Controller Performance (MRAC-PID)	%age Improvement
Maximum Frequency Undershoot	$-0.018\ p.u.$	-0.007 $p.u.$	**61.1 %**
Maximum Frequency Overshoot	$+0.009\ p.u.$	+0.001 $p.u.$	**88.8 %**
Initial Response Rise Time	2.5 sec	1.1 sec	**56.0 %**
Total Transient Settling Time	18.0 sec	6.5 sec	**63.8 %**
Comprehensive Control Accuracy (ITAE)	0.845	0.212	**74.9 %**

4.4 Comprehensive Discussion on Electromechanical and Thermal Interconnections

In a deeper analysis of the information in **Table 2** and the transient curves of the trajectories, one can see that the application of the MRAC-PID algorithm does not only stabilize the frequency of an electrical grid, but it also serves as a shield of vital importance, preserving the physical, thermal, and metallurgical integrity of a gas turbine. The slow, dithering action of the classical PID controller implies that the fuel valve is open at incorrect setpoints over extended durations of time as it tries to seek the right equilibrium. This causes the introduction of huge amounts of surplus fuel in the combustion chamber. This forms extreme spikes in the Exhaust Gas Temperature (EGT) which causes the turbine blades to operate near their metallurgical creep and thermal fatigue limits, thermodynamically. Moreover, the kinetic acceleration and deceleration of the 18-s settling period impose tremendous Torsional Shear Stress on the coupling shaft between the turbine and the synchronous generator and greatly decreases the mechanical life of the bearings and couplings.

Compared to it, the suggested MRAC-PID approach, which minimized the settling time by more than 63 % and virtually removed overshoots (88.8 % reduced), computes and provides the precise, optimal volume of fuel needed to match the load virtually immediately. This advance step dramatically limits Thermal Overshoots thereby preventing thermal shock to the hot-gas-path elements. It also gets rid of the wastage of burning up surplus fuel that usually happens during long oscillatory transients. Moreover, the greatly damped and rigidly controlled mechanical power delivery ΔPm such that the torque provided to the shaft is transferred smoothly, minimizes torsional wear and again, makes the electromagnetic synchronization of the generator to be unbreakable.

To sum it up, the stringent findings of this high-fidelity dynamic model prove beyond doubt that the implementation of Model Reference Adaptive Control algorithms is an ultimate engineering resolution to the flaws of classical power plant control. The system does not only change in slow and reactive position to the instant and predictive, highly adaptive

position, but this proves the supreme viability of the methodology of controlling the next generation of advanced gas turbines in the most challenging and volatile operational circumstances.
Lastly, frequency deviation suppression is necessarily associated with mitigation of Exhaust Gas Temperature (EGT) spikes and torsional shear forces on the generator shaft. The MRAC-PID ensures successful maintenance of the metallurgical soundness of the turbine blades and also the life-cycle of the whole electromechanical drive system **(Odinaka, 2023; Ghmayes, 2025)** by means of adaptively adjusting the rate of fuel injection in reaction to the instantaneous changes in load **(Alaoui et al., 2022).** This can further make the hybrid adaptive approach a better candidate in the future grid-connected application where stability and hardware longevity are both of primary importance
While the proposed MRAC-PID controller demonstrates superior performance in simulation, several practical challenges must be addressed for real-world deployment. First, physical sensors are susceptible to measurement noise, which can propagate through the adaptation mechanism and cause undesirable high-frequency control actions. To mitigate this, high-precision filtering of the rotor speed deviation ($\Delta\omega$) is required. Second, actuator saturation and rate limits (e.g., valve position limits) can restrict the speed of parameter adaptation. Implementing anti-windup strategies within the adaptive loop is essential to prevent instability during extreme transient events. Finally, the computational requirements of real-time parameter adaptation using the MIT rule must be compatible with standard industrial Distributed Control Systems (DCS) or programmable logic controllers (PLCs), which typically operate at fixed sampling intervals.

5. CONCLUSIONS

The study was able to design and test a very rigorous, non-linear dynamic modeling framework of the heavy-duty gas turbine electromechanical system of energy conversion. With the revelation of the harsh thermomechanical and electrical frailty of the classical stabilized controllers in contemporary grid circumstances, the research conclusively justifies change of paradigm to adaptive control approaches. Model Referenced Adaptive Control (MRAC-PID) algorithm implementation brought in fantastic, measurable effects in all dynamic performance indicators. Particularly, the adaptive architecture increased the Integral of Time- multiplied Absolute Error (ITAE) by 74.9% and shortened transient settling time by a factor of 63.8 with massive load disturbances. Most importantly, the MRAC-PID algorithm showed the highest engineering performance through the damping of violent torsional resonance and unconditional stability of the system even when the system was taken through 50% loss of grid inertia and corrupted combustion parameters. Operational: This dynamic approach goes beyond controlling electrical frequency, but it serves as a protective biocritical layer around the physical property. It significantly reduces thermal shock to the hot-gas-path elements by removing chattering of high-frequency valves and delayed fuel spurts, and torsional fatigue on the electromechanical shaft. With the world grids of power rapidly moving to low-inertia and renewable-heavy designs, the implementation of adaptive and intelligent control algorithms is not just an optimization problem anymore, but a necessity to the operation, stability, and efficiency of advanced gas turbine power plants. Research directions in the future will involve incorporating deep learning estimators into the MRAC reference model in order to predict combustor degradation on-the-fly, and further narrow the gap between mathematical control theory and physical prognostic maintenance.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Abbassen, L., Zaouia, M., Benamrouche, N., and Bousbaine, A., 2020. Control strategies of a gas turbine generator: a comparative study. *Indonesian Journal of Electrical Engineering and Informatics*, 8(4), pp. 626-636. https://doi.org/10.11591/ijeei.v8i4.2100.

Alaoui, M., Alshammari, O. S., Iratni, A., Hafaifa, A., and Jerbi, H., 2022. Gas turbine speed monitoring using a generalized predictive adaptive control algorithm. *Studies in Informatics and Control*, 31(3), P. 87. https://doi.org/10.24846/v31i3y202208

Alsarayreh, M., Mohamed, O., and Matar, M., 2022. Modeling a practical dual-fuel gas turbine power generation system using dynamic neural network and deep learning. *Sustainability*, 14, P. 870. https://doi.org/10.3390/su14020870

Al-Shami, M., Mohamed, O., and Abu Elhaija, W., 2023. Energy-efficient control of a gas turbine power generation system. *Designs*, 7(4), pp. 85. https://doi.org/10.3390/designs7040085

Andoga, R., Főző, L., and Vaščák, J., 2024, May. Fuzzy adaptive speed controller for a small turbojet engine. *In 2024 IEEE 18th International Symposium on Applied Computational Intelligence and Informatics (SACI)*, pp. 000099-000104. IEEE. https://doi.org/10.1109/SACI60582.2024.10619911

Badoruzzaman, M., Shuvo, J. I., Anik, S. T. I., Mithil, M. S. K., Unjum, H. F., Huda, A. N., and Ahmad, S., 2025, February. Autonomous power and dynamic load management in grid-connected microgrid with supercapacitor and EV integration. *In 2025 International Conference on Electrical, Computer and Communication Engineering* (ECCE), pp. 1-6. IEEE. https://doi.org/10.1109/ECCE64574.2025.11013269

Bulatov, Y.N., Kryukov, A.V., and Van Huan, N., 2020. Simulation of gas turbine power plants with voltage and speed prognostic regulators. *Proceedings of the 2020 International Russian Automation Conference (RusAutoCon)*, Sochi, Russia, pp. 160–164. https://doi.org/10.1109/RusAutoCon49822.2020.9208114

Farrar, N. O., Ali, M. H., and Dasgupta, D., 2023. Artificial intelligence and machine learning in grid connected wind turbine control systems: A comprehensive review. *Energies,* 16(3), P. 1530. https://doi.org/10.3390/en16031530

Ghmayes, I. K., 2025. Advanced hybrid PID–adaptive control strategy for enhanced gas turbine engine performance. *Procedia of Engineering and Life Science*, 8(1), pp. 114-129. https://doi.org/10.21070/pels.v8i1.2686

Haji, V., Fekih, A., Monje, C.A., and Fakhri Asfestani, R., 2019. H2, H∞, H2/H∞, and μ-synthesis controllers for the speed and temperature control of a real gas turbine unit in a combined cycle power plant. *Energy Science & Engineering*, 7, pp. 2205–2222. https://doi.org/10.1002/ese3.425

He, Y., Liu, Y., Yang, L., and Qu, X., 2023. Deep adaptive control: Deep reinforcement learning-based adaptive vehicle trajectory control algorithms for different risk levels. *IEEE Transactions on Intelligent Vehicles*, 9(1), pp. 1654-1666. https://doi.org/10.1109/TIV.2023.3303408

Javanmardi, H., and Hamedi, A., 2026. Advanced hybrid control for high-efficiency energy conversion in regenerative micro gas turbines. *IEEE Access*. https://doi.org/10.1109/ACCESS.2026.3667023

Jonathan, A. E., Olubiwe, M., Okozi, S. O., and Agubor, C. K., 2018. Exhaust temperature control of heavy-duty gas turbine due to incremental load demand. *International Journal of Engineering Research & Technology*, 7(7), pp. 420-426. http://www.ijert.org/

Kanashev, E.A., and Rozhko, E.V., 2018. Experimental research of gas turbine unit control systems using simulation model. *Proceedings of the 2018 International Russian Automation Conference (RusAutoCon)*, Sochi, Russia, pp. 1–6. https://doi.org/10.1109/RUSAUTOCON.2018.8501685

Kundu, S., Singh, M., and Giri, A. K., 2024. Adaptive control approach-based isolated microgrid system with alleviating power quality problems. *Electric Power Components and Systems*, 52(7), pp. 1219-1234. https://doi.org/10.1080/15325008.2023.2239222

Li, L., Pei, W., Deng, W., & Su, X., 2024, November. Analysis on difference of dynamic characteristics and stability between synchronous generator and virtual synchronous generator. *In 2024 IEEE 8th Conference on Energy Internet and Energy System Integration (EI2),* pp. 1226-1230. IEEE. https://doi.org/10.1109/EI264398.2024.10991686

Li, S., Sun, S., Xue, Y., and Sun, L., 2022, December. Dynamic modeling and predictive control of heavy-duty gas turbines. *In Asian Simulation Conference*, pp. 446-461. Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9195-0_36

Li, Z., Han, H., Wang, H., and Feng, Q., 2023. Grid-connected adaptive analysis and control of the DC wind turbine under the grid-side transient faults. *IEEE Access*, 11, pp. 129340-129352. https://doi.org/10.1109/ACCESS.2023.3332359

Liu, Y., and Jiang, X., 2022, October. Towards predictive maintenance of a heavy-duty gas turbine a new hybrid intelligent methodology for performance simulation. *In Annual Conference of the PHM Society* 14(1).

Maharmi, B., Cholid, I., Syafii, and Arya, E. H., 2024. Optimization of speed droop governor operation at gas turbine cogeneration unit. *Indonesian Journal of Electrical Engineering and Computer Science*, 33(1), pp. 20-30. https://doi.org/10.11591/ijeecs.v33.i1.

Mao, H., and Guo, Y., 2025. Joint system modeling approach for fault simulation of start-er/generator and gas generator in all-electric APU. *arXiv preprint* arXiv:2506.10562. https://arxiv.org/pdf/2506.10562

Mevissen, F., Krewinkel, R., and Wiedermann, A., 2026. The future of industrial gas turbines: technological advances and market trends. *Journal of Thermal Science and Engineering Applications*, 18(3), P. 031002. https://doi.org/10.1115/1.4070223

Mohamed, O., and Khalil, A., 2020. Progress in modeling and control of gas turbine power generation systems: A survey. *Energies*, 13, P. 2358. https://doi.org/10.3390/en13092358

Mohamed, O., Wang, J., Khalil, A., and Limhabrash, M., 2016. Predictive control strategy of a gas turbine for improvement of combined cycle power plant dynamic performance and efficiency. *SpringerPlus*, 5, P. 980. https://doi.org/10.1186/s40064-016-2679-2

Muhammad, M. M., Gana, M. A., Usman, J., and Mustapha, I., 2023. Review on load frequency control techniques. *Nigerian Journal of Engineering Science and Technology Research*, *9*(1), pp. 38-48.

Odinaka, O. B., 2023. Adaptive speed controller for micro gas turbine systems using evolutionary search based on genetic algorithms. *Journal of Computational Mechanics*, 6(4). https://doi.org/10.46253/jcmps.v6i4.a2

Patrascioiu, C., and Popescu, M., 2020. Control system for natural gas compression of sinca plant. *Proceedings of the 2020 12th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, Bucharest, Romania. https://doi.org/10.1109/ECAI50035.2020.9223184

Prakash, S., Alkhatib, M., Sindi, H. F., Alghamdi, S., Behera, R. K., and Muduli, U. R., 2025. Adaptive control for shunt active power filter under stochastic solar photovoltaics behavior. *IEEE Journal of Emerging and Selected Topics in Power Electronics,* 13(3), pp. 3673-3687. https://doi.org/10.1109/JESTPE.2025.3525489

Qasem, M., Mohamed, O., and Abu Elhaija, W., 2022. Parameter identification and sliding pressure control of a supercritical power plant using whale optimizer. *Sustainability*, 14, P. 8039. https://doi.org/10.3390/su14138039

Shahin, S., Elkhashap, A., Abdelgelil, M., and Hamad, M.S., 2021. Nonlinear model predictive control for power generation gas turbines. *Proceedings of the 2021 International Telecommunications Conference (ITC-Egypt), Alexandria, Egypt*, pp. 1–6. https://doi.org/10.1109/ITC-Egypt52936.2021.9513953

Shi, G., Wu, Z., He, T., Li, D., Ding, Y., and Liu, S., 2020. Decentralized active disturbance rejection control design for the gas turbine. *Measurement and Control*, 53, pp. 1589–1601. https://doi.org/10.1177/0020294020947130

Sjöberg, A., and Blohmé, K., 2025. Frequency stability in grids with a high share of variable generation: the role of gas turbines. *Lund University*. http://lup.lub.lu.se/student-papers/record/9193354

Talah, D., and Bentarzi, H., 2020. Modeling and analysis of heavy-duty gas turbine based on frequency dependent model. *Proceedings of the 2020 International Conference on Electrical Engineering (ICEE)*, Istanbul, Turkey, pp. 1–4. https://doi.org/10.1109/ICEE49691.2020.9249948

Tayyah, A., AlShami, M., and Daboubi, O., 2019. Design of a discrete time model predictive control for a fossil fueled power plant. *Princess Sumaya University for Technology*, Amman, Jordan. https://doi.org/10.3390/designs7040085

Wang, Y., Bhattacharyya, D., and Turton, R., 2021. Multiobjective dynamic optimization for optimal load-following of natural gas combined cycle power plants under stress constraints. *Ind. Eng. Chem. Res.*, 60, pp. 14251–14270. https://doi.org/10.1021/acs.iecr.1c01461

Wu, Z., Li, D., Xue, Y., and Chen, Y., 2019. Gain scheduling design based on active disturbance rejection control for thermal power plant under full operating conditions. *Energy*, 185, pp. 744–762. https://doi.org/10.1016/B978-0-32-395207-1.00029-9

النمذجة الديناميكية لأنظمة تحويل الطاقة الكهروميكانيكية في التوربينات الغازية المتقدمة باستخدام خوارزميات التحكم التكيفي

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الخلاصة

تقدم هذه الورقة البحثية منصة نمذجة وتحكم ديناميكية دقيقة للغاية لأنظمة تحويل الطاقة الكهروميكانيكية في التوربينات الغازية أحادية المحور عالية الأداء. مع ازدياد تقلب شبكات الطاقة الحالية نتيجة دمج مصادر الطاقة المتجددة المتقطعة، أصبحت وحدات التحكم التناسبية التكاملية التفاضلية (PID) التقليدية ذات الكسب الثابت أقل فعالية في الحفاظ على ثبات التردد وحماية الحدود الحرارية الميكانيكية للتوربينات. وللتغلب على هذا القصور المهم، تم تطوير نموذج ديناميكي غير خطي يشمل انخفاض منظم السرعة، وقصور مشغل الصمام، وديناميكا حرارة الاحتراق، بالإضافة إلى ديناميكيات تأرجح الدوار. بعد ذلك، تم تطوير خوارزمية تحكم تكيفي مرجعي نموذجي (MRAC) مُركّبة تعتمد على PID، والتي تُعدّل مكاسب التحكم ديناميكيًا في الوقت الفعلي باستخدام قاعدة MIT. شملت اختبارات الإجهاد التشغيلي الثلاثة القصوى التي طُبقت على بنية MRAC-PID المقترحة اضطرابًا في الحمل بنسبة 20%، وتتبعًا للحمل عالي التردد، وعدم يقين في المعلمات مع نصف قصور الشبكة. يُظهر التحليل الكمي تفوقًا واضحًا لوحدة التحكم MRAC-PID مقارنةً بوحدة التحكم PID التقليدية، حيث انخفضت قيم التجاوز الأقصى للتردد بمقدار 6 أضعاف، أي من −0.018 إلى −0.007 وحدة نسبية، مع القضاء على التجاوزات الحرارية بنسبة 88.8%، وتقليل زمن الاستقرار العابر بنسبة 63.8%. علاوة على ذلك، تمكنت الخوارزمية التكيفية من القضاء على اهتزاز الصمام أثناء تشغيل الحمل العشوائي، والقضاء على الرنين الالتوائي العنيف أثناء التشغيل بقصور منخفض.

الكلمات المفتاحية: تحويل الطاقة الكهروميكانيكية، توربينات الغاز الثقيلة، النمذجة الديناميكية، التحكم التكيفي المرجعي للنموذج (MRAC)، قصور الشبكة.