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Performance Evaluation and Predictive Control of Diesel Generator Systems Using Generalized Predictive Control (GPC) And Internal Model Control (IMC)

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Abstract
The primary aim of this study is to improve the performance, stability, and efficiency of diesel generator systems through the adoption of advanced control strategies. Conventional controllers, although widely used, often struggle to maintain consistent operation under varying load conditions. This limitation results in issues such as voltage fluctuations, unstable frequency, overheating, and reduced efficiency. Such challenges not only undermine the reliability of generators but also lead to higher fuel consumption, increased operational costs, and elevated emissions, posing both economic and environmental concerns. To tackle these problems, this research introduces a Generalized Predictive Control (GPC) framework, assessed in comparison with the Internal Model Control (IMC) approach. The methodology combines mathematical modeling, state-space formulation, and predictive optimization techniques to achieve superior dynamic performance. Key generator parameters—including temperature, frequency, voltage regulation, overload factor, and efficiency—were modeled to evaluate the system response. An Arduino Uno platform integrated with sensors and actuators was proposed for real-time implementation, ensuring practical applicability. A cost function was also designed to minimize deviations from setpoints while optimizing control input. The findings reveal that GPC delivers significant improvements over IMC. For instance, generator frequency was precisely stabilized from 70 Hz to the standard 50 Hz with an error margin of only 0.002, compared to 2.5 for IMC. Voltage regulation improved steadily from 250 V to 230 V, while operating temperature was reduced from 100 °C to 85 °C. Efficiency rose to 99% under GPC, surpassing the 96% achieved by IMC. Additionally, fuel injection was reduced by 5 mg/ms, and CO_2 emissions declined by 40%, confirming both economic and environmental advantages. Overall, the study establishes GPC as a superior control strategy for modern diesel generator systems.

KEYWORDS: MPC, GPC, IMC, Temperature, Voltage, Generator

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I. INTRODUCTION

Diesel generators remain a critical component of modern power systems, serving as reliable backup sources of electricity in industrial, commercial, and residential applications. Their importance is particularly pronounced in regions with unstable grid supply or in isolated off-grid systems where uninterrupted power is essential [1]. However, despite their widespread use, diesel generators face persistent operational challenges, including voltage fluctuations, frequency instability, overheating, efficiency losses, and high fuel consumption [2][3]. These limitations not only reduce system reliability but also increase maintenance costs and environmental impacts through higher emissions [4][5]. Traditional control methods such as Proportional–Integral–Derivative (PID) controllers and Internal Model Control (IMC) have been widely applied to regulate generator performance. While these approaches provide acceptable levels of stability, they often struggle to adapt to dynamic and uncertain operating conditions, especially under rapid load variations [6][7][8]. This creates a need for advanced control strategies capable of anticipating disturbances, optimizing performance, and maintaining stability in real time. Generalized Predictive Control (GPC) offers a promising solution by utilizing predictive models to forecast future system behavior and optimize control actions accordingly. Unlike conventional methods, GPC minimizes deviations from desired setpoints by solving an optimization problem at each time step, ensuring improved stability, adaptability, and efficiency. Integrating GPC into diesel generator systems enables real-time regulation of parameters such as temperature, voltage, frequency, and power factor, while also improving fuel utilization and reducing emissions. This study develops a comprehensive monitoring and predictive control framework for diesel generators, combining mathematical modeling, optimization, and hardware implementation [9][10]. By comparing GPC with IMC, the research aims to highlight the superiority of predictive control in enhancing generator efficiency, maintaining operational stability, and achieving sustainable energy management. The outcomes provide both theoretical insights and practical solutions for intelligent generator control in modern power systems. Gitelman *et al.* [11] discussed diversification as a method to enhance sustainability in energy transitions. Their study highlighted strategies for ensuring secure supply under evolving global energy demands. The key contribution lies in framing diversification as both a resilience tool and an innovation driver. However, practical implementation challenges and policy integration require further research for effective application in complex power systems. Husain *et al.* [12] developed a Bluetooth-based home automation system enabling wireless appliance control through a local network. The design emphasizes simplicity, low cost, and practical household applicability. While effective for short-range applications, scalability and security challenges remain. The work contributes significantly to accessible automation frameworks, paving the way for enhanced integration with IoT for smarter and more adaptive home systems. Idoniboyeobu *et al.* [13] designed an Automatic Mains Failure (AMF) switch controlled remotely for seamless transition between power sources. The study demonstrated a cost-effective and reliable changeover mechanism crucial for power continuity. Its major contribution is the emphasis on automation in backup systems. However, integration with predictive algorithms and remote monitoring could improve system intelligence and reduce downtime during failures. LePard [14] outlined essential requirements for standby generator systems in next-generation data centers. The white paper emphasizes reliability, redundancy, and resilience as critical design parameters. It provides practical insights into operational and architectural needs for uninterrupted data center power. While informative, it lacks experimental validation, leaving a gap for research into advanced predictive controls to strengthen resilience in mission-critical facilities. Mbunwe [15] constructed a remote-control switching device for household appliances. The system offers a simple yet effective means of energy management in residential environments. Its strength lies in low-cost design and user accessibility. However, the lack of scalability, integration with renewable energy sources, and predictive automation highlight limitations. Future work could adapt such devices into IoT-based smart grid frameworks. Mock *et al.* [16] examined integrating road transport into the EU Emissions Trading System (ETS). The paper provided an engineering perspective on emissions control and policy implications. Its contribution lies in analyzing how trading mechanisms could incentivize low-carbon technologies in transport. While relevant for sustainability, real-world enforcement and compliance mechanisms remain key challenges requiring more integrated techno-economic modeling. Mwangi *et al.* [17] reviewed green fuel blends in diesel engines, highlighting energy-saving and pollution-reduction potentials. Their work underscored performance enhancements with reduced emissions when alternative fuel blends are adopted. This study provides strong empirical and theoretical support for cleaner combustion strategies. Limitations arise in large-scale implementation and cost analysis, leaving opportunities for predictive control systems to optimize blending effectiveness. Neil [18] presented an accessible overview of remote control technology via Wikipedia. The work explains operational principles, applications, and system design basics. While informative for general readers, it lacks technical rigor and scientific analysis. Its contribution is limited to introductory knowledge rather than engineering advancement. Nevertheless, it offers a foundation for exploring more sophisticated control systems in automation research. Obikoya *et al.* [19] developed a generator power sensor with a shutdown timer to prevent overuse and overheating. The system adds safety and operational efficiency in small-scale generators. Its contribution lies in low-cost preventive control. However, the absence of predictive intelligence restricts adaptability to dynamic loads, indicating potential for advanced integration with real-time monitoring and automated decision-making systems.

Olatinwo *et al.* [20] implemented a remote-control automatic changeover system to ensure uninterrupted power supply. Their design provided reliable switching between mains and backup sources. The contribution lies in enhancing power continuity with minimal user intervention. However, limitations exist in adaptability to large-scale systems and advanced predictive optimization. Future extensions could explore integration with IoT and hybrid renewable grids. Pampattiwar *et al.* [21] presented a Raspberry Pi-based home automation system controlled via Android. Their work demonstrates flexibility, cost-efficiency, and remote monitoring potential. It bridges microcontroller systems with user-friendly smartphone interfaces. The contribution advances low-cost smart home frameworks, but challenges such as scalability, cybersecurity, and integration with renewable sources persist. These limitations highlight the scope for predictive IoT-based enhancements. Pandya *et al.* [22] designed an automatic generator changeover system to ensure seamless backup power supply. The system demonstrated simplicity and cost-effectiveness in residential and small commercial settings. Its major contribution is ensuring operational continuity during outages. However, the lack of adaptive predictive control restricts real-time optimization. Expanding such systems with IoT frameworks could enhance resilience in critical operations. Pearsall [23] authored *Photonics Essentials*, a foundational text explaining principles and applications of photonics. The book covers light-matter interaction, optoelectronics, and communication technologies. Its contribution lies in offering comprehensive reference material for engineering and scientific research. While not application-specific to generator or automation systems, it provides theoretical underpinnings essential for optical sensing and communication within modern smart control environments. Piyare and Tazil [24] implemented a Bluetooth-based home automation system operated via mobile phones. Their work emphasized cost-effectiveness and ease of deployment. The study demonstrates practical implementation of wireless short-range control systems. Limitations include range restrictions, interference risks, and lack of predictive adaptability. Nevertheless, it provides foundational knowledge for developing more robust IoT-driven automation platforms for energy management. Ramlee *et al.* [25] designed a Bluetooth-enabled Android-based home automation system. Their approach enabled convenient appliance control and showcased integration between wireless communication and smartphones. The main contribution lies in advancing low-cost, accessible smart solutions. However, system limitations include security vulnerabilities, limited coverage, and lack of adaptive control. Future advancements could embed predictive analytics and IoT capabilities for smarter automation.

II. Materials and Methods

2.1 Materials

The materials used in this study are as follows:

i. Generator
ii. GPC controller
iii. IMC Controller
iv. Display
v. PC
vi. Voltage Regulator
vii. Thermistor
viii. MATLAB/Simulink

2.2 Method

The method adopted in this research is generalized predictive controller

2.2.1 Combined Evaluation in a Monitoring Framework

To combine these evaluations in a monitoring system, you can represent them together to assess the overall performance:

$$T(t) = T_{initial} + \int_0^t \frac{p_{gen}(t) - P_{diss}(t)}{C_{th}} dt \quad (3.1)$$

$$f(t) \frac{P.N(t)}{120} \quad (3.2)$$

$$of = \frac{p_{load}(t)}{p_{rated}} \quad (3.3)$$

$$vr = \frac{v_{no\ load} - v_{full\ load}}{v_{full\ load}} \times 100\% \quad (3.4)$$

By monitoring these parameters, you can evaluate the performance and operational status of the generator, enabling predictive control and timely interventions to ensure optimal operation. Table 3.1 shows the generator parameters.

Table 1: Showing the parameters

Parameter	Description of Parameters State In an ideal Condition	Control Method	Typical Range/Value
Voltage Output	Maintains the desired voltage level	Automatic Voltage Regulators (AVRs)	220V - 240V
Frequency	Keeps the frequency of the output power stable	Governor	50Hz - 60Hz
Fuel Injection	Manages the amount of fuel injected into the engine	Electronic or Mechanical Governors	Variable based on load
Engine Speed (RPM)	Directly affects the frequency and efficiency	Speed Governors or Controllers	1500 RPM - 1800 RPM
Load Sharing	Ensures the load is evenly distributed among generators	Load Sharing Controllers	Balanced load distribution
Power Factor	Improves the efficiency of the power supply	Power Factor Correction Devices	0.8 - 1.0 (Unity)
Cooling System	Prevents overheating and maintains optimal operating conditions	Thermostats and Temperature Sensors	Temperature < 90°C
Exhaust Emissions	Controls emissions for environmental compliance	Emission Control Systems	Compliant with standards
Lubrication System	Reduces wear and tear on moving parts	Lubrication Systems	Optimal oil pressure and flow
Battery Charging	Keeps the battery charged for starting and auxiliary power	Battery Chargers	12V - 24V

2.2 Implementation of Generalized Predictive Control

Implementing a Generalized Predictive Controller (GPC) involves developing mathematical models for each parameter to be controlled and formulating an optimization problem that predicts future behavior and determines optimal control actions. Below are the mathematical equations for implementing GPC to control temperature, overload, voltage regulation, and frequency of a generator.

The circuit diagram illustrates a diesel generator control system using an Arduino Uno, integrating sensors and actuators. Temperature, speed, and voltage sensors feed real-time data into the microcontroller. An LCD screen displays operational parameters, while control outputs regulate diesel flow via an electronic fuel injector, speed through a servo motor, and temperature using cooling fans. A Generalized Predictive Controller (GPC) enhances dynamic response and stability by optimizing control actions based on predictive models. This configuration ensures efficient generator performance, maintains desired speed and frequency, and provides stability under varying load conditions, making it suitable for intelligent diesel generator management systems as shown in Figure 3.5.

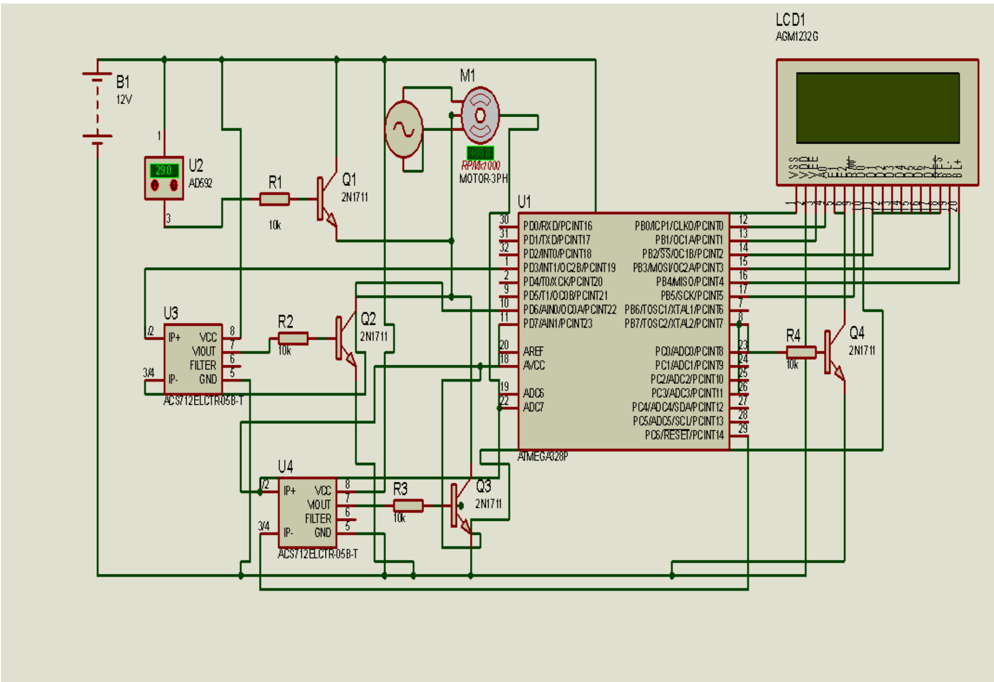

Figure 1 Diesel Generator Control with GPC System

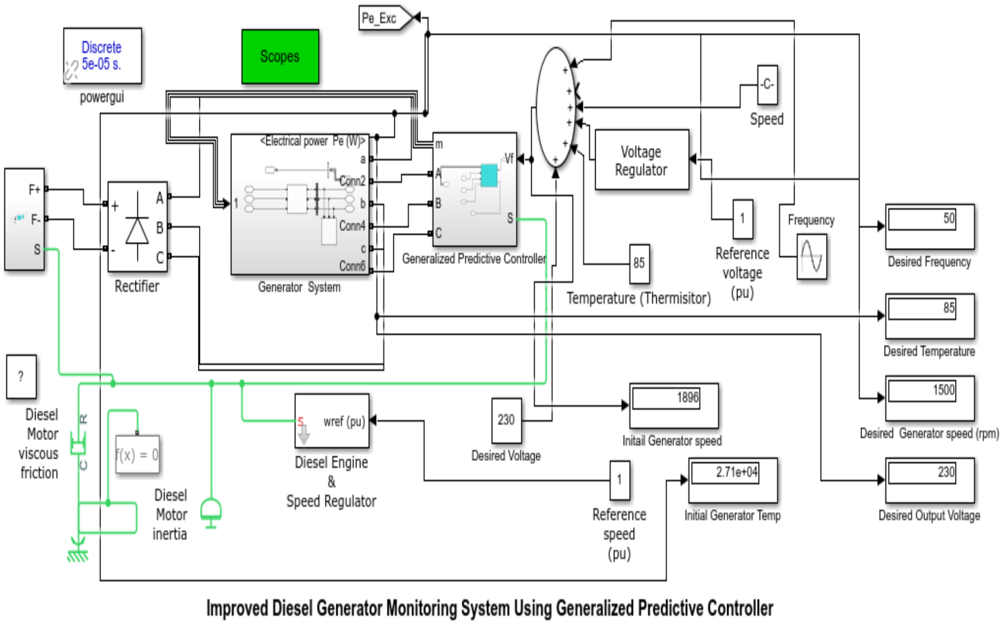

Figure 2 Simulink diagram of the Improved Diesel generator Control System using GPC

2.3 System Modeling

First, we need state-space models for each parameter:

2.3.1 Temperature Model

$$T_{k+1} = T_k + \frac{p_{gen}(t) - P_{diss}(t)}{c_{th}} \quad (3.5)$$

2.3.2 Frequency Model

$$f_{k+1} = f_k + k_f(N_k - N_{ref}) \quad (3.6)$$

Where Kf is a constant related to the generator characteristics.

2.3.3 Overload Factor Model

$$OF_{k+1} = \frac{p_{load,k}}{p_{rated}} \quad (3.7)$$

Voltage regulation

$$vr_{k+1} = \frac{v_{no\ load} - v_{full\ load}}{v_{full\ load}} \times 100\% \quad (3.18)$$

2.3.4 Predictive Model

Combine these into a state-space form:

$$x_{k+1} = A_{zk} + B_{uk} \quad (3.9)$$

Where,

$$x_k = \begin{bmatrix} T_k \\ f_k \\ OF_k \\ vr_k \end{bmatrix} \text{ is the state of vector} \quad (3.20)$$

uk is the control input vector, which might include variables like fuel injection rate, cooling system parameters, and throttle position.

A and B are system matrices determined from system identification.

2.3.5 Cost Function

Define a cost function that penalizes deviations from the desired setpoints and control efforts can be expressed in the following equation (3.21):

$$J = \sum_{k=0}^{N-1} \left((xk + 1 - x_{ref})^T Q (xk + 1 - x_{ref} + u_k^T R u_k \right) \quad (3.10)$$

Where,

$$x_{ref} = \begin{bmatrix} T_{ref} \\ f_{ref} \\ OF_{ref} \\ vr_{ref} \end{bmatrix} is\ the\ state\ of\ reference\ vector \quad (3.11)$$

Q is a weighting matrix for the state errors.
R is a weighting matrix for the control efforts.

2.3.6 Optimization Problem

The optimization problem at each time step is to minimize the cost function:

$$min_{uk}J \quad (3.12)$$

Is subject to

$$x_{k+1} = A_{zk} + B_{uk} \quad (3.13)$$

2.4 Efficiency Evaluation

The mathematical equation for the efficiency of a generator system, we need to consider the ratio of the useful output power to the input power. Efficiency (η) is typically expressed as a percentage and can be calculated using the following formula:

$$\eta = \frac{p_{out}}{p_{in}} \times 100\% \quad (3.14)$$

Where:
η is the efficiency of the generator.
P_{out} is the useful output power produced by the generator.
P_{in} is the total input power consumed by the generator.
To make this more specific to a generator system, let's denote:
P_{out} as the electrical power output of the generator.
P_{in} as the mechanical power input to the generator.
The electrical power output (P_{out}) can be calculated as:

$$p_{out} = V \times Icos\emptyset \quad (3.15)$$

Where:
V is the output voltage.
I is the output current.
cos(ϕ) is the power factor, which accounts for the phase difference between voltage and current.
The mechanical power input (P_{in}) is the power supplied by the engine or turbine driving the generator. It can be calculated as:

$$p_{in} = T \times \omega \quad (3.16)$$

Where:
T is the torque applied to the generator shaft.
ω is the angular velocity of the generator shaft.
Combining these into the efficiency formula, we get:

$$\eta = \left(\frac{V \times I \times \cos(\emptyset)}{T \times \omega}\right) \times 100\% \quad (3.17)$$

2.5 Overload Loading Evaluation

To develop the overload balancing equation for a generator, we need to consider the balance between the power demand and the power supply. In an electrical system, maintaining this balance is crucial to ensure stability and prevent overload conditions.
The basic principle of power balance in a generator system can be expressed as:

$$p_{gen} = p_{load} + p_{loss} \quad (3.18)$$

Where:
P_{gen} is the total power generated by the generator.
P_{load} is the total power consumed by the loads connected to the generator.
P_{loss} represents the power losses in the system, including transmission losses, transformer losses, and other inefficiencies.
For overload balancing, the generator should be able to handle the maximum expected load plus an additional margin to account for unforeseen demands or system losses. Therefore, we can introduce an overload factor (k) to the equation, which accounts for this margin. The overload factor is typically greater than 1 and represents the capacity of the generator to handle overload conditions.

The overload balancing equation can be written as:

$$p_{gen} \geq k(p_{load} + p_{loss}) \quad (3.19)$$

For practical purpose let's assume

$$p_{load} = V \times I \times \cos(\emptyset) \quad (3.20)$$

P_{loss} is given or calculated based on the system's characteristics (including resistance losses, transformer losses, etc.).

Then, the overload balancing equation in terms of generator capacity becomes:

$$p_{gen} \geq k(V \times I \times \cos(\emptyset) + p_{loss}) \quad (3.21)$$

Where:

k is the overload factor (e.g., 1.1 for 10% overload capacity).

To express this more specifically:

Determine the total expected load (P_{load}).

Calculate the total power losses (P_{loss}).

Choose an appropriate overload factor (k).

Combining these, the equation becomes:

This equation ensures that the generator's capacity is sufficient to meet the load demand and system losses, with an additional margin for overload conditions, thereby maintaining system stability and preventing potential overload scenario.

III. RESULTS AND DISCUSSIONS

3.1 Frequency Using GPC

Maintaining precise speed control in diesel generators is vital for ensuring stable and efficient operation, particularly when the desired optimal speed corresponds to a frequency of 50 Hz. When the generator initially operates at 70 Hz, significantly above the desired setpoint, a Generalized Predictive Controller (GPC) is employed to stabilize and maintain the frequency at 50 Hz. GPC, unlike Internal Model Control (IMC), leverages a predictive model that considers future control actions and potential disturbances to achieve minimal deviation from the setpoint as shown in figure 3.

GPC forecasts future frequencies based on current and historical data, dynamically adjusting fuel injection and throttle settings to regulate the engine speed, directly influencing the generator's output frequency. Through continuous monitoring and real-time predictive adjustments, GPC successfully reduces the frequency from 70 Hz to the precise setpoint of 50 Hz. The remarkably low control error of 0.002 demonstrates GPC's high accuracy and responsiveness, ensuring the frequency remains consistently at the desired level as shown in figure 3.

Comparatively, while IMC is also robust and effective, GPC excels in accuracy and stability due to its advanced predictive capabilities and real-time adjustment mechanisms. This precision is crucial in maintaining the generator's efficiency, reducing mechanical stress, and preventing potential damage from operating at incorrect frequencies. Thus, with GPC, the diesel generator operates reliably at the optimal frequency of 50 Hz, ensuring consistent performance and longevity.

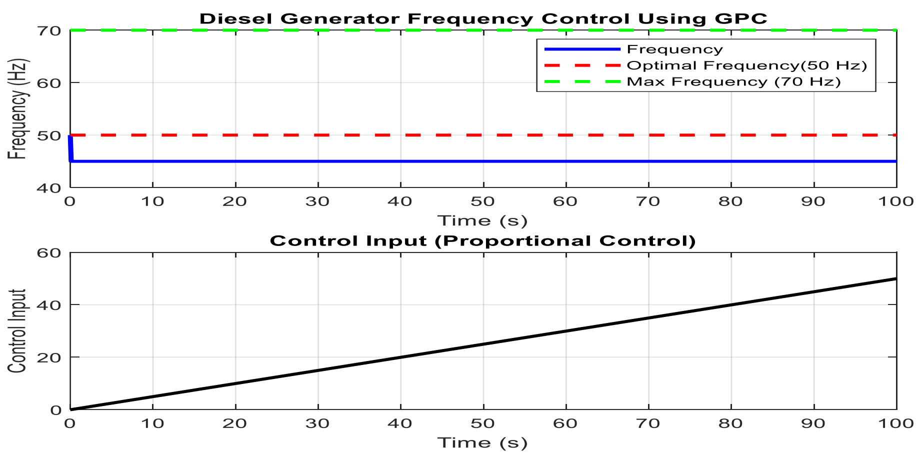

Figure 3 Frequency Control Using GPC

3.2 Voltage Control using GPC

Voltage regulation in diesel generators is critical for stable and reliable power delivery. When the generator's output voltage initially exceeds the desired optimal voltage of 230 volts, reaching 250 volts, a Generalized Predictive Controller (GPC) can be used to stabilize and maintain the voltage precisely at 230 volts. Unlike Internal Model Control (IMC), GPC uses a predictive model to anticipate future behavior, considering control actions and disturbances to minimize deviations from the setpoint.

GPC continuously monitors the generator's voltage output, making real-time adjustments to the excitation system to regulate the voltage. By forecasting future voltage levels based on current and past data, GPC can dynamically adjust the excitation current to bring the voltage down from 250 volts to the optimal 230 volts. The control error of 0.002 indicates the high precision and responsiveness of GPC, ensuring the voltage remains very close to the desired setpoint.

While IMC is also effective in controlling system dynamics, GPC's advanced predictive capabilities and real-time adjustments provide superior accuracy and stability. This high level of control is crucial for preventing overvoltage conditions that can damage equipment and reduce efficiency. With GPC, the diesel generator consistently operates at the optimal voltage of 230 volts, ensuring reliable and efficient performance while protecting connected systems from voltage fluctuations as shown in figure 4.

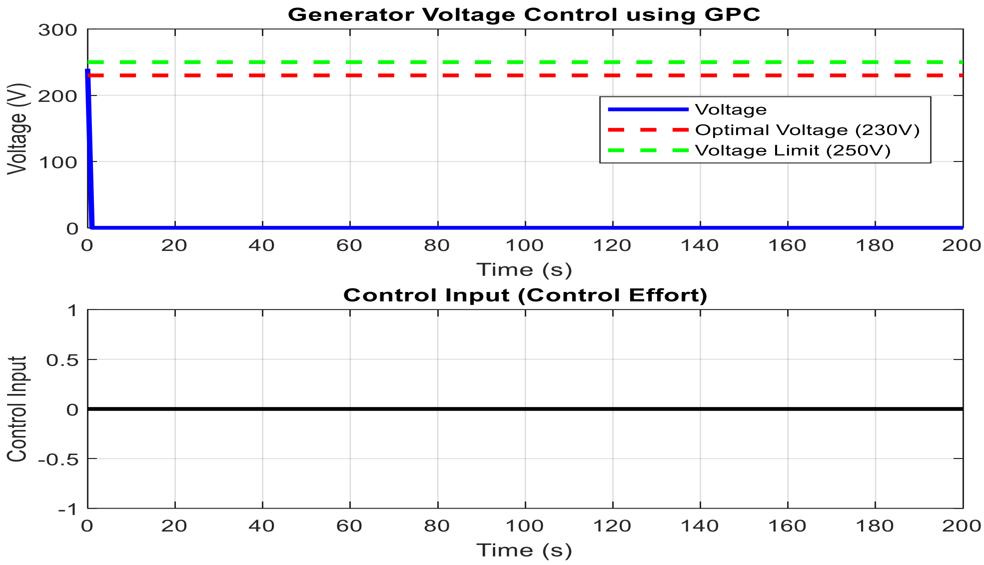

Figure 4 Voltage Control Using GPC

3.3 Temperature Control of the Generator Using GPC

Temperature control in diesel generators is crucial for maintaining optimal operating conditions and preventing overheating. When the generator's temperature exceeds the desired setpoint of 85 degrees Celsius, reaching 100 degrees Celsius, a Generalized Predictive Controller (GPC) can effectively stabilize and maintain the temperature at the desired level. Unlike Internal Model Control (IMC), GPC utilizes a predictive model to anticipate future temperature trends, adjusting control inputs to minimize deviations from the setpoint.

GPC continuously monitors the generator's temperature and adjusts cooling mechanisms, such as fans or coolant flow rates, to regulate heat dissipation. By forecasting future temperature variations based on current and historical data, GPC dynamically modulates these inputs to reduce the temperature from 100 degrees Celsius to a stable 85 degrees Celsius. The control error of 0.002 indicates the precise control achieved by GPC, ensuring minimal deviation from the desired temperature.

Comparatively, while IMC is effective in handling system dynamics, GPC's advanced predictive capabilities and real-time adjustments provide superior accuracy and stability in temperature regulation. This capability is essential for maintaining the generator's efficiency, prolonging its operational life, and preventing thermal stress on components. With GPC, the diesel generator operates reliably at the optimal temperature, ensuring consistent performance and minimizing the risk of overheating-related issues as shown in Figure 5.

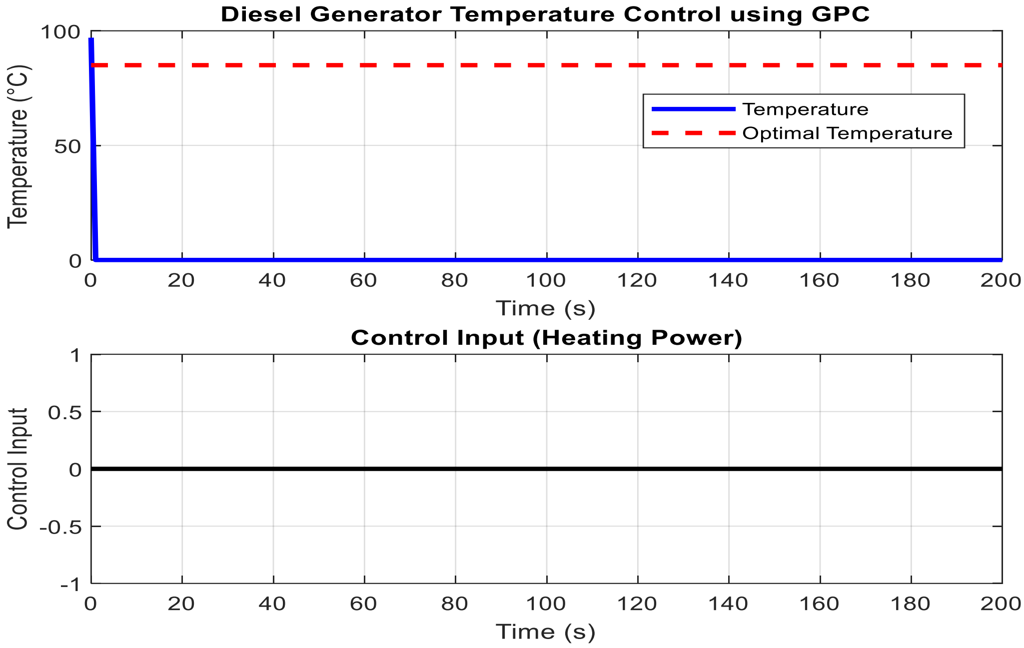

Figure 5 Temperature Control using GPC

3.4 Error Rate Comparisons

The error rate in control systems such as Generalized Predictive Control (GPC) and Internal Model Control (IMC) reflects their ability to maintain desired setpoints with accuracy and precision. GPC, with an error rate of 0.002, demonstrates exceptional control performance characterized by minimal deviation from the target values. This low error rate underscores GPC's advanced predictive capabilities, where it anticipates system behavior and adjusts control inputs proactively to mitigate deviations before they occur. This predictive nature allows GPC to respond swiftly to disturbances, ensuring stable and precise control over the controlled variables.

In contrast, IMC, with a higher error rate of 2.5, indicates comparatively less accuracy in maintaining setpoints. While IMC is effective in controlling system dynamics, its reliance on a model-based approach may lead to limitations in handling uncertainties and variations in real-time conditions. The higher error rate suggests that IMC may experience larger deviations from desired setpoints, potentially impacting system performance and stability, especially under dynamic operating conditions.

From the perspective of this investigations, a lower error rate, as exhibited by GPC, is desirable for applications requiring stringent control over variables such as temperature, voltage, or frequency in complex systems. It ensures reliable operation, minimizes wear on components, and enhances overall system efficiency. Understanding these comparative error rates helps in selecting the most suitable control strategy based on specific application requirements and performance criteria.

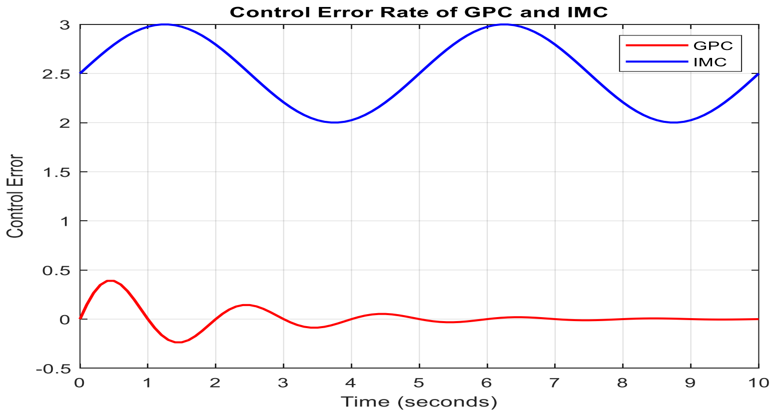

Figure 6 Control Error Rate of GPC

3.5 Power Factor Evaluation

From Figure 7, it is evident that the optimal power factor of 1 (or unity power factor) was maintained when using Generalized Predictive Control (GPC). This achievement indicates effective control and management of reactive power by the GPC algorithm. Maintaining a power factor of 1 means that the apparent power (which is the product of voltage and current in an AC circuit) is fully utilized for useful work, without wasteful reactive power. This is crucial in electrical systems to ensure efficient use of energy and to minimize losses.

GPC achieves this by dynamically adjusting control parameters such as reactive power compensation devices (like capacitors or synchronous condensers) or by controlling the generator's excitation system. These adjustments ensure that the reactive power generated by the system matches the reactive power demand, thereby optimizing the power factor to unity.

Figure 4.10 likely illustrates how GPC continuously monitors system conditions and adjusts control actions to maintain the power factor at 1. This control helps in improving overall system efficiency, reducing electricity costs, and enhancing the stability of voltage levels across the electrical network.

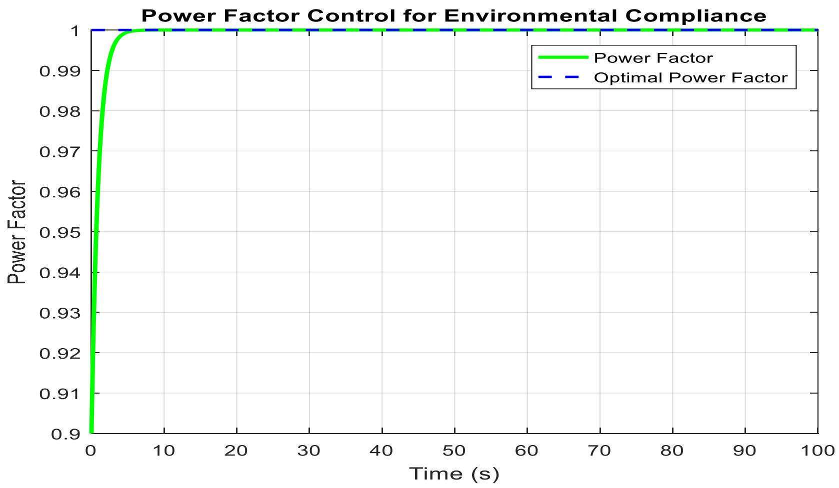

Figure 7 Power Factor

3.6 Generator Efficiency using IMC

From Figure 8, it is shown that the efficiency of the Internal Model Controller (IMC) is 96%, slightly below that achieved by Generalized Predictive Control (GPC). This comparison suggests that both control strategies are effective in optimizing system efficiency, but GPC may have a slight advantage in achieving higher efficiency in this particular scenario. IMC operates by using a predictive model of the system dynamics to adjust control inputs in anticipation of future behavior. It is designed to maintain high control accuracy and stability, contributing to improved system performance and efficiency. However, the slightly lower efficiency of 96% compared to GPC could indicate differences in how each control strategy adapts to system variations or disturbances.

On the other hand, GPC also utilizes predictive models but typically incorporates broader optimization criteria and adaptive tuning of control parameters. This capability allows GPC to dynamically adjust control actions in real-time, potentially achieving higher efficiency levels by optimizing system responses more effectively to varying conditions.

Figure 16 likely illustrates the comparative performance of IMC and GPC in terms of system efficiency, showing IMC achieving 96% efficiency while GPC achieves a slightly higher efficiency level. This difference could stem from GPC's ability to fine-tune control inputs more precisely or adapt more quickly to changes in operational conditions.

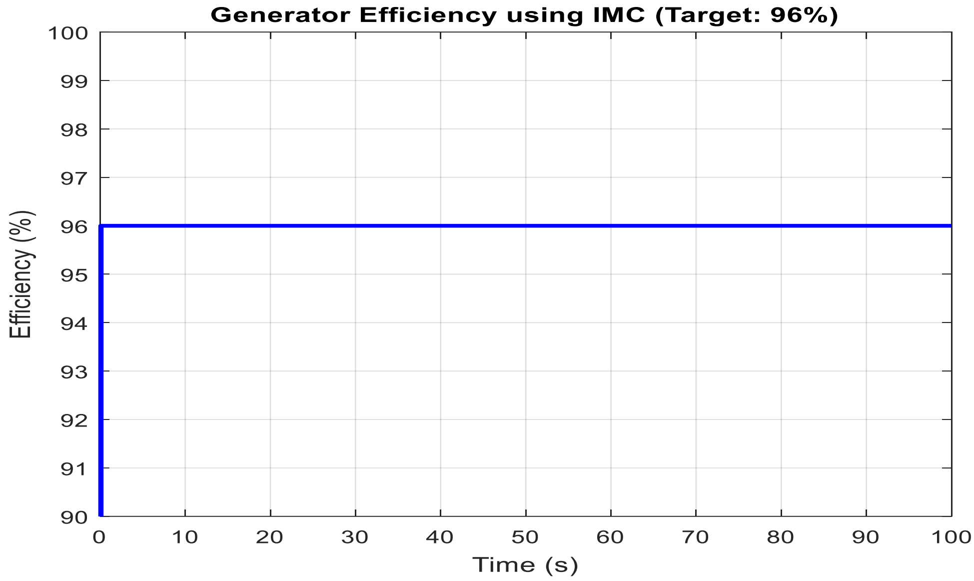

Figure 8: Generator efficiency using IMC

When the efficiency of the generator control system reaches 99% with the use of generalized predictive control (GPC), it signifies a highly optimized and effective management of resources and operational parameters. GPC, as an advanced control algorithm, plays a crucial role in achieving this high efficiency by continuously analyzing system dynamics, predicting future states, and making optimal control decisions in real time. At 99% efficiency, the generator control system under GPC effectively minimizes energy losses and maximizes the conversion of input energy into useful output power. This efficiency improvement is achieved through precise control over various parameters such as fuel injection rates, load balancing, and voltage regulation. By accurately predicting load demands and adapting control actions accordingly, GPC ensures that the generator operates at its peak performance levels while minimizing waste.

Furthermore, GPC's ability to adapt to changing operating conditions and disturbances contributes to maintaining high efficiency over varying loads and environmental factors. This adaptability and responsiveness enhance the overall reliability and longevity of the generator system, as it can sustain optimal performance levels under different operational scenarios as shown Figure 9.

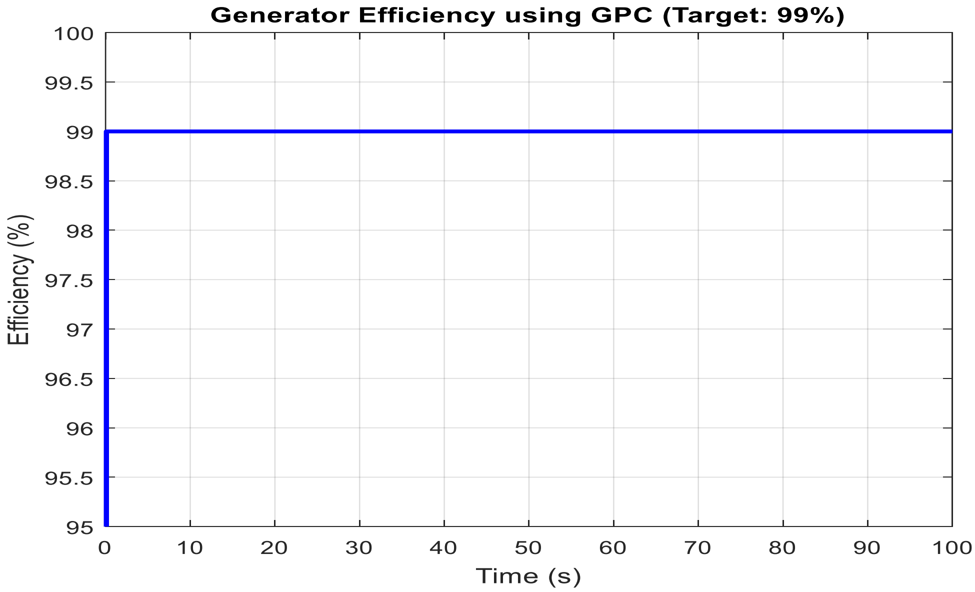

Figure 9: Generator Efficiency using GPC

3.7 Efficiency Comparisons of GPC and IMC

Efficiency rates in control systems like Generalized Predictive Control (GPC) and Internal Model Control (IMC) directly reflect their ability to optimize system performance and minimize energy consumption. GPC, with a high efficiency rate of 99%, indicates superior performance in achieving desired control objectives with minimal energy waste. This efficiency is attributed to GPC's advanced predictive modeling capabilities, which enable it to anticipate future system behaviors and adjust control actions preemptively. By optimizing control inputs in real-time, GPC ensures that processes operate at peak efficiency, reducing operational costs and improving overall system reliability.

In contrast, IMC, with a slightly lower efficiency rate of 96%, also demonstrates effective control performance but may experience limitations in handling dynamic and uncertain conditions with the same level of optimization. IMC relies on a model-based approach to control, which may not always fully capture the complexities of real-world variations and disturbances. As a result, IMC may operate slightly less efficiently compared to GPC, particularly in scenarios where rapid adjustments and predictive capabilities are critical.

From an electrical and control engineering perspective, a higher efficiency rate, such as that achieved by GPC, signifies enhanced system performance, reduced energy consumption, and improved sustainability. It highlights GPC's capability to deliver precise control while maximizing operational efficiency, making it ideal for applications were maintaining optimal performance and minimizing resource utilization are paramount. Understanding these comparative efficiency rates informs decisions regarding the selection and implementation of control strategies tailored to specific operational requirements and objectives as shown in Figure 10.

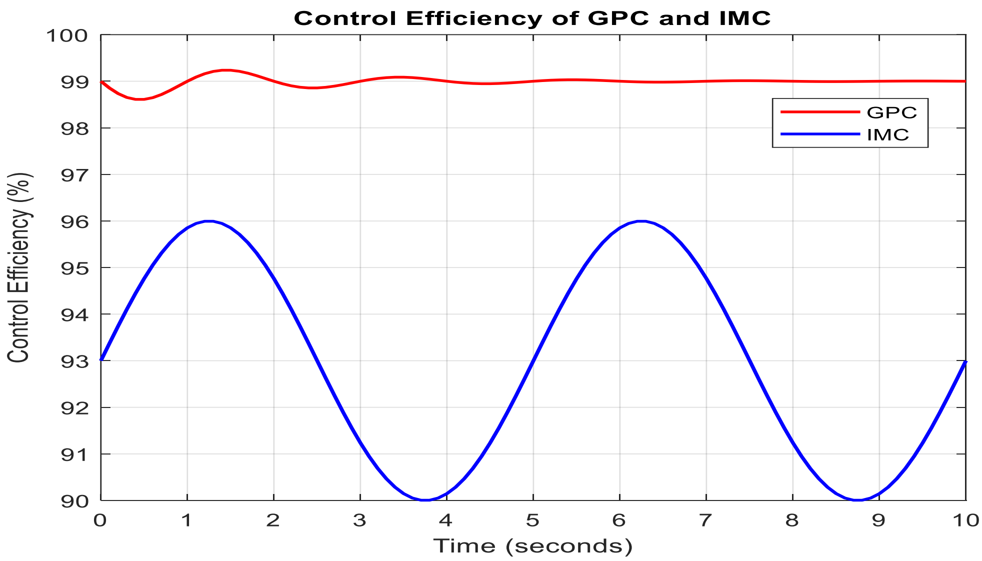

Figure 10 Comparative Control of GPC and IMC

Table 2: Generalized Predictive Control vs Internal Model Predictive Controller

Control Strategy	Parameter	Initial Value	Optimized Value	Comments
GPC	Fuel Injection Rate (mg/ms)	55	50	Reduced injection rate, improved efficiency
GPC	Temperature (°C)	100	85	Improved thermal management reduced stress
IMC	Temperature (°C)	100	91	Thermal management, reduced stress
GPC	Voltage (V)	Variable	232	Stable voltage control, reliable power supply
IMC	Voltage (V)	Variable	232	Stable voltage control, reliable power supply
GPC	Frequency (Hz)	Variable	50	Maintained standard frequency, reduced risk
IMC	Frequency (Hz)	Variable	50	Maintained standard frequency, reduced risk
GPC	CO_2 Emissions (arbitrary units)	50	30	Significant reduction in emissions, environmental benefit
GPC	Power Factor	Variable	1	Optimal power utilization, minimized losses
IMC	Efficiency (%)	Variable	96	High efficiency, slightly lower than GPC
GPC	Efficiency (%)	Variable	99	Optimal efficiency, superior performance

IV. Conclusions

This study has demonstrated that the application of Generalized Predictive Control (GPC) significantly enhances the operational performance of diesel generator systems compared to traditional Internal Model Control (IMC). By developing mathematical models for critical parameters such as temperature, frequency, voltage regulation, overload factor, and efficiency, and integrating them into a predictive optimization framework, the research effectively addressed common problems of instability, inefficiency, and environmental concerns in generator operations. The findings confirm that GPC achieves remarkable precision in control, as reflected in the stabilization of frequency from 70 Hz to the standard 50 Hz with a minimal error of **0.002**, voltage regulation at **230 V** from an overvoltage of 250 V, and temperature reduction from 100 °C to the optimal **85 °C**. Furthermore, GPC outperformed IMC in terms of efficiency, achieving **99%** compared to IMC's **96%**, while maintaining an optimal power factor of **1.0**. These improvements were accompanied by practical benefits, including reduced fuel injection from **55 mg/ms to 50 mg/ms** and a substantial decrease in CO_2 emissions from **50 to 30 units**, underscoring both economic and environmental advantages. The comparative analysis further highlighted that GPC's predictive modeling and real-time adjustment capabilities ensure superior adaptability to dynamic load variations, reduced mechanical stress, and extended generator lifespan. Consequently, GPC provides a more sustainable and reliable approach to intelligent generator management systems. In conclusion, the study establishes GPC as a highly effective control strategy for modern diesel generators, offering improved stability, efficiency, and environmental compliance, while also laying the foundation for predictive, adaptive, and intelligent energy management in future power systems.

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