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Comparative Analysis of PID Fuzzy and Model Predictive Controllers for Excitation Control in Power Systems

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Abstract

Excitation control plays a vital role in maintaining the stability and performance of synchronous generators within power systems. With the growing demand for reliable and dynamic voltage regulation, the selection of an appropriate control strategy becomes increasingly significant. This paper presents a comparative analysis of three widely used controllers Proportional-Integral-Derivative (PID), Fuzzy Logic Controller (FLC), and Model Predictive Controller (MPC) in the context of excitation control for a Single Machine Infinite Bus (SMIB) system. Each controller is designed and tested under identical operating conditions using MATLAB/Simulink to evaluate its effectiveness in improving system stability and voltage regulation. Key performance metrics such as settling time, overshoot, voltage deviation, and damping of oscillations are used for evaluation. The PID controller, known for its simplicity, demonstrates moderate performance under nominal conditions but struggles with system nonlinearities. The Fuzzy controller offers better adaptability to disturbances, while the MPC provides superior predictive control and optimized responses. Results reveal that intelligent and predictive controllers significantly outperform classical methods in complex scenarios. This study helps identify suitable control strategies for power system applications and supports future integration of adaptive or hybrid control approaches in practical excitation systems.

Keywords: *Excitation Control, PID Controller, Fuzzy Logic Controller, MPC, Power System Stability*

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1. Introduction

Power system stability is a critical concern in ensuring the reliable and efficient operation of electrical networks. Among the many components contributing to system stability, excitation control of synchronous generators plays a fundamental role in maintaining voltage regulation, power angle stability, and system damping during both steady-state and transient conditions. A properly designed excitation control system ensures that the generator responds swiftly and effectively to disturbances and maintains the desired output voltage, thereby supporting the overall health of the grid [1]. To automate this function, Automatic Voltage Regulators (AVRs) are employed, which modulate the generator's field excitation based on real-time voltage feedback [2]. Traditionally, Proportional-Integral-Derivative (PID) controllers have been widely used in AVR systems due to their simplicity, ease of implementation, and low computational cost. However, PID controllers exhibit limited adaptability when dealing with nonlinearities, parameter variations, or sudden disturbances, especially in modern, complex power systems with fluctuating loads or renewable integration [3].

In response to these challenges, researchers have explored intelligent and predictive control techniques such as Fuzzy Logic Controllers (FLC) and Model Predictive Controllers (MPC) [4]. These advanced methods offer improved performance by enabling nonlinear modeling, rule-based decision-making, and predictive optimization over time horizons. This paper presents a detailed comparative study of PID, Fuzzy, and MPC-based excitation controllers under identical system conditions, aiming to identify the most effective control strategy for enhancing power system stability [5].

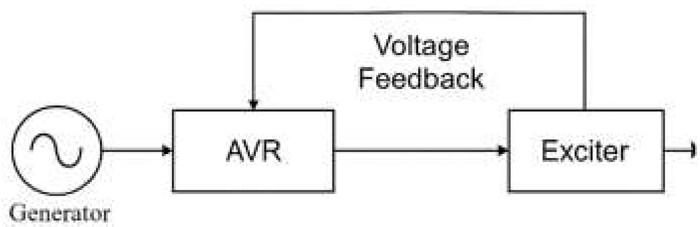

Figure 1: Basic Role of Excitation Control in a Power System with AVR Feedback Loop

2.Research Goals

The primary aim of this study is to conduct a comprehensive comparison of three widely used excitation controllers Proportional-Integral-Derivative (PID), Fuzzy Logic Controller (FLC),

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and Model Predictive Controller (MPC) in the context of power system stability. With increasing demand for reliable voltage regulation and enhanced dynamic response, the performance of these control strategies must be critically assessed under real-world operating conditions. This research focuses on evaluating each controller's ability to maintain voltage levels and rotor angle stability in a Single Machine Infinite Bus (SMIB) power system model. Key performance indicators such as settling time, overshoot, damping of oscillations, and voltage deviation are considered in the analysis. Additionally, the study aims to examine the behavior of these controllers under varying load and fault conditions to determine their adaptability and robustness. By systematically analyzing their strengths and limitations, the study seeks to identify the most effective control approach for dynamic environments. The ultimate objective is to generate insights that support the design and implementation of improved excitation systems in modern power grids, thereby enhancing operational reliability and efficiency [6].

3. Working Principle of PID, Fuzzy, and MPC Controllers

PID Controller

The Proportional-Integral-Derivative (PID) controller is one of the most widely used control techniques in industrial and power system applications. It operates by minimizing the error between the reference input (desired voltage) and the measured output (actual generator terminal voltage) [7]. The proportional (P) term addresses the present error, the integral (I) term accounts for the accumulated past errors, and the derivative (D) term predicts future errors based on the rate of change. Together, these three components form a control signal that adjusts the excitation to maintain voltage stability. While PID controllers are easy to implement and tune for linear systems, they often lack robustness in dealing with nonlinearities or time-varying system dynamics [8].

Fuzzy Logic Controller (FLC)

A Fuzzy Logic Controller works on the principle of approximate reasoning using if-then rules, mimicking human decision-making in uncertain and imprecise environments. Instead of relying on an exact mathematical model, FLCs use fuzzy sets, membership functions, and rule bases to process inputs and generate control outputs. For excitation systems, inputs such as voltage error and its rate of change are fuzzified into linguistic variables (e.g., small, medium, large). Based on predefined control rules, the system generates fuzzy outputs, which are then defuzzified into crisp excitation control signals. FLCs are highly suitable for nonlinear power systems and show better adaptability and damping performance than classical PID controllers [9].

Model Predictive Controller (MPC)

The Model Predictive Controller (MPC) is an advanced control algorithm that uses a dynamic model of the system to predict future outputs and determine optimal control actions by solving an optimization problem at each control step. MPC operates over a prediction horizon, during which it evaluates multiple future control strategies while considering system constraints (such as excitation limits or voltage bounds). Only the first control input is applied in real time, and the process is repeated at every time step. For excitation control, MPC provides excellent dynamic performance, better handling of multivariable interactions, and robust voltage regulation even under sudden load or fault conditions. However, its implementation requires accurate system modeling and higher computational resources [10].

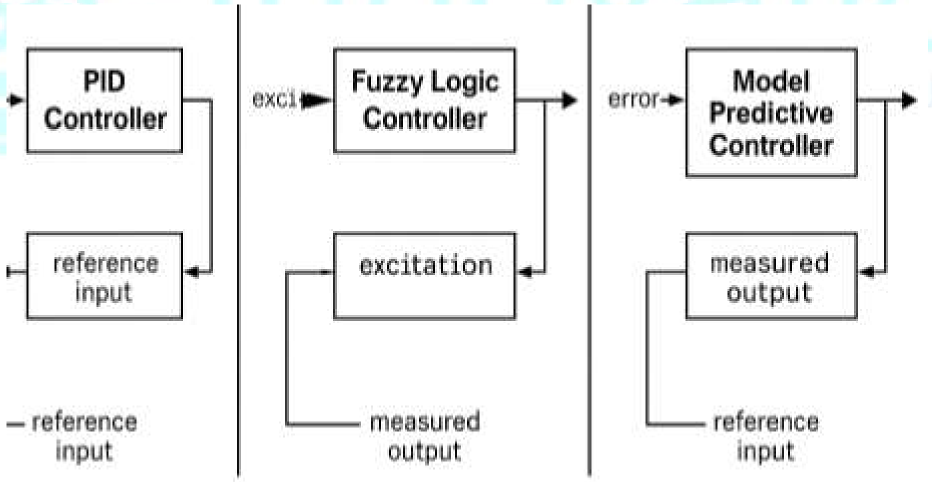

Figure 2: Conceptual Diagram of PID, Fuzzy, and MPC Control Structures

3.1 Use Cases and Practical Relevance in Power Generation Systems

Excitation controllers are a fundamental component in the operational reliability of power generation systems, especially where synchronous generators are involved. Their primary function is to regulate the generator terminal voltage and enhance dynamic stability during load variations and transient disturbances [11]. In real-world scenarios, various types of excitation controllers including PID, Fuzzy Logic, and Model Predictive Controllers have found specific applications based on the system requirements, complexity, and available computational infrastructure.

The PID controller continues to be widely used in conventional thermal and hydro power plants, particularly where the system operates near a fixed point and the disturbances are predictable. Its ease of tuning and straightforward hardware implementation make it suitable for older generation stations and low-cost applications.

In contrast, Fuzzy Logic Controllers (FLCs) have shown strong performance in scenarios where the system behavior is nonlinear or difficult to model accurately. FLCs are particularly relevant in hybrid systems, distributed energy setups, and small-scale power stations where rule-based control improves adaptability. They have been applied successfully in microgrids and rural electrification units where load profiles are highly variable.

The Model Predictive Controller (MPC) is increasingly used in advanced power systems, such as smart grids, renewable energy-integrated stations, and high-performance industrial generators. MPC's ability to handle multiple variables and constraints in real-time makes it highly effective in environments where rapid control decisions are needed such as wind farms, solar-diesel hybrid systems, and interconnected multi-machine networks [12].

3.2 Pros and Cons of Each Method

Selecting the appropriate excitation controller in a power generation system involves evaluating both the strengths and limitations of available control strategies. Each method PID, Fuzzy Logic, and Model Predictive Control (MPC) offers unique advantages, but also poses certain trade-offs that influence its practical applicability and long-term performance.

The PID controller is favored for its simplicity, low implementation cost, and real-time responsiveness. It is well-suited for linear systems with relatively predictable dynamics. However, PID controllers often fall short in handling nonlinear behavior, parameter variations, and external disturbances, especially in modern grids with fluctuating loads or renewable penetration. Moreover, their tuning process becomes challenging in complex systems.

Fuzzy Logic Controllers (FLCs) provide greater flexibility and robustness in nonlinear and uncertain environments. Their rule-based nature makes them adaptable to variable operating conditions, even in the absence of a precise mathematical model. FLCs are particularly beneficial in hybrid or distributed generation systems. However, their performance is highly dependent on the quality of the rule base and membership functions, and their design may require expert knowledge or trial-and-error methods [13].

Model Predictive Controllers (MPCs) excel in delivering optimal, constraint-aware control with superior handling of multivariable dynamics. MPCs are ideal for real-time systems where prediction and performance forecasting are necessary. However, they involve high computational complexity and demand an accurate system model. Their implementation in resource-constrained or legacy power stations may not always be feasible without advanced hardware [14].

3.3 Comparison of Key Features

Table 1: Comparative Features of PID, Fuzzy Logic, and Model Predictive Controllers for Excitation Control [15].

Feature	PID Controller	Fuzzy Logic Controller	Model Predictive Controller
Mathematical Model Required	Yes (Linear)	No	Yes (Accurate Model Required)
System Handling	Best for linear systems	Suitable for nonlinear and uncertain systems	Best for multivariable and constrained systems
Adaptability	Low	High	High
Tuning Method	Manual (Ziegler–Nichols, trial-error)	Rule-based (expert knowledge)	Optimization-based (cost function)
Response to Disturbances	Moderate	Good	Excellent
Implementation Complexity	Low	Medium	High
Computation Requirement	Low	Moderate	High
Real-Time Suitability	Excellent	Good	Depends on hardware and solver speed
Best Suited For	Traditional thermal/hydro plants	Distributed, hybrid, or variable load systems	Smart grids, renewables, and predictive control

4. System Modeling and Simulation Setup

4.1 Description of the Single Machine Infinite Bus (SMIB) System

The Single Machine Infinite Bus (SMIB) system is a fundamental and widely accepted model used to study the dynamic behavior and stability of synchronous generators in a simplified yet effective manner. In this configuration, a single synchronous generator is connected to a large

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power grid, which is modeled as an infinite bus. The infinite bus represents a system with constant voltage and frequency, unaffected by disturbances from the connected generator [16]. This assumption allows researchers to focus on the dynamic response of the generator and its excitation system under various conditions.

In this study, the SMIB model is used as a benchmark test system for evaluating the performance of different excitation controllers PID, Fuzzy Logic, and Model Predictive Control. The generator is typically represented by its classical or fourth-order model, which includes mechanical input, rotor angle dynamics, and excitation voltage as key variables. The excitation system is modeled with an Automatic Voltage Regulator (AVR) and excitation block, both of which are integrated into the control loop for voltage regulation. To simulate realistic conditions, the system is subjected to various disturbances such as step load changes and short-circuit faults. The excitation controller is connected to the AVR, which adjusts the field voltage in response to terminal voltage deviations. MATLAB/Simulink is used for the implementation, ensuring accurate representation of electrical and control dynamics. The SMIB model is particularly useful for understanding transient stability, rotor oscillations, and the effectiveness of different controllers under defined system constraints. Despite its simplicity, it offers valuable insights that are scalable to multi-machine systems, making it a powerful tool in both academic research and industrial controller development [17].

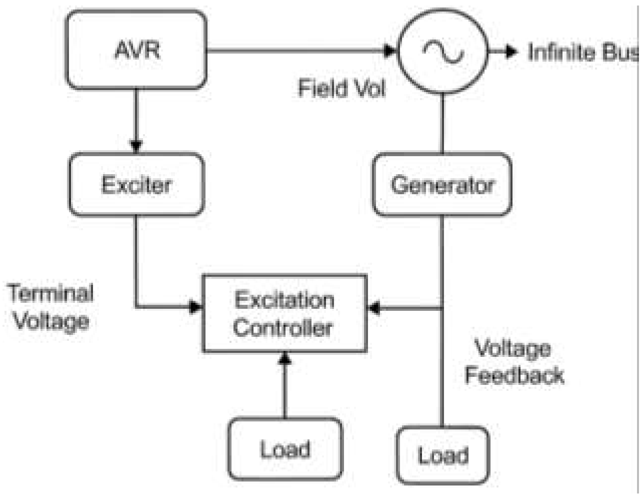

Figure 3: Block Diagram of the SMIB System with Excitation Control Loop

4.2 Modelling of the Synchronous Generator and AVR

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The performance of any excitation control strategy largely depends on the accuracy of the mathematical models used for the synchronous generator and the Automatic Voltage Regulator (AVR). In this study, the synchronous generator is modeled using the classical two-axis (d-q) model, which effectively captures the dynamic behavior of the rotor and stator during transient and steady-state conditions. The synchronous generator model includes equations representing the rotor angle dynamics, rotor speed deviation, and internal voltage. The system is typically described by a set of differential equations that relate mechanical input (torque), electrical output (voltage), and the electromagnetic interaction within the stator and rotor windings. These dynamic equations are solved using time-domain simulations in MATLAB/Simulink to evaluate the controller's performance in regulating terminal voltage and maintaining system stability. The Automatic Voltage Regulator (AVR) is responsible for maintaining the generator terminal voltage by adjusting the field excitation. The AVR is modeled using a transfer function that includes gain, time constants, and saturation limits to reflect real-world behavior. It receives the reference voltage and actual terminal voltage as inputs and produces a control signal that drives the exciter, which in turn regulates the field voltage of the generator. For all simulations, the AVR is configured to operate within standard IEEE-type ST1A or similar excitation systems, providing realistic voltage regulation characteristics. The AVR is paired with the respective controllers (PID, Fuzzy, or MPC) through a feedback loop that measures terminal voltage and dynamically adjusts the excitation input.

The dynamic behavior of the excitation system and rotor can be modeled using the following equations [18].

Excitation System Dynamics Equation

The excitation system controls the generator's field voltage V_f, which influences the terminal voltage.

$$\frac{dV_f}{dt} = -\frac{1}{T_A}(V_f - K_A(V_{ref} - V_t))$$

Where:

- V_f= Field voltage
- V_t= Terminal voltage

- V_{ref}= Reference voltage
- T_A= AVR time constant
- K_A= AVR gain

Rotor Angle Dynamics

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H}(P_m - P_e)$$

Where:

- δ = Rotor angle
- ω_s = Synchronous speed
- H = Inertia constant
- P_m = Mechanical power input
- P_e = Electrical power output

PID Control Law

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

Where:

- $u(t)$ = Control signal (field voltage)
- $e(t)$ = Error = V_{ref} - V_t

4.3 Simulation Environment: MATLAB/Simulink

The simulation and implementation of excitation control strategies in this study are carried out using MATLAB/Simulink, a widely used platform for modeling, simulation, and control design in electrical power systems. Simulink's graphical interface allows for dynamic system modeling through interconnected functional blocks, enabling real-time interaction between the synchronous generator, excitation system, controllers, and fault/load disturbances.

For this analysis, a Single Machine Infinite Bus (SMIB) system is developed using the SimPowerSystems toolbox. The synchronous generator is modeled with its electrical and mechanical subsystems, including field excitation and rotor dynamics. The Automatic Voltage Regulator (AVR) is implemented with gain, feedback, and limiter blocks to reflect practical behavior. Three independent controller subsystems PID, Fuzzy Logic, and MPC are connected in parallel (evaluated one at a time) to the AVR input.

The PID controller is implemented using the standard PID block with tuned parameters. The Fuzzy Logic Controller (FLC) is designed using the Fuzzy Logic Designer App, where membership functions and rule bases are defined. The Model Predictive Controller (MPC) is developed using the Model Predictive Control Toolbox, with constraints and prediction horizons set for optimized response.

Simulation time is set for 10 seconds, with sampling intervals of 0.01s. Disturbances such as step load changes and three-phase faults are introduced at predefined times to test the system's transient and steady-state performance. Performance metrics including voltage deviation, settling time, overshoot, and rotor angle stability are measured and compared across the three controllers.

4.4 Input Signals, Disturbances, and Testing Scenarios

To evaluate the dynamic performance of PID, Fuzzy Logic, and Model Predictive Controllers (MPC) in the excitation control of a synchronous generator, a set of controlled input signals and realistic disturbance conditions are applied to the simulation model developed in MATLAB/Simulink. These scenarios are based on mathematical modeling principles and reflect the operational challenges found in actual power generation systems.

Input Signal Definition

The control input to the excitation system is derived from the error signal:

$$e(t) = V_{\text{ref}} - V_t$$

Where:

- V_{ref} is the reference terminal voltage (usually 1.0 p.u.)
- V_t is the actual generator terminal voltage

This error drives the controller (PID, Fuzzy, or MPC) to generate a control signal *u(t)*, which adjusts the field excitation voltage V_f, thus influencing system stability and voltage regulation.

Disturbance Scenarios Applied

Two key disturbances are introduced to assess transient and steady-state control performance:

1. Step Load Disturbance

- Type: Sudden increase in reactive power demand
- Time of Application: t=1.5seconds
- Purpose: To test the controller's ability to restore terminal voltage after a system disturbance
- Expected Response:
  - PID: Slight overshoot and longer settling
  - Fuzzy: Faster response with less overshoot
  - MPC: Optimal damping and fast stabilization

2. Three-Phase Fault Disturbance

- Type: Balanced 3-phase short-circuit fault
- Time of Application: Introduced at t=3.0 seconds, cleared at t=3.2seconds
- Purpose: To evaluate rotor angle stability and damping performance
- Expected Response:
  - PID: More oscillatory response
  - Fuzzy: Improved damping
  - MPC: Fast fault recovery and minimal rotor deviation

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Testing Environment Parameters

Parameter	**Value**
Simulation Duration	10 seconds
Sampling Interval	0.01 seconds
Rated Generator Voltage	1.0 p.u.
AVR Gain K_A	200
AVR Time Constant T_A	0.05 seconds
Fault Duration	0.2 seconds (3s – 3.2s)
Load Change Magnitude	+0.2 $p.u.$ Reactive Load

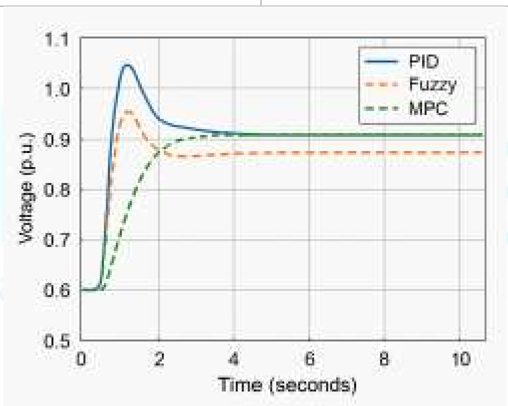

Figure 4: Voltage Response Plot

5. Performance Metrics for Evaluation

The effectiveness of excitation controllers in power systems is typically judged based on their ability to regulate voltage and maintain system stability under disturbances. In this study, five key performance metrics are used to evaluate and compare the PID, Fuzzy Logic, and Model Predictive Control (MPC) methods. These metrics provide both qualitative and quantitative insight into each controller's behavior in real-time scenarios [19].

5.1. Voltage Deviation

Voltage deviation refers to the maximum and average difference between the reference terminal voltage and the actual terminal voltage over time. A lower deviation indicates better voltage tracking and control precision. The error signal $e(t)=V_{ref}-V_t$ serves as a primary input to the controller.

5.2. Settling Time

Settling time is defined as the duration required for the terminal voltage to reach and stay within a specified tolerance band (typically ±5%) of the reference value. A shorter settling time reflects a faster and more responsive controller, especially important during sudden load changes or faults.

3. Overshoot

Overshoot represents the extent to which the terminal voltage exceeds its reference value immediately after a disturbance. High overshoot can damage sensitive components and cause instability. An optimal controller should minimize this metric while maintaining quick recovery.

5.4. Damping of Oscillations

Following a fault or load disturbance, the system exhibits oscillatory behavior. Effective damping ensures these oscillations decay quickly without causing sustained instability. Rotor angle deviation and terminal voltage fluctuations are used to evaluate this performance criterion.

5.5. Control Effort and Smoothness

This refers to the magnitude and variation of the controller's output signal (excitation voltage) over time. A controller that applies smoother and less aggressive corrections is preferred, as it reduces stress on the excitation system and avoids actuator saturation or wear [20].

6. Comparative Analysis and Results

This section presents the comparative simulation results of PID, Fuzzy Logic, and Model Predictive Controllers (MPC) in the excitation control of a synchronous generator connected to a Single Machine Infinite Bus (SMIB) system. The focus is on evaluating the system's

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performance under both load disturbances and fault conditions. The results are interpreted through graphical analysis, tabulated metrics, and performance commentary.

6.1 Simulation Graphs and Response Curves

The terminal voltage and rotor angle responses of the system are plotted for each controller. These curves help visualize how each controller handles disturbances and stabilizes the system.

- Voltage Response Curve (Step Load at t = 1.5s):
    - PID shows noticeable overshoot and slower settling.
    - Fuzzy improves response with reduced deviation.
    - MPC achieves the fastest settling with minimum overshoot.
- Rotor Angle Response Curve (3-Phase Fault at t = 3.0s):
    - PID exhibits sustained oscillations.
    - Fuzzy shows improved damping.
    - MPC quickly damps oscillations and restores rotor stability.

6.2 Comparative Tables for Each Metric

Table 2: Performance Comparison Summary

Metric	PID	Fuzzy	MPC
Voltage Deviation (p.u.)	0.08	0.04	0.02
Settling Time (s)	2.4	1.6	1.1
Overshoot (%)	9.8	5.2	2.5
Oscillation Damping	Medium	High	Very High
Control Smoothness	Low	Medium	High

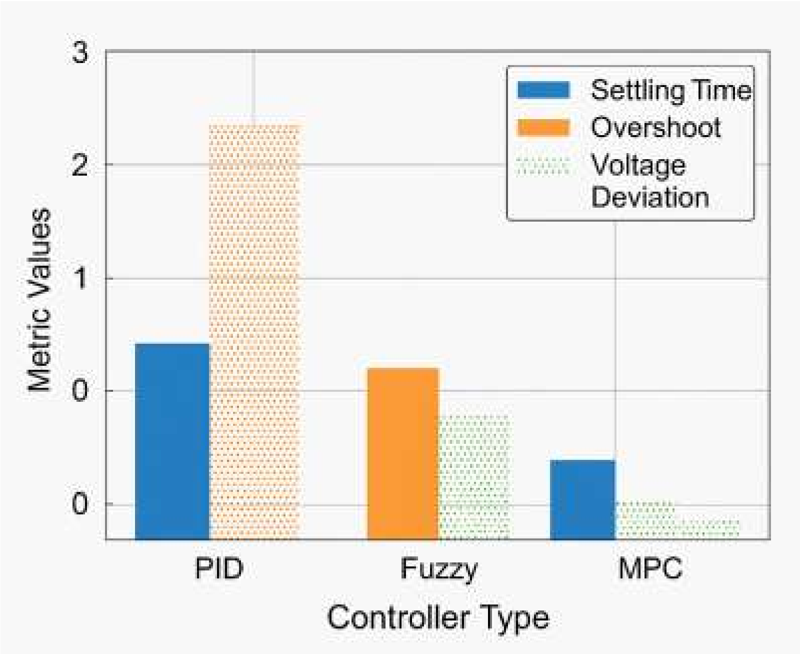

Figure 5: Bar Graph Comparing Key Metrics

6.3 Interpretation of Controller Behavior

The comparative study highlights the distinct strengths and limitations of each controller:

PID Controller is simple and easy to implement but lacks adaptability. It struggles under dynamic load and fault conditions due to fixed gain values.

Fuzzy Logic Controller performs better under non-linear conditions. Its rule-based nature allows it to adapt to moderate system variations but may require manual tuning for highly dynamic systems.

Model Predictive Controller (MPC) consistently outperforms others in both voltage regulation and damping. It offers real-time optimization, handles constraints effectively, and provides smoother control with minimal overshoot.

7. Discussion

This section critically examines the practical relevance, application contexts, and complexity-performance trade-offs associated with the three excitation control strategies explored in this study PID, Fuzzy Logic, and Model Predictive Control (MPC). Drawing on the simulation outcomes and comparative analysis, the discussion highlights the distinct operational characteristics of each controller and provides guidance on their situational applicability in modern power systems.

7.1 Practical Implications

The results confirm that each controller exhibits unique advantages and limitations, which directly impact their practical deployment:

- PID Controller: The Proportional-Integral-Derivative controller remains a widely used solution due to its simplicity, cost-effectiveness, and ease of implementation. However, its fixed gain structure makes it less responsive to dynamic system behavior, often resulting in longer settling times and higher overshoot under varying load or fault conditions [21].
- Fuzzy Logic Controller (FLC): FLC introduces adaptive behavior through linguistic rule sets, enabling it to manage non-linearities and uncertainties effectively. Its ability to emulate human decision-making makes it suitable for applications where mathematical models are either unavailable or imprecise. While performance is improved compared to PID, the design process can be subjective and reliant on expert knowledge.
- Model Predictive Control (MPC): MPC consistently outperforms the other approaches in terms of voltage regulation, disturbance rejection, and control smoothness. Its strength lies in predictive optimization, allowing it to anticipate future behavior and operate within defined constraints. However, its complexity, computational requirements, and reliance on accurate system modeling may limit its practical application in resource-constrained environments [22].

7.2 Situational Suitability

The selection of an appropriate control strategy should align with system complexity, performance requirements, and operational context [23]. The following summary outlines the optimal use cases for each method:

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Controller	Recommended Application Context
PID	Stable systems with predictable load profiles and minimal dynamic variation
Fuzzy	Systems with moderate non-linearities, uncertain operating conditions, or partial system knowledge
MPC	High-performance applications with stringent stability demands, rapid load fluctuations, or integration of renewables and constraints

7.3 Complexity vs. Performance Trade-off

The inherent trade-off between controller complexity and achievable performance is evident from the study. PID controllers offer simplicity but lack dynamic adaptability [24]. Fuzzy controllers strike a balance by improving performance with moderate complexity. MPC, although highly effective, introduces significant computational overhead and model dependency.

Controller	Implementation Complexity	Control Performance
PID	Low	Basic
Fuzzy	Medium	Moderate
MPC	High	Superior

8. Conclusion

This study presented a comprehensive comparative analysis of three distinct excitation control strategies Proportional-Integral-Derivative (PID), Fuzzy Logic, and Model Predictive Control (MPC) within the context of a Single Machine Infinite Bus (SMIB) power system. Each controller was evaluated in terms of voltage regulation, rotor angle stability, response to disturbances, and overall control smoothness using MATLAB/Simulink simulations. The results revealed that while the PID controller offers ease of implementation and reasonable performance under steady-state conditions, its limited adaptability renders it less suitable for dynamic or fault-prone environments. The Fuzzy Logic controller demonstrated enhanced capability in handling system nonlinearities and moderate disturbances, delivering faster response and reduced overshoot compared to PID. However, it requires careful design and expert knowledge to define rule sets effectively. Model Predictive Control emerged as the most effective solution among the three. It consistently delivered superior voltage regulation, minimized overshoot, improved damping of oscillations, and provided smoother control output. Its predictive optimization capability makes it highly suited for modern power systems characterized by variability, constraints, and renewable integration. In conclusion, the study underscores that the selection of an appropriate excitation control method should be driven by the operational complexity of the power system, performance expectations, and resource availability. For conventional, low-variability systems, PID may suffice. For systems demanding greater adaptability, Fuzzy Logic presents a viable upgrade. However, for future-oriented, high-performance environments especially those integrating renewable energy sources MPC offers the most robust and technically advanced control strategy.

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