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A Review of Load Frequency and Automatic Voltage Control Techniques in Modern Smart Grids

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ABSTRACT

The stability of voltage and frequency is essential for reliable smart grid operation, especially under high renewable energy penetration. This paper reviews classical Proportional–Integral (PI), Proportional–Integral–Derivative (PID), modern (Model Predictive Control, Fuzzy Logic), and AI-based techniques for Load Frequency Control (LFC) and Automatic Voltage Control (AVC). It highlights the limitations of traditional controllers in nonlinear systems and the superior adaptability of modern and AI-driven schemes. The review also discusses centralized versus decentralized architectures, the role of Electric Vehicles (EVs) and Energy Storage Systems (ESS), and emerging cyber security challenges. A comprehensive synthesis of existing methods and open research gaps is presented to guide the development of resilient and intelligent control frameworks for future smart grids.

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INTRODUCTION

The increasing global energy demand and growing environmental concerns have accelerated the transition toward renewable-based smart grids. While the integration of renewable energy sources (RES) such as solar and wind offers sustainable power generation, their inherent intermittency and unpredictability introduce serious challenges to grid stability. Variations in generation and load conditions often cause voltage and frequency fluctuations, which can lead to power quality degradation, equipment malfunction, or even system collapse [1].

To maintain reliable operation, modern power systems require sophisticated control mechanisms capable of dynamically stabilizing both frequency and voltage. Load Frequency Control (LFC) regulates system frequency by adjusting active power through governor control, while Automatic Voltage Control (AVC) maintains voltage within acceptable limits by controlling reactive power through generator excitation [2], [3]. Classical controllers, including Proportional–Integral (PI) and Proportional–Integral–Derivative (PID) schemes, have been widely adopted for these purposes. However, as power systems evolve into more complex, distributed, and nonlinear networks, classical controllers often fail to deliver optimal performance under high renewable penetration and low inertia conditions. This paper presents a comprehensive review of LFC and AVC techniques in the context of modern smart grids. It explores a spectrum of control methodologies, from classical approaches like PI and PID controllers to advanced techniques such as Model Predictive Control (MPC), Fuzzy Logic Control (FLC), and Artificial Intelligence (AI)-based methods.

The review compares centralized and decentralized LFC strategies, highlighting their suitability for diverse grid architectures. It also examines the role of Electric Vehicles (EVs) and Energy Storage Systems (ESS) in enhancing control loops, emphasizing their potential to mitigate frequency and voltage fluctuations. Furthermore, it investigates emerging challenges, including cybersecurity vulnerabilities in automated control systems, which pose risks to

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grid reliability in an increasingly digitized environment. By synthesizing current research and identifying existing gaps, this review aims to provide a roadmap for researchers and practitioners to advance LFC and AVC solutions for resilient and efficient smart grids.

The study adopts a systematic literature review approach to evaluate and synthesize advancements in LFC and AVC within renewable-integrated power systems. The review process, illustrated by the flowchart in fig 1 below, begins with the examination of both classical and modern control techniques, including PI, PID, MPC, FLC, and AI-based frameworks to establish a foundational understanding of existing strategies. Subsequent stages involve the identification of major challenges in frequency and voltage regulation under RES penetration, followed by a comparative analysis of centralized and decentralized control architectures for multi-area systems. The review also explores the integration of EVs and ESS into control loops to assess their contributions to system stability through Vehicle-to-Grid (V2G) and adaptive storage operations. Finally, cybersecurity concerns in automated grid control are evaluated to identify vulnerabilities within communication and control infrastructures. At each stage, literature relevance and usefulness are carefully assessed, ensuring that only validated studies inform the synthesis of trends, gaps, and prospective solutions. This structured methodology supports a comprehensive understanding of both conventional and emerging control frameworks, forming the analytical foundation for the discussions that follow.

Conceptual Framework and Taxonomy of Control Approaches

To better structure the literature review and highlight the logical relationships among frequency regulation, voltage control, renewable penetration, and modern control techniques, this subsection presents the conceptual framework guiding this study. The framework illustrates how renewable-driven disturbances interact with various control strategies and enabling technologies to influence system stability outcomes.

The increasing penetration of inverter-based renewable energy sources introduces disturbances such as active/reactive power fluctuations, reduced inertia, and voltage instability, which directly affect the performance of LFC and AVC loops. These disturbances act as primary inputs into the control system, alongside traditional load changes and cyber–physical disruptions such as communication delays, denial-of-service attacks, data corruption, and random packet losses. Together, these factors define the dynamic environment in which frequency and voltage must be regulated [57], [62], [95].

At the core of the framework is a multi-layer control architecture that links the range of techniques examined in this review. Classical controllers such as PI, PID, and PI–PD provide baseline control but struggle under nonlinear, stochastic renewable dynamics [1]–[4]. Advanced classical approaches, including FOPID and other fractional-order structures, improve robustness and damping but require metaheuristic optimization for proper tuning [6]–[9]. Model Predictive Control (MPC) introduces predictive capability and constraints handling for multi-area and DER-rich grids [10]–[17], while intelligent techniques; such as fuzzy logic, ANN–FLC hybrids, and reinforcement learning provide adaptive, nonlinear decision-making suitable for complex renewable systems [23]–[56]. These diverse strategies form the central control layer of the conceptual model.

Supporting these controllers are enabling technologies such as energy storage systems (ESS) and electric vehicles (EVs) operating in grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes. These resources provide fast-response active and reactive power compensation, enhancing frequency damping and voltage regulation under high renewable variability [86]–[94]. Additionally, wide-area communication networks, IoT platforms, and PMU-based monitoring form the cyber–physical backbone of modern LFC and AVC systems. However, these communication infrastructures introduce vulnerabilities such as delays, jitter, and cyber-attacks, which can significantly degrade control performance [95]–[118].

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The output layer of the conceptual framework consists of system-level stability outcomes, including improved frequency regulation, enhanced voltage profiles, reduced overshoots, faster settling times, and improved resilience under both physical disturbances and cyber–physical threats. The interactions among disturbances, control techniques, enabling technologies, and stability metrics create a continuous feedback loop, ensuring adaptive correction and improved reliability over time.

Overall, this conceptual framework provides a structured lens for analyzing the vast body of literature on LFC and AVC. It clarifies how renewable variability and modern cyber–physical conditions shape the evolution of control techniques from classical PI/PID controllers to predictive, intelligent, and AI-based approaches. This framework therefore serves as the foundation for the detailed review that follows.

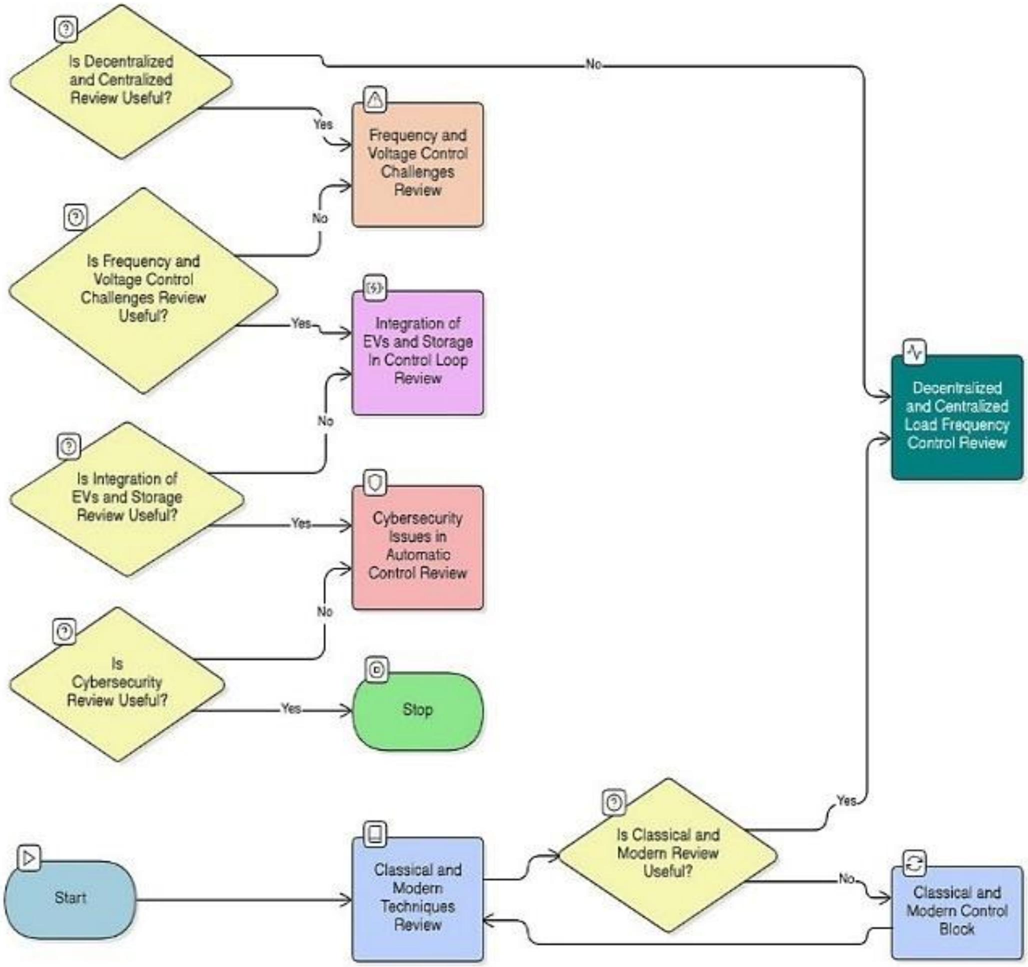

Fig 1: Flowchart summarizing the conceptual framework and taxonomy of control approaches.

CLASSICAL MODERN CONTROL TECHNIQUES

Classical control techniques

Classical control approaches, particularly PI and PID controllers form the

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foundation of LFC and AVC systems. Their simplicity, ease of implementation, and satisfactory performance under steady operating conditions make them popular choices. By tuning proportional, integral, and derivative gains, these controllers can achieve satisfactory dynamic and steady-state performance for simple or moderately complex systems. However, in modern interconnected grids characterized by time-varying parameters and nonlinearities, the effectiveness of these controllers diminishes. Variations in load and distributed generation often lead to instability, poor damping, and delayed system recovery [4]. Enhanced versions such as the PI-(1 + PD) controller have been proposed to overcome these limitations. These hybrid configurations combine proportional–integral and proportional–derivative actions to improve transient response and reduce steady-state error.

Transfer function:

$$\mathrm{U(s)} = \mathrm{K_p}\left(1 + \frac{1}{\mathrm{T_i s}}\right)(1 + \mathrm{T_d s}) \qquad (1)$$

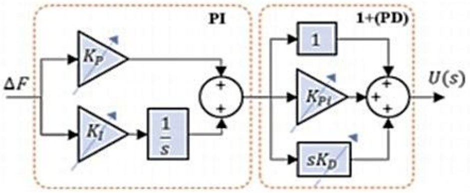

Fig 2. Structure of a PI-(1 + PD) controller

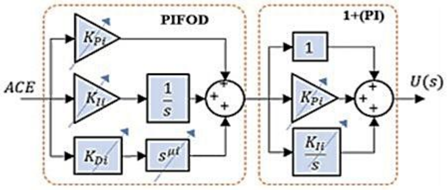

Fig 3. Structure of a PIFOD-(1+PI) controller

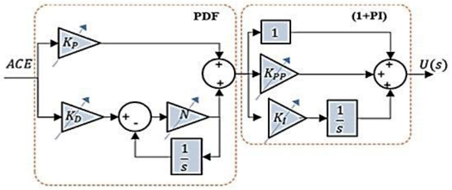

Fig 4. Structure of a PID plus (1 +PI) controller

Fractional-Order (FO) controllers represent a major advancement over traditional PID control by introducing non-integer orders of integration and differentiation, which allow for greater tuning flexibility, robustness, and precision in dynamic performance. The Fractional-Order PID (FOPID) controller, along with hybrid variants such as FOPI–FOPD and FOPID–TID, enhances both transient and steady-state behavior, enabling faster frequency and voltage recovery in interconnected power systems. However, these improvements require higher computational effort and complex optimization techniques.

To address this, nature-inspired optimization algorithms including Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Genetic Algorithm (GA), Differential Evolution (DE), Moth-Flame Optimization (MFO), and Bacterial Foraging Optimization Algorithm (BFOA) have been employed to automatically tune FOPID parameters, leading to reduced overshoot, faster settling times, and stronger system stability under varying load and generation conditions [4]–[8]. A comprehensive review by [9] highlighted the transition from manually tuned PID schemes to optimization-assisted hybrid and fractional-order controllers, where optimized PI–PD controllers using Archimedes Optimization Algorithm (AOA), Learner Performance-Based Optimization (LPBO), and Modified Particle Swarm Optimization (MPSO) demonstrated superior voltage and frequency regulation across two- and three-area interconnected power systems.

Model predictive control

Model Predictive Control (MPC) effectively overcomes many limitations of classical controllers through its predictive optimization framework. Unlike conventional Proportional–Integral–Derivative (PID) control, which reacts to current or past system states, MPC predicts future system behavior over a specified prediction horizon and computes optimal control actions accordingly. By incorporating dynamic models and operational constraints directly into its optimization process, MPC can handle multivariable interactions and system nonlinearities more effectively than traditional methods [10]. In

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modern power systems, MPC has gained wide adoption within Load Frequency Control (LFC) and Automatic Voltage Control (AVC) applications due to its ability to maintain stability and minimize energy losses under varying operating conditions. The controller minimizes a cost function that balances the trade-off between performance and control effort:

$$J = \sum_{i=1}^{Np}[wf(\Delta f(k+i))^2 + wv(\Delta V(k+i))^2] + \sum_{i=1}^{Nc-1} wu(\Delta u(k+i))^2 \qquad (2)$$

Where:

J = cost function
Δf(k+i) = frequency deviation
ΔV(k+i) = voltage deviation
Δu(k+i) = control input increment
wf,wv,wu = weighting factors for frequency, voltage, and control effort
Np,Nc = prediction and control horizons

Model Predictive Control (MPC) enhances system stability by predicting future disturbances and optimizing control actions in real time to minimize both system deviation and control effort. Its ability to explicitly handle multivariable interactions, nonlinear dynamics, and system constraints makes it highly effective for Load Frequency Control (LFC) and Automatic Voltage Control (AVC) in renewable-integrated smart grids [10]. By incorporating stochastic behavior and time-varying dynamics, MPC ensures smoother and faster frequency and voltage recovery compared to conventional PI/PID controllers.

Studies such as [10] have shown that MPC provides superior constraint handling and robustness in nonlinear renewable systems, while tube-based MPC approaches have improved the dynamic performance of aggregated electric vehicles (EVs) in islanded systems by stabilizing frequency under renewable intermittency [11]. Similarly, [12] developed an improved MPC that achieved faster settling time and enhanced frequency regulation. Further research expanded MPC's role in wind and hybrid energy system. applied adaptive MPC for wind turbines, while Sun et al. [14] and Shaltout et al. [15] developed economic MPC frameworks that optimized both cost and reliability [16].

Advanced implementations include two-layer MPC architectures for microgrids with wind and plug-in electric vehicles (PEVs), achieving up to 30% cost reduction and improved peak-load balancing [17], and hierarchical nonlinear MPCs for hybrid vehicles integrating energy management and actuator-level control [18]. MPC applications have also expanded to battery health-aware charging, HVAC systems, and hybrid vehicle optimization [19], [20], establishing MPC as a core intelligent control strategy for decentralized smart grids [21], [22]. Despite these advances, MPC faces challenges of computational complexity and model dependency, which constrain real-time implementation in large-scale systems. Ongoing research is focused on distributed MPC architectures, adaptive predictive algorithms, and reduced-order modeling techniques to enhance scalability, robustness, and efficiency in future smart grid applications.

The choice of MPC over a well-tuned FOPID is justified in systems where forecast information is available and explicit constraint handling (e.g., on EV charging rates or ESS state-of-charge) is a primary concern. However, for simpler systems, the computational burden of MPC may not be warranted

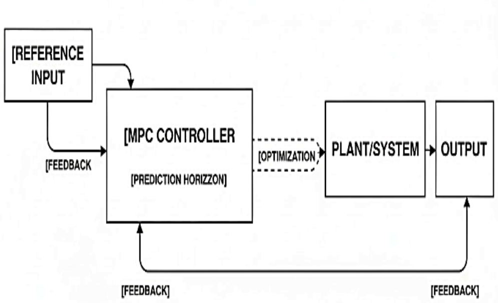

Fig 5: Block diagram of Model Predictive Control showing the prediction horizon, optimization process, and feedback mechanism that enables proactive system regulation.

Fuzzy logic control (FLC)

Fuzzy Logic Control (FLC) provides a rule-based, model-free control approach that effectively manages the nonlinearities and

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uncertainties in renewable-integrated power systems [23]. Using heuristic "IF–THEN" rules derived from expert knowledge, FLC determines control actions without relying on complex mathematical models [24]. Studies have shown that FLC offers faster response, reduced steady-state error, and improved damping compared to classical PI and PID controllers in Load Frequency Control (LFC) applications [25]–[28].

In multi-area systems, hybrid frameworks such as Artificial Neural Network–Fuzzy Logic Control (ANN–FLC) have been developed to automatically tune controller parameters, enhancing stability and transient performance [29], [30]. Further improvements involve adaptive fuzzy tuning schemes and nature-inspired optimization algorithms such as Particle Swarm Optimization (PSO), Cuckoo Search, and Firefly Algorithm (FA), which refine fuzzy parameters for greater robustness and precision [31]–[36]. However, despite these advancements, traditional FLC designs still depend heavily on expert-defined rules and heuristic tuning, limiting scalability and real-time adaptability prompting ongoing research into AI-enhanced fuzzy controllers that integrate neural and evolutionary learning for autonomous and self-optimizing control systems.

FLC provides a more intuitive and model-free alternative to MPC, excelling where accurate system models are difficult to derive. Its performance, however, is highly dependent on the quality of the rule base, whereas MPC relies on the accuracy of the dynamic model.

AI-Based and learning control

Artificial Intelligence (AI)-based control techniques have transformed modern control system design by enabling adaptive, robust, and data-driven decision-making in nonlinear and uncertain environments [37]. Unlike traditional controllers dependent on explicit models, AI allows systems to learn and optimize control strategies from operational data using methods such as Machine Learning (ML), Neural Networks (NNs), and Reinforcement Learning (RL) [38]–[40]. ML enhances predictive maintenance, trajectory tracking, and fault detection, while RL develops optimal policies through reward-based learning, making it ideal for autonomous vehicles, drones, and smart grids [37], [38], [41]–[50].

Neural Networks (NNs), particularly deep learning architectures, improve control accuracy and robustness by approximating nonlinear functions and enabling real-time adaptive control under uncertainty [39], [54]. When combined with Fuzzy Logic (FL) and bio-inspired algorithms such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), AI further enhances flexibility, stability, and self-tuning capability in adaptive systems [40]–[42]. These hybrid AI–based controllers have been successfully applied in robotics, renewable energy systems, and industrial process control. Integration of AI into adaptive and predictive control frameworks has led to significant advancements, such as AI-enhanced Model Predictive Control (MPC) and Reinforcement Learning–based MPC, which improve energy efficiency, system stability, and responsiveness in nonlinear and stochastic environments [43], [46], [47], [53].

Furthermore, multi-agent AI systems have facilitated decentralized coordination in swarm robotics and smart grids, allowing multiple agents to collaborate effectively [52], [53]. For highly dynamic systems, Deep Reinforcement Learning (DRL) and neural adaptive controllers have shown exceptional capability in managing uncertainty and turbulence [50]–[54]. AI-driven control has achieved notable success in autonomous vehicles, drone navigation, soft robotics, energy management, and healthcare, demonstrating reliable performance and real-time adaptability [43], [45], [53], [55]. However, challenges remain, particularly computational complexity, scalability, and lack of interpretability. The emerging field of Explainable Artificial Intelligence (XAI) seeks to address these issues by improving transparency, reliability, and trustworthiness in AI-based control frameworks, ensuring their safe and verifiable deployment in critical smart grid and automation applications [56].

AI-based methods represent the frontier of control, moving from model-based or rule-

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based design to data-driven learning. They are most suited for future grid scenarios that are too complex for conventional modeling, though their 'black-box' nature currently poses a challenge for trust and verification in critical infrastructure.

Comparative analysis of control techniques.

To provide a comprehensive understanding of the various control strategies discussed, this section presents comparative analyses of their characteristics and performance metrics.

Table1. Comparative Summary of LFC and AVC Control Techniques

Control Technique	Strengths	Weaknesses	Performance Metrics	Typical Applications
PI / PID	Simple, robust, low computational load	Poor performance under high nonlinearity	Moderate settling time, higher overshoot	Basic LFC/AVC in stable grids
MPC	Handles constraints, predictive, multivariable	High computational demand	Fast response, low overshoot	Smart grids, microgrids
Fuzzy Logic	Model-free, handles uncertainty well	Rule tuning complexity	Fast settling, low steady-state error	Nonlinear LFC, RES-integrated systems
FOPID	High precision, robust tuning flexibility	Requires optimization	Very low overshoot, strong damping	High-performance multi-area LFC
AI-based	Adaptive, self-learning	Black-box behavior, high computation	Best robustness under uncertainty	Autonomous, renewable-rich grids

Quantitative Comparison from Literature

Table 2 presents a quantitative comparison of major control techniques based on published studies. The metrics include settling time, overshoot, frequency deviation, and computational demand under typical dynamic disturbances in multi-area power systems.

Table 2: Performance Comparison of LFC/AVC Control Techniques from Literature

Controller	Settling Time (s)	Overshoot (%)	Freq. Deviation (Hz)	Computational Demand
PI	12–18	18–25	±0.12	Low
PID	10–15	10–20	±0.10	Low
MPC	4–7	0–5	±0.03	High
FLC	6–10	0–8	±0.05	Medium
FOPID	4–8	0–3	±0.02	Medium–High
AI-based	3–6	0–2	±0.01	High

The data clearly illustrates the performance-complexity trade-off, where advanced controllers like AI-based and FOPID achieve superior dynamic response at the cost of higher computational requirements, making them suitable for different grid applications based on specific performance needs and available computational resources.

Decentralized Vs Centralized Load Frequency Control

In modern power systems, maintaining frequency and voltage stability after disturbances

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is a critical objective achieved primarily through centralized and decentralized control strategies. In centralized control, a Central Controller (CC) collects system-wide data from all subsystems, processes the information, and determines control actions for each unit. This approach ensures global coordination and optimal system-wide response but demands extensive communication infrastructure and computational resources, making it complex and costly to implement in large, geographically dispersed networks [70].

Despite these challenges, centralized Load Frequency Control (LFC) and Model Predictive Control (MPC) strategies have been successfully demonstrated for multi-area systems, providing coordinated responses across interconnected regions [71]–[79]. Conversely, decentralized control assigns Local Controllers (LCs) to individual units or subsystems, allowing each to operate independently with minimal or no inter-controller communication. This structure enhances scalability, fault tolerance, and robustness against communication failures, making it suitable for distributed and renewable-rich grids [80]–[85]. However, its lack of global coordination can lead to suboptimal system performance, especially when inter-area coupling is weak. To address these limitations, advanced decentralized techniques—such as sliding mode control, fuzzy-based adaptive control, and output feedback control—have been introduced to improve dynamic response and stability [84], [85].

With the growing penetration of distributed energy resources (DERs), electric vehicles (EVs), and energy storage systems (ESS), neither purely centralized nor purely decentralized architectures can fully meet modern grid requirements. Consequently, hybrid and distributed control frameworks that combine the coordination of centralized schemes with the flexibility of decentralized systems are increasingly favored. These approaches enable cooperative control among local agents while preserving scalability and resilience, making them particularly effective for microgrids and multi-area smart power systems. The choice between centralized and decentralized control is a trade-off between global optimality and local resilience. Centralized control is preferable for well-connected, high-bandwidth networks, while decentralized or hybrid approaches are essential for distributed grids with high penetration of DERs and potential communication bottlenecks.

Challenges in Frequency and Voltage Control with Res Penetration

The integration of Renewable Energy Sources (RES) into modern power systems introduces significant challenges to both voltage and frequency stability, which are vital for maintaining reliable and high-quality electricity supply. These challenges stem mainly from the variable and intermittent nature of renewable generation and the extensive use of power electronic converters in grid interfacing [57]. The intermittent output of solar and wind energy causes voltage sags and fluctuations, as sudden environmental changes—such as passing clouds or wind speed variations—lead to rapid shifts in power generation. These fluctuations require fast-responding control systems to maintain voltage within permissible limits [58], [59].

Moreover, the widespread use of inverter-based RES introduces harmonic distortions, producing voltages or currents at multiples of the fundamental frequency. Such harmonics increase line losses, cause equipment overheating, and can interfere with communication and protection systems [60], [61]. Frequency stability is also affected because inverter-based sources lack the inherent inertia characteristic of conventional synchronous generators. This reduction in system inertia makes the grid more vulnerable to disturbances, leading to faster and more severe frequency deviations under high renewable penetration [62], [63].

Similarly, reactive power management becomes problematic since most RES, such as photovoltaic (PV) systems, operate near unity power factor and provide limited reactive power support. The resulting weak voltage regulation can trigger voltage instability, especially in low-inertia or weak-grid conditions [64], [65]. Finally, the non-dispatchable nature of RES introduces power imbalances between generation and demand, leading to frequency deviations, voltage flicker,

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and degraded power quality [66]–[68]. These fluctuations also complicate compliance with grid codes, which set standards for voltage stability, reactive power provision, and fault ride-through performance [69].

Integration of Electric Vehicles and Energy Storage in Control Loops

The integration of Electric Vehicles (EVs) and Energy Storage Systems (ESS) into modern power grids introduces significant flexibility and responsiveness for Load Frequency Control (LFC) and Automatic Voltage Control (AVC). Through Vehicle-to-Grid (V2G) technology, EVs can exchange power bidirectionally with the grid, acting as fast-response power reserves that provide ancillary services and improve system stability under dynamic operating conditions [86]–[94].

Numerous studies have demonstrated that incorporating EVs into power systems enhances frequency regulation and voltage support, particularly when combined with intelligent and optimized control strategies. For instance, comparative analyses of PI, Ziegler–Nichols (ZN), Model Predictive Control (MPC), Fuzzy Logic Control (FLC), and Fractional-Order PID (FOPID) techniques reveal that fuzzy-tuned FOPID controllers achieve superior dynamic performance in multi-area systems with integrated PV, wind, and EV generation [87]. Optimization-based V2G models, including those employing Teaching–Learning-Based Optimization (TLBO) and Particle Swarm Optimization (PSO), have effectively minimized frequency deviations in two- and three-area power systems, especially under high EV penetration [88], [89].

On a modified IEEE 39-bus system, a fuzzy PI-based V2G controller tuned using the Imperialist Competitive Algorithm (ICA) outperformed conventional approaches, achieving faster frequency recovery and smaller overshoots [89]. Different EV charging strategies—dumb, smart, and continuous charging, have been analyzed for their effects on LFC performance. Among these, smart charging provides the best mitigation of frequency fluctuations in interconnected multi-area power systems (IMAPSs) [90].

Similarly, decentralized MPC schemes have shown improved performance over centralized approaches in EV-integrated four-area smart grids, demonstrating enhanced robustness and lower communication dependency [91]. Further investigations confirm that V2G-enabled EVs can serve as fast frequency regulators, particularly in renewable-rich systems where rapid compensation is required [92]. Advanced approaches, such as Adaptive Dynamic Programming (ADP)-based hierarchical control, have been applied to handle stochastic disturbances in EV-aggregated smart grids, achieving optimal dynamic responses [93]. Likewise, Linear Quadratic Gaussian (LQG), Linear Quadratic Regulator (LQR), and Integral LQG (ILQG) controllers have been developed to enhance frequency stability in unified grid systems with plug-in EVs [94].

However, the growing reliance on advanced control mechanisms, communication networks, and data-driven algorithms introduces new cybersecurity vulnerabilities. Threats such as data manipulation, communication failures, and coordinated cyberattacks can compromise the integrity of LFC and AVC systems. Ensuring cyber-resilient, adaptive, and secure control architectures is therefore essential to maintain reliable operation in EV- and ESS-integrated smart grids

Cybersecurity Issues in Automatic Control

Smart grids depend heavily on open communication networks and extensive data exchange, making cybersecurity a critical concern [95], [96], [97]. To reduce communication load and mitigate denial-of-service (DoS) attacks, several studies have proposed various strategies to address load frequency control (LFC) challenges in smart grids [98], [99], [100], [101]. Cyber attackers have attempted to disrupt system operations [102], manipulate utility pricing data [103], and block the transmission of measurements or control signals [104].

To address these threats, LFC in interconnected multi-area power systems

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(IMAPSs) has been analyzed using PI controllers and Lyapunov-based methods under DoS conditions [105]. Adaptive and resilient event-triggering schemes have been suggested to minimize communication requirements while maintaining system stability under uncertainty. DoS attacks have been modeled using Bernoulli distributions [106], and energy-limited attack scenarios have been studied to optimize attack scheduling and minimize impact on system performance [107]. Markov-based models have also been applied to represent DoS attacks for risk-sensitive stochastic control, allowing the design of protective strategies for power systems [108], [109]. Some studies have assumed partial knowledge of DoS signals, considering lower bounds for off-time intervals and transitions [110], while others examined the effects of partially known power-constrained pulse width-modulated jamming devices [111].

Control loops incorporating DoS attacks and transmission delays have been simulated using PI-based LFC in IMAPSs to evaluate system resilience [112]. Several mitigation approaches have been proposed in the literature, broadly classified into switched strategies [113], [114], [115] and active state-estimation methods [116]. For IMAPSs experiencing communication delays, event-triggered control techniques have been developed to reduce the frequency of control updates and transmitted signals, thereby alleviating network load while maintaining system stability. Adaptive event-triggered control combined with $H\infty$ methods has been applied to evaluate LFC performance under limited-bandwidth and energy-constrained DoS attack scenarios [117], [118].

Frequency security assessment in power systems aims to predict frequency trajectories during disturbances to determine available safety margins. Model-driven approaches, including time-domain simulation (TDS) and equivalent frequency model (EFM) methods, are commonly used [119]. TDS methods, which employ numerical analysis, can accurately replicate power system dynamics by modeling network topologies, control interactions, and state variable relationships such as frequency, voltage, and power angles. These methods start from a steady-state condition and simulate the evolution of system states over time, providing highly accurate frequency dynamic analysis [120]. While TDS approaches form the basis of commercial software such as PSASP, PSS/E, and BPA, they are computationally intensive and primarily suited for offline studies. The increasing penetration of renewable energy sources (RESs) and power electronic converters (PECs) necessitates hybrid electromechanical-electromagnetic simulations to capture fast-response dynamics accurately [121].

Research Gaps

While significant advancements have been achieved in Load Frequency Control (LFC) and Automatic Voltage Control (AVC) using advanced controllers such as Model Predictive Control (MPC), Fuzzy Logic Control (FLC), Fractional-Order PID (FOPID), and AI-based hybrid schemes, several critical gaps remain. First, most of the reviewed studies are confined to simulation-based analyses without experimental validation or hardware-in-the-loop (HIL) implementation. Consequently, the real-world performance, scalability, and robustness of these control strategies under practical operating conditions remain largely unverified.

Second, there is a notable lack of integrated frameworks that simultaneously address frequency control, voltage regulation, and power quality within renewable-dominated multi-area systems. Many existing approaches treat these parameters independently, neglecting their strong interdependencies in dynamic grid operation.

Third, while techniques such as FOPID and MPC offer superior control precision, they often suffer from high computational complexity, limiting their feasibility for large-scale or real-time applications. Adaptive and distributed implementations remain underdeveloped, especially in systems with heterogeneous energy resources and limited communication bandwidth.

Fourth, the integration of Electric Vehicles (EVs) and Energy Storage Systems (ESS) into grid control frameworks is still in early stages. Current

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models often assume idealized charging behaviors and perfect communication between EV aggregators and control centers, which is rarely achievable in practice.

Fifth, despite the widespread adoption of AI-based and data-driven controllers, there is insufficient attention to explainability, data transparency, and cybersecurity resilience. Many control models rely on black-box machine learning algorithms, making it difficult to interpret decisions or ensure secure and reliable operation under cyber-physical threats. Collectively, these gaps underscore the need for comprehensive, real-time, and experimentally validated solutions capable of operating in complex, uncertain, and decentralized grid environments.

Future Directions

Future work should focus on developing Distributed Adaptive Cyber-Resilient Control Systems (DACR-CS) that combine classical controllers with intelligent learning modules for real-time mode switching under disturbances, renewable fluctuations, and cyber threats. Another priority is building a Hardware-Validated Intelligent Microgrid Testbed (HIMT) using hardware-in-the-loop simulation and embedded controllers to validate new frequency and voltage control algorithms under realistic grid conditions.

Research should also advance a Multi-Agent DER Coordination Architecture (MADCA), where DERs, EVs, and ESS operate as autonomous agents using consensus and game-theoretic strategies for coordinated energy sharing and stability. To improve transparency, an XAI-Driven Predictive Control Model (XAI-PCM) should be developed, merging explainable AI with MPC for interpretable, constraint-aware decision-making in renewable-rich systems.

Cybersecurity efforts must deliver a Secure Control and Anomaly Detection Engine (SCADE) with encrypted communication, distributed intrusion detection, and attack-resilient control loops capable of handling DoS and false-data injection scenarios. Finally, robust LFC and AVC will require a unified Holistic Energy-Frequency-Voltage Optimization Framework (HEFVOF) that integrates multi-objective optimization and real-time scheduling for coordinated grid stability in renewable-dominated smart grids.

CONCLUSION

This paper reviewed classical, modern, and intelligent LFC and AVC techniques in the context of renewable-integrated smart grids. Classical controllers such as PI and PID remain useful for basic control, while MPC, FLC, and AI-based strategies offer superior adaptability and robustness. The integration of EVs and ESS further enhances stability, though cybersecurity remains a key vulnerability. Future advancements must emphasize real-time, secure, and explainable control frameworks to ensure sustainable, resilient, and intelligent power systems.

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