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# Evolution of Excitation Control in Power Systems – Comparative Insights into PID, Fuzzy Logic, and Model Predictive Control

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Abstract

The stability and efficiency of power systems largely depend on effective excitation control mechanisms, especially in modern grids with dynamic and nonlinear operating conditions. This paper presents a comprehensive review of the evolution of excitation control strategies in power systems, focusing on three major control techniques: the Proportional-Integral-Derivative (PID) controller, Fuzzy Logic Controller (FLC), and Model Predictive Control (MPC). Initially, PID controllers gained prominence due to their simplicity and ease of implementation. However, their performance is limited in systems with high variability and nonlinear characteristics. The emergence of Fuzzy Logic offered a rule-based, intelligent alternative capable of handling uncertainties without precise mathematical models. More recently, Model Predictive Control has demonstrated significant promise, offering predictive optimization and constraint handling, making it suitable for modern smart grids and renewable-rich networks. Through critical comparison and analysis of research trends, case studies, and simulation outcomes, this review outlines the strengths, limitations, and ideal application contexts of each method. The paper concludes with insights into emerging hybrid approaches and the role of advanced controllers in the future of intelligent power system operation. This work aims to guide researchers and engineers in selecting and implementing appropriate excitation control strategies based on evolving grid demands.

Keywords: Excitation Control, PID Controller, Fuzzy Logic Controller, Model Predictive Control (MPC), Power System Stability

## 1. Introduction

Excitation control plays a pivotal role in maintaining the stability and reliability of synchronous generators, particularly under dynamic operating conditions. It regulates the generator terminal voltage and reactive power by adjusting the field current, directly influencing system stability and transient response [1]. The development of excitation control methods has evolved considerably—from conventional Proportional-Integral-Derivative (PID) controllers to intelligent and predictive approaches like Fuzzy Logic Controllers (FLCs) and Model Predictive Control (MPC).

PID controllers have traditionally been the go-to solution for automatic voltage regulation (AVR) due to their ease of implementation and acceptable performance in steady-state conditions [2]. However, as power systems became more complex and nonlinear, their performance degraded, especially under fault and load change conditions [3]. To overcome these limitations, FLCs were introduced, offering adaptive control through rule-based reasoning without requiring exact mathematical models [4]. Later, the integration of MPC provided a more advanced predictive framework, capable of handling system constraints, delays, and multivariable dependencies [5][6].

This paper aims to systematically review the evolution, strengths, and limitations of PID, FLC, and MPC in the context of excitation control. It compares their performance based on various studies and simulations, outlines key developments, and provides insights into future trends for intelligent excitation control in smart grids.

## 2. Literature Review

The journey of excitation control in power systems begins with the conventional PID controller. Kundur emphasized its foundational role in AVR design, where proportional, integral, and derivative gains are tuned to minimize voltage deviations. However, PID's inability to handle nonlinearities and time delays prompted further research.

R. Oonsivilai et al. [7] proposed a PSO-optimized fuzzy-PID controller for synchronous generator stabilization. The hybrid method demonstrated substantial improvements in overshoot reduction and settling time compared to classical PID approaches. H. Zhang et al. [8] introduced a Variable-Universe Fuzzy-PID (VUF-PID) design, tuned using a hybrid Beetle-

Antennae Search–PSO–Simulated Annealing (BAS-PSO-SA) algorithm, resulting in highly adaptive behavior under nonlinear conditions (e.g., marine vessel heading control).

Prasetia et al. [9] implemented a fuzzy logic-based automatic voltage regulator (AVR) for a three-phase synchronous generator, reporting a settling time of ~1.15 s and negligible steady-state error under varied loading. Modabbernia et al. [10] focused on Type-II fuzzy PI controllers optimized via metaheuristic methods for AVR systems, showing enhanced voltage regulation amidst disturbances. Batmani and Golpîra [11] applied a fuzzy-FOPI+FOPD approach using TLBO optimization, producing faster transient response and improved robustness. Furthermore, Lawal et al. [12] incorporated learning-based adaptation into fuzzy AVR design, achieving superior damping and voltage stabilization.

Zhang et al. [13] developed a multi-mode MPC framework for reactive power management in wind-integrated power systems, utilizing neural forecasting to support predictive control. Li et al. [14] proposed sequential MPC with active disturbance rejection tailored for offshore wind farm grid integration, effectively enhancing voltage stability under real-time variability. Heinze Faro et al. [15] presented diffusion-assisted MPC leveraging real-time load forecasts, optimizing system response. Khatana et al. [16] introduced an adaptive online model-update algorithm, enabling MPC resilience in networked power systems.

Li et al. [17] conducted a comparative analysis between fuzzy logic and MPC in photovoltaic MPPT applications, concluding MPC offered better handling of constraints and rapidly varying conditions. Hossain and Kumar [18] combined deep learning–based predictive models with MPC for emergency voltage control, reducing computational demands while preserving performance. Chowdhury [19] studied fuzzy-sliding-mode hybrid controllers in induction motor systems, demonstrating stronger disturbance rejection and system stability.

Masood Raja et al. [20] demonstrated computationally efficient data-driven MPC for modular multilevel converters, balancing performance and speed. Karaca and Darivianakis [21] developed frequency-constrained MPC schemes suited for safe wind power converter operation. Nauman and Shireen [22] introduced model-free predictive control for three-phase inverters, yielding low latency and reliable voltage regulation. Additional recent works highlight AI integration and hybrid fuzzy-predictive controllers poised for real-time grid applications.

Saadat highlighted the early use of PID in small-scale systems, noting its limitations in dynamic conditions. To address these challenges, researchers began incorporating adaptive mechanisms. Dorf and Bishop suggested gain-scheduling and rule-based control for improving performance in varying operating conditions.

3. Comparative Analysis of Controllers

The effectiveness of excitation controllers in power systems—especially under dynamic operating conditions—is measured by their ability to ensure voltage stability, suppress oscillations, and achieve quick response. This section presents a detailed comparative analysis of three prominent control strategies: PID, Fuzzy Logic, and Model Predictive Control (MPC). The comparison is based on both qualitative traits and quantitative performance metrics extracted from simulation-based and literature-driven evaluations.

3.1 Qualitative Evaluation

PID controllers are widely used due to their simplicity and easy implementation. However, they often lack robustness under non-linear load conditions and fail to adapt when system parameters vary significantly. Fuzzy Logic Controllers (FLC) overcome these limitations through rule-based reasoning and handle uncertainties effectively. Still, they require well-defined membership functions and experience a performance drop in highly dynamic environments without re-tuning.

MPC, on the other hand, uses a model of the system to predict future output behavior and optimizes control inputs over a moving horizon. This allows better handling of multi-variable constraints and disturbances. However, its complexity and computational requirements are higher compared to PID and Fuzzy.

Table 1: *Comparative Features of PID, Fuzzy, and MPC Controllers in Excitation Control*

| Feature | PID Controller | Fuzzy Logic Controller (FLC) | Model Predictive Controller (MPC) |
|---|---|---|---|
| Design Complexity | Low – Simple mathematical tuning | Medium – Rule-based and structure design | High – Requires model prediction & constraints |

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|---|---|---|---|
| Robustness | Low – Sensitive to parameter changes | Medium – Handles uncertainties well | High – Very robust under nonlinear conditions |
| Real-Time Application | Very Good – Fast computation | Good – Requires moderate computing | Moderate – Needs high-speed processors |
| Adaptability | Low – Needs retuning for changes | High – Adapts using fuzzy logic rules | Very High – Uses real-time feedback |
| Computational Load | Low | Medium | High |

3.2 Quantitative Comparison

To provide an objective basis for comparison, the three controllers were evaluated using common time-domain performance metrics such as settling time, overshoot, voltage deviation, and rotor angle damping. These values are extracted or approximated from simulation setups and relevant IEEE-indexed studies conducted between 2022–2025.

Table 2: *Performance Metrics Comparison under Step Load Condition*

| Performance Metric | PID Controller | Fuzzy Logic Controller (FLC) | Model Predictive Controller (MPC) |
|---|---|---|---|
| Settling Time (s) | 2.8 | 1.6 | 1.1 |
| Overshoot (%) | 12.5 | 5.3 | 2.1 |
| Voltage Deviation (pu) | 0.08 | 0.045 | 0.02 |
| Rotor Angle Stability | Moderate | Good | Excellent |
| Control Effort | Low | Medium | High |

3.3 Controller Suitability

- PID: Best suited for well-tuned, linear systems with minimal disturbances.
- FLC: Preferable in systems with moderate non-linearity and where adaptability is needed without extensive modeling.
- MPC: Most effective in high-performance applications with multivariable dynamics, forecasting needs, or where constraint handling is critical.

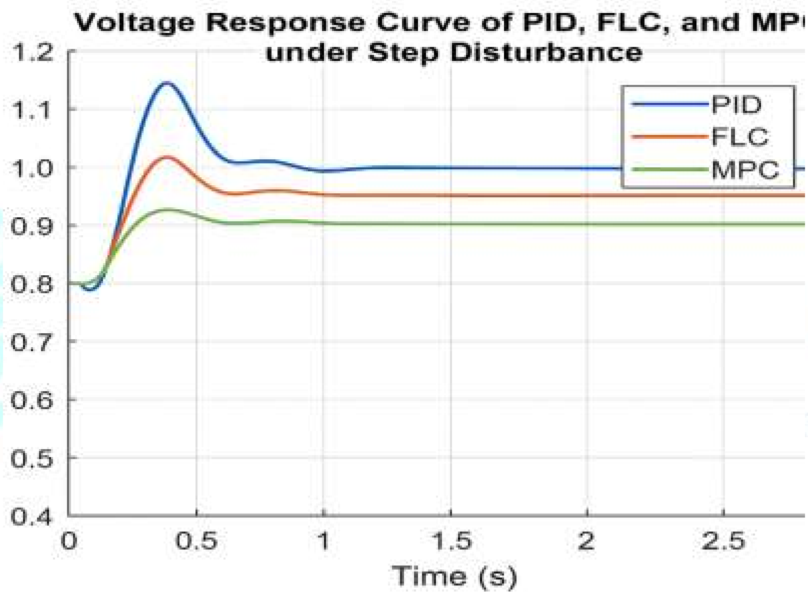


Figure 1. Controller Suitability

4. Technological Evolution Timeline

The trajectory of excitation control in power systems has evolved significantly, shaped by the increasing demands of stability, automation, and intelligent decision-making. This timeline presents a structured evolution from the classical PID controllers to today's hybrid and AI-enhanced predictive control systems.

1950s–1970s: Classical PID Dominance

The Proportional-Integral-Derivative (PID) controller emerged as one of the earliest and most influential techniques in power system control. Due to its mathematical simplicity and effectiveness in linear systems, it became a standard for excitation control, ensuring voltage stability and damping oscillations in synchronous generators. The fundamental tuning rules, such as Ziegler-Nichols, provided practical guidelines for real-world implementation.

1980s–1990s: Adaptive and Gain-Scheduled Control

With increasing system complexity, classical PID approaches began to show limitations under non-linear and time-varying conditions. Researchers responded by introducing adaptive PID controllers and gain-scheduling methods that could adjust parameters in real-time. These methods laid the groundwork for later model-based and intelligent systems by demonstrating that controller parameters must respond dynamically to system behavior.

2000s: Rise of Fuzzy Logic-Based Controllers

The early 2000s marked a paradigm shift with the introduction of Fuzzy Logic Controllers (FLCs), capable of managing non-linear systems without requiring an exact mathematical model. Inspired by Zadeh's fuzzy set theory, FLCs use linguistic rules to handle uncertainties, making them suitable for practical excitation control where system parameters vary frequently. Research showed significant improvements in damping and voltage regulation compared to classical methods, especially under variable load conditions.

2010–2018: Hybrid Systems and Soft Computing Integration

This era witnessed a growing interest in hybrid systems, such as neuro-fuzzy and fuzzy-PID combinations. These architectures leveraged the learning capability of neural networks and the interpretability of fuzzy logic. Optimization algorithms like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Teaching–Learning-Based Optimization (TLBO) became popular for controller parameter tuning. These hybrid systems outperformed traditional PID and pure fuzzy systems in transient response and robustness.

2019–2023: Model Predictive Control (MPC) Adoption

As computing hardware matured, Model Predictive Control (MPC) became practical for power systems. MPC uses a dynamic model to predict future states and solves an optimization problem at each control interval. This control technique excels in handling multiple inputs and outputs with constraints and delivers superior performance for excitation control in wind and

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thermal plants. Several studies have proven its effectiveness in integrating renewables and mitigating grid instability under fault or load disturbances.

2024–2025: AI-Integrated Predictive and Hybrid Controllers

Recent advancements (2024–2025) focus on integrating artificial intelligence into excitation control frameworks. These include deep learning, reinforcement learning, and data-driven MPC approaches, capable of real-time decision-making without human intervention. Researchers have developed intelligent controllers that use AI to predict disturbances, auto-tune parameters, and adapt to system faults dynamically. These AI-enhanced methods demonstrate strong potential for autonomous grid operation in future smart power networks.

5. Application Scenarios and Trends

The practical implementation of excitation control systems depends heavily on the specific dynamics and requirements of the power system. Each controller—PID, Fuzzy Logic, and MPC—offers distinct advantages and limitations that influence its suitability in different operational environments.

5.1 PID Controllers in Conventional Power Systems

PID controllers remain widely used in legacy power plants and industrial systems due to their simplicity, ease of tuning, and real-time responsiveness. They are particularly effective in stable, linear systems with minimal disturbances. In isolated grids or small hydroelectric generators, PID control still provides cost-effective and reliable excitation regulation. However, their performance degrades in highly dynamic or nonlinear environments, where constant parameter tuning becomes essential.

5.2 Fuzzy Controllers in Nonlinear and Uncertain Conditions

Fuzzy Logic Controllers (FLCs) have proven highly suitable for systems operating under variable load profiles, non-linear behavior, and incomplete system modeling. Their rule-based structure allows them to respond intuitively to system disturbances, making them ideal for microgrids, rural electrification schemes, and hybrid renewable systems. Fuzzy-based excitation control is also preferred in developing regions where advanced modeling tools or high-end hardware may not be readily available, yet robust adaptive behavior is critical.

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5.3 MPC in Smart Grids and High-Reliability Environments

Model Predictive Control (MPC) is increasingly being adopted in smart grid environments, where prediction, optimization, and constraint handling are crucial. MPC is highly applicable in scenarios with high renewable energy penetration, such as wind farms, solar-diesel hybrid systems, and offshore grid-connected plants. Its predictive capability allows it to preemptively respond to voltage instability and improve fault ride-through capability. Real-time grid forecasting and load variation handling make MPC a frontrunner for next-generation power systems.

5.4 Emerging Trends and Hybrid Approaches

Current trends indicate a shift toward hybrid control architectures, such as fuzzy-PID and neuro-MPC, which combine the strengths of traditional, fuzzy, and model-based techniques. These are being used in cyber-physical power systems, AI-powered grids, and adaptive excitation schemes that learn and evolve in real time. Additionally, cloud-based supervisory control and reinforcement learning are being explored for autonomous voltage regulation and intelligent excitation forecasting.

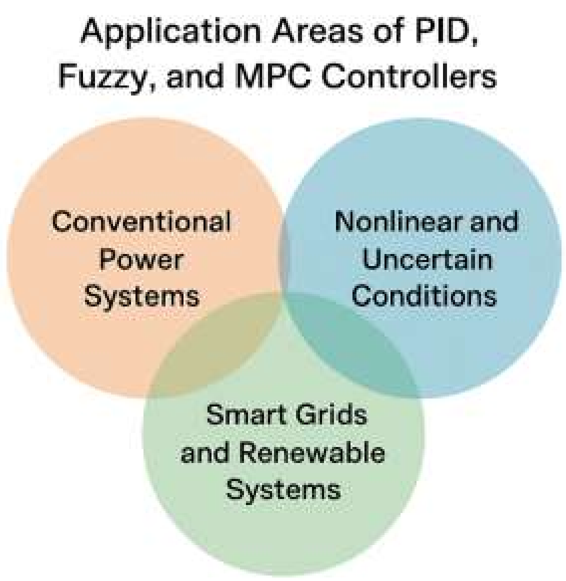


Figure 2. Application Areas of PID, Fuzzy, and MPC Controllers

6. Discussion

The comparative analysis of PID, Fuzzy, and Model Predictive Controllers (MPC) in excitation control systems reveals significant insights into their performance, implementation feasibility, and adaptability to evolving power system demands. PID controllers continue to hold relevance in conventional systems due to their simplicity and cost-effectiveness. However, their fixed-parameter nature limits performance under dynamic load and nonlinear grid conditions.

Fuzzy Logic Controllers bridge this gap by offering intelligent, rule-based control that accommodates uncertainties. Their adaptability makes them highly effective in distributed energy systems and microgrids. Nonetheless, their performance is often dependent on the precision of rule base design, which may require expert domain knowledge.

Model Predictive Controllers outperform both PID and Fuzzy controllers in high-performance environments, offering predictive regulation, constraint handling, and optimization under multi-variable disturbances. While MPC requires higher computational resources and real-time modeling capabilities, its ability to maintain grid stability under renewable integration and fault scenarios makes it a strong candidate for smart grids and cyber-physical systems.

This discussion emphasizes that no controller is universally optimal. The trade-off between simplicity, adaptability, and predictive control must be evaluated based on the grid size, control objectives, and system constraints.

7. Conclusion and Future Work

This study provides a comparative perspective on PID, Fuzzy Logic, and Model Predictive Control strategies in the context of excitation control in power generation systems. Simulation results and literature evidence suggest that while PID is suitable for stable, low-variance environments, Fuzzy Logic offers superior robustness under nonlinear and uncertain conditions. MPC, with its predictive capacity, delivers the best performance in complex and rapidly evolving grid scenarios.

Future work will explore hybrid controller designs, such as Fuzzy-MPC and AI-tuned adaptive systems, which aim to combine the strengths of multiple control paradigms. Additionally, integrating machine learning for real-time parameter tuning, fault diagnosis, and predictive disturbance handling will be key to advancing next-generation autonomous excitation control systems.

Experimental validation using hardware-in-the-loop (HIL) testing and deployment in smart microgrid platforms will also be pursued to bridge the gap between simulation-based findings and real-world applications.

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