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AI-Driven Strategies for Enhancing Power Quality in Renewable Systems

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ABSTRACT

The increasing integration of renewable energy sources into modern power systems has introduced significant challenges in maintaining power quality, frequency stability, and system resilience due to the intermittent and variable nature of solar, wind, and hydropower generation. Machine learning and deep learning techniques, combined with energy storage systems and optimization-based control strategies, have emerged as effective tools for real-time monitoring, predictive analytics, and uncertainty mitigation. Advanced scenario-based modeling and AI-enabled controllers enhance operational efficiency, reliability, and sustainability. This review highlights the latest methodologies, challenges, and future directions for achieving intelligent, resilient, and low-carbon power systems.

Keywords: *Renewable Energy, Machine Learning, Power Quality, Energy Storage, System Resilience.*

I. INTRODUCTION

The rapid global transition toward renewable energy integration in modern power systems has ushered in a complex era of electrical grid management, wherein the conventional paradigms of stability, reliability, and operational efficiency are being challenged by the inherent variability and intermittency of sources such as solar, wind, and hydropower, alongside the proliferation of distributed energy resources (DERs) and microgrids, as highlighted in contemporary research (Sayed et al., 2026; Prasad et al., 2024). The unpredictable nature of renewable generation, compounded by fluctuating electricity prices, dynamic load demands, and the growing penetration of electric vehicles—including fuel cell-based and battery-operated variants—has intensified concerns regarding frequency stability, voltage regulation, and the broader resilience of power systems, necessitating the development of innovative control strategies and adaptive planning frameworks (Şahin & Ayas, 2026; Manousakis et al., 2023). Conventional indicators of power system performance, traditionally quantified through static metrics such as SAIDI and SAIFI, have been found inadequate in capturing the nuanced impacts of high renewable penetration, prompting the adoption of multi-dimensional key performance indicators (KPIs) that encompass technical, economic, environmental, and social dimensions, enabling a more robust assessment of grid reliability, responsiveness to demand-side management, cost-effectiveness, and stakeholder engagement (Sayed et al., 2026). Recent studies have explored the integration of machine learning and deep learning methodologies to address these emerging challenges, leveraging predictive analytics, real-time optimization, and scenario-based planning to enhance system performance under uncertainty (Rahmani et al., 2025; Kumar et al., 2023). For instance, hybrid control architectures employing deep reinforcement learning, such as Deep Deterministic Policy Gradient (DDPG) algorithms combined with optimized PI and PIDn controllers, have demonstrated significant improvements in load frequency regulation and dynamic response, achieving reductions of up to 75% in integral time-weighted absolute errors under diverse operational disturbances, including intermittent renewable supply, parameter uncertainties, and communication delays (Şahin & Ayas, 2026). Complementarily, the integration of energy storage systems, including battery energy storage (BESS), virtual inertia (VI), and redox flow batteries (RFBs), has been recognized as critical in mitigating fluctuations induced by renewable sources, providing active, reactive, and combined power functionalities that enhance system flexibility and reliability (Datta et al., 2021). Moreover, the decreasing utilization of synchronous generators due to the increasing share of renewables has highlighted the issue of reduced system inertia, which, if left unaddressed, may precipitate frequency instability and increase susceptibility to cascading failures during major contingencies, necessitating a precise evaluation of critical inertia thresholds and the development of inertia-supporting mechanisms (Hadavi et al., 2025; Yang et al., 2021). Integrated optimization approaches have also been widely investigated to reconcile the trade-offs between generation, transmission, storage, and flexibility, employing deterministic, stochastic, robust, and AI-enhanced frameworks that account for long-duration storage, centralized versus decentralized planning, and regulatory and market drivers of grid expansion, thereby providing comprehensive guidance for system operators and planners in managing high-renewable penetration scenarios (Barrera-Singaña et al., 2025). In addition, scenario-based stochastic programming, supported by advanced deep learning techniques, has emerged as a promising approach for modeling and mitigating uncertainties in renewable generation, electricity prices, and load demand, through processes that involve scenario generation and reduction to balance computational tractability with the preservation of critical system information (Rahmani et al., 2025). The deployment of these intelligent, adaptive methodologies not only enhances operational performance but also supports strategic decision-making in energy system planning, ensuring that modern power grids remain resilient, efficient, and environmentally sustainable while facilitating the incorporation of emerging technologies such as electric vehicles, hydrogen refueling infrastructure, and smart microgrid operations (Manousakis et al., 2023; Sayed et al., 2026). Collectively, these advances underscore a paradigm shift in power system management from conventional rule-based control to data-driven, AI-enabled, and predictive frameworks that integrate multi-objective optimization, real-time monitoring, and adaptive learning, providing the foundation for resilient, low-carbon, and future-ready energy systems capable of accommodating unprecedented levels of renewable penetration while maintaining operational integrity, system reliability, and environmental sustainability, thereby charting a path toward an intelligent, automated, and highly responsive energy infrastructure that addresses both current operational challenges and anticipates future uncertainties in an increasingly complex power system landscape.

II. RESEARCH BACKGROUND

Sayed et al. (2026) were reported to have examined the growing complexity of modern energy systems, highlighting the increasing role of microgrids and distributed energy resources (DERs) in enhancing power system resilience. Their review was said to have synthesized key performance indicators (KPIs) employed to evaluate resilience, particularly in the context of renewable energy integration, electric vehicles—including fuel cell EVs—and intelligent control strategies. The authors were noted to have categorized KPIs across technical, economic, environmental, and social dimensions, encompassing reliability indices (e.g., SAIDI, SAIFI), renewable energy penetration, demand response responsiveness, cost-effectiveness, and community engagement. Special attention was reportedly given to the limitations of conventional KPIs in high-renewable systems and the necessity for dynamic, context-specific metrics tailored to evolving grid structures. They were claimed to have explored advanced approaches such as machine learning and artificial intelligence for predictive resilience analytics and compared traditional indicators with multi-criteria decision-making methods, like the TOPSIS-based Vulnerability Function. Additionally, their study was said to have discussed the impact of hydrogen procurement reliability on energy system resilience and the importance of fuel cell refueling infrastructure. By identifying gaps in existing frameworks, the authors were suggested to have offered recommendations for more adaptive, scalable, and data-driven KPIs, emphasizing the need for standardization, real-world validation, and integration of AI tools to guide resilient energy system planning and policy-making.

Şahin and Ayas (2026) were reported to have highlighted that maintaining frequency stability had emerged as a significant challenge in contemporary power systems, particularly when renewable energy sources such as photovoltaic and wind power were integrated. They noted that the inherent unpredictability of renewable energy generation contributed to this instability, underlining the critical need for effective load frequency management to ensure system stability. Their study was described as introducing a novel hybrid control framework aimed at enhancing frequency control in renewable-integrated power systems through deep reinforcement learning. It was indicated that, within a two-area power system containing PV, wind, and thermal energy units, they had implemented a deep deterministic policy gradient (DDPG) algorithm as a supplementary controller in conjunction with optimised PI and PIDn controllers. The authors were observed to have conducted extensive simulations under diverse operating conditions—including step load changes, communication delays, parameter uncertainties, intermittent renewable supply, and random disturbances—to assess the effectiveness of the proposed system. They were reported to have achieved up to a 75% improvement in integral time-weighted absolute error values, demonstrating that the DDPG-assisted approach significantly outperformed conventional controllers. Furthermore, they were mentioned to have validated the practical applicability of the method through OPAL-RT based real-time simulations, confirming its feasibility for real-world deployment in modern power systems.

Rahmani et al. (2025) were reported to have observed that, with the accelerating global transition toward renewable energy sources, the effective modeling of inherent uncertainties in these units had become increasingly critical. They had noted that sustainable energy sources, such as solar and wind power, exhibited high variability and were challenging to predict, which complicated their integration into power systems. Moreover, they had acknowledged that other uncertainties, including fluctuations in electricity prices and variations in load demand, also affected power system operations. To address these challenges, they had indicated that stochastic programming had been widely employed. Their study described that the preparation of scenarios for stochastic programming generally involved two key steps: scenario generation and scenario reduction. Scenario generation was explained as creating a diverse set of potential future outcomes based on the considered uncertainties, while scenario reduction aimed at refining these scenarios to a manageable number without losing essential information. The authors had explored innovative methods for both scenario generation and reduction, emphasizing the application of deep learning approaches. They had also provided recommendations for future research, identified areas requiring further development, and discussed the challenges associated with implementing deep learning techniques in this context.

Hadavi, Hagh, and Zadeh (2025) had investigated the recent developments in the electricity sector and noted that the increasing adoption of Renewable Energy Sources (RESs) had led to a decline in the utilization of synchronous generators. They had argued that power grid systems were progressively optimizing the integration of RESs and that, as the proportion of renewable resource generators increased, the overall inertia of the power system had diminished, thereby affecting frequency stability. They had characterized this inertial reduction as either structural and permanent or as fluctuating daily and hourly, depending on the characteristics of the renewable resources involved. The study had sought to address a significant research gap concerning the complex relationship between renewable energy integration and system inertia, particularly in relation to frequency stability. While prior studies had touched upon these themes, Hadavi et al. had aimed to provide a more comprehensive analysis by examining the effects of varying levels of renewable energy penetration on a simplified power system's frequency stability. They had identified the critical inertia threshold required to sustain system stability during major disturbances and had highlighted that substantial reductions in inertia could increase the risk of frequency instability and potential grid failure.

Barrera-Singaña et al. (2025) were reported to have examined the expanding integration of wind and photovoltaic (PV) energy and its impact on power system planning processes. They highlighted that the incorporation of these renewable sources had posed limitations to forecasting due to their inherent variability. Their review was said to have compiled ninety studies conducted between 2019 and 2025, and it was indicated that they presented, for the first time, an integrated approach simultaneously optimizing generation, transmission, storage, and flexibility under high renewable penetration. They were noted to have systematically categorized conflicting optimization approaches—including deterministic, stochastic, robust, and AI-enhanced methods—illustrating mathematical formulations, real-world case studies, and trade-offs between optimality, scale, and runtime. Through bibliometric analysis, they reportedly identified emerging international cooperation clusters and provided practical method selection via tabulated case study snapshots. Other issues they analyzed were long-duration storage, centralized versus decentralized planning, and regulatory and market drivers of grid expansion. Finally, they were said to have identified gaps in the literature—such as resilience, sector coupling, and policy uncertainty—emphasizing areas needing further research, and they concluded that their integrated perspective offered critical insights for researchers and planners addressing generation and transmission expansion under uncertainty.

Prasad et al. (2024, January) were reported to have highlighted that the integration of renewable energy into modern power systems had presented considerable challenges while simultaneously offering significant opportunities, as the global shift toward sustainable energy progressed. They were observed to have emphasized that renewable sources, such as solar, wind, and hydropower, were deemed crucial for reducing carbon emissions and combating climate change, yet their variable nature had posed substantial difficulties for grid stability, reliability, and operational efficiency. The article was noted to have examined the complexities of renewable energy incorporation, addressing issues like intermittency, infrastructural limitations, and economic and regulatory constraints. Technological advancements, including energy storage systems, smart grid deployment, and demand response strategies, were described as effective solutions to these challenges. Moreover, the authors were said to have underscored the multifaceted benefits of renewable integration, encompassing economic growth, environmental protection, and technological innovation, as well as fostering new industries. Their study was concluded to have outlined a pathway toward a resilient, adaptive, and renewable energy future through detailed analyses of case studies and emerging trends.

Manousakis et al. (2023) were reported to have highlighted that electric vehicles (EVs) had been recognized as a promising green technology for mitigating environmental impacts, although their widespread adoption was noted to have significant implications for the management, monitoring, and control of power systems. They were observed to have emphasized that integrating renewable energy sources (RESs), often described as green or alternative energy sources, into network infrastructures had been considered a sustainable approach to addressing these challenges. Their review was described as comprehensive in analyzing the integration of RESs and EVs into power systems, revealing through bibliographic analysis that IEEE Access had exerted the highest journal impact. The authors were said to have provided an analytical summary to enhance literature classification, facilitating the recognition of primary objectives explored in the reviewed works, including EV and RES classification, incorporation into power systems with emission focus, EV charging and parking infrastructure, battery systems, integration management strategies, EV aggregators, and financial considerations. They were reported to have bifurcated the papers into mathematical and heuristic algorithm classifications, noting that mixed integer linear programming and particle swarm optimization algorithms were commonly utilized, with MATLAB/Simulink serving as the primary execution platform and CPLEX as the dominant optimization tool. Finally, it was concluded that the study had offered avenues for further research and discussion on unexplored areas in the integration of RESs and EVs.

Kumar et al. (2023) were reported to have addressed the concurrent voltage and frequency control problem for an interconnected three-area system, each comprising thermal and diesel units alongside renewable energy integration from separate sources. In their first case study, they were said to have incorporated renewable sources such as wind, solar, and geothermal using a static transfer function-based model without accounting for variability in wind and solar. In the second case study, they were noted to have employed a dynamic model of wind and solar, including deterministic drifts and stochastic fluctuations. The study was described as presenting a Harris Hawks optimized model predictive controller (MPC-HHO) aimed at mitigating frequency and voltage fluctuations resulting from sudden load changes. Additionally, it was observed that they had integrated dynamic energy storage devices, including virtual inertia and redox flow batteries (VI-RFB), in coordination with the MPC-HHO controller. The results were reported to validate that the transient response under the MPC-HHO controller coordinated with VI-RFB exhibited superior characteristics compared to existing state-of-the-art methodologies. Furthermore, the authors were indicated to have considered prevalent nonlinearities in realistic power systems, investigated their effects on controller performance, and successfully validated the robustness of the proposed MPC-HHO controller with VI-RFB.

Datta et al. (2021) were reported to have investigated the integration of renewable energy sources (RES), such as photovoltaics (PV) and wind turbines, as alternative energy solutions to mitigate environmental concerns and meet energy demand. They observed that large-scale incorporation of intermittent RES had induced reliability and stability issues in the electric grid. To address these fluctuations, they considered battery energy storage systems (BESS) as highly effective arrangements that could enhance the operational flexibility of power systems. Their review highlighted various applications of BESS in mitigating the adverse impacts of PV and wind integration, focusing on battery connection techniques, power conversion systems, individual PV/wind setups, and hybrid configurations. They categorized BESS applications into active, reactive, and active-reactive power functionalities and summarized key findings from existing studies along with simulation results. Through this comprehensive assessment, they identified challenges in BESS deployment, including battery charging/discharging strategies, connection configurations, conversion efficiency, RES forecasting, and battery lifespan, and suggested directions for future research to improve the design, operation, and implementation of BESS technologies in power systems.

Yang et al. (2021) were reported to have examined the impact of substantial uncertainty on power systems and its potential to increase vulnerability to cascading failures. The study was said to have aimed at analyzing power system vulnerability under stricter security criteria and assessing variations in vulnerability with the integration of renewable energy. To achieve this, the researchers were described to have employed a graph-based model for cascade propagation, constructed using a thermal inertia-based cascades model combined with an N-k contingency sampling algorithm. Based on this model, comprehensive evaluation indices were proposed to assess system vulnerability across variable operational states and different levels of generation uncertainty. The findings were indicated to demonstrate that the graph-based method could effectively reveal cascade propagation and facilitate visualization and analysis of system vulnerability. Additionally, results were noted to suggest that power system vulnerability was highly sensitive to variations in renewable generation, with systems being particularly prone to cascading failures when uncertainty exceeded certain thresholds. It was concluded that the proposed approach could assist operators in testing system resilience and analyzing scenario-based risks.

III. KEY FINDINGS FROM STUDY

Author(s)	Year	Objective	Methodology	Key Findings	Notes
Sayed et al.	2026	Assess power system resilience with high renewable penetration	Review of KPIs for technical, economic, environmental, social dimensions	Identified limitations of conventional KPIs; proposed adaptive, multi-dimensional metrics; emphasized AI integration	Focused on microgrids, DERs, EVs, and renewable integration
Şahin & Ayas	2026	Enhance frequency regulation in renewable-integrated systems	Deep reinforcement learning (DDPG) combined with PI/PIDn controllers; real-time simulation with OPAL-RT	Achieved up to 75% improvement in integral time-weighted absolute error; better performance than conventional controllers	Two-area system with PV, wind, thermal; accounted for load changes and uncertainties
Rahmani et al.	2025	Model uncertainties in renewable energy systems	Stochastic programming with scenario generation & reduction; deep learning for predictive analysis	Highlighted challenges in scenario preparation; suggested deep learning for better uncertainty modeling	Focused on solar/wind variability and load/electricity price fluctuations
Hadavi, Hagh & Zadeh	2025	Analyze frequency stability under reduced inertia	Analytical modeling of inertia variations with different renewable penetration	Identified critical inertia thresholds; reduced inertia increases frequency instability risk	Distinction between structural/permanent vs fluctuating daily/hourly inertia
Barrera-Singaña et al.	2025	Optimize generation, transmission, storage under high renewable penetration	Review of deterministic, stochastic, robust, AI-enhanced optimization	Categorized conflicting optimization approaches; provided integrated planning insights; highlighted gaps like resilience and policy uncertainty	Bibliometric analysis of 90 studies (2019-2025)

Prasad et al.	2024	Examine challenges & opportunities of renewable integration	Case study review; system-level analysis	Highlighted grid stability issues due to intermittency; suggested storage, smart grids, demand response	Emphasized economic, environmental, and technological benefits of renewables
Manousakis et al.	2023	Integrate EVs and RES in power systems	Review of mathematical & heuristic approaches; MATLAB/Simulink simulations	Identified integration challenges; EV/RES classification; recommended financial and management strategies	Included particle swarm optimization, MILP, EV aggregators
Kumar et al.	2023	Voltage & frequency control in multi-area renewable system	MPC-HHO controller with VI-RFB; dynamic modeling of wind/solar	Demonstrated superior transient response; robustness validated	Considered nonlinearities and dynamic energy storage coordination
Datta et al.	2021	Evaluate BESS functionalities in RES integration	Literature review; simulation studies	BESS improves flexibility; categorized applications (active, reactive, active-reactive); highlighted operational challenges	Focus on battery connection, efficiency, lifespan, and forecasting
Yang et al.	2021	Analyze power system vulnerability to cascading failures	Graph-based model; thermal inertia cascades; N-k contingency sampling	Vulnerability sensitive to renewable variation; graph-based approach effective for visualization and scenario analysis	Proposed indices to assess variable operation states and uncertainty levels

IV. CONCLUSION

The integration of renewable energy sources into modern power systems has undeniably transformed the landscape of electrical grid operations, presenting both opportunities and challenges that necessitate advanced analytical and control strategies. From the comprehensive reviews and empirical studies, it has been observed that the inherent variability of renewable resources such as solar, wind, and hydropower significantly impacts frequency stability, voltage regulation, and overall system resilience. Machine learning and deep learning techniques, including reinforcement learning, stochastic scenario analysis, and predictive modeling, have emerged as essential tools to address these complexities, enabling real-time adaptation, uncertainty mitigation, and improved operational performance. Energy storage systems, such as battery energy storage, virtual inertia devices, and redox flow batteries, have been shown to provide effective solutions for balancing supply-demand fluctuations, maintaining critical inertia, and supporting ancillary services. Optimization-based planning frameworks, encompassing deterministic, stochastic, and AI-enhanced approaches, have further facilitated the coordinated integration of generation, transmission, and storage while accounting for economic, environmental, and policy considerations. Collectively, these advancements demonstrate that resilient and sustainable power systems require an integrated, data-driven approach that leverages both intelligent control and scenario-based planning. Future research should continue to refine multi-dimensional key performance indicators, incorporate real-time adaptive learning, and explore the synergistic effects of emerging technologies such as electric vehicles, hydrogen infrastructure, and decentralized microgrids. In conclusion, the convergence of renewable energy, energy storage, and machine learning offers a promising pathway toward robust, reliable, and environmentally sustainable power systems capable of addressing the dynamic challenges of contemporary and future energy landscapes.

V. FUTURE SCOPE

- **Advanced AI and Machine Learning Integration** – Future research can focus on developing more sophisticated AI and deep learning algorithms for predictive control, adaptive fault detection, and real-time power quality monitoring in grids with high renewable penetration. These approaches can improve decision-making under uncertainties and dynamic operating conditions, enabling faster and more accurate responses to disturbances and enhancing overall system resilience.
- **Optimized Energy Storage Coordination** – There is significant scope to design intelligent frameworks that coordinate battery energy storage systems (BESS), virtual inertia devices, and redox flow batteries for frequency regulation, voltage stabilization, and mitigation of renewable intermittency. Advanced control strategies can enable efficient charge-discharge cycles, enhance storage utilization, and extend battery lifespan while maintaining grid reliability.
- **Microgrid and Distributed Energy Resource (DER) Management** – Research can explore decentralized, AI-enabled microgrid architectures that integrate multiple DERs, renewable generators, and energy storage units. Intelligent management systems can optimize local generation, load sharing, and islanding strategies, increasing operational flexibility and resilience against grid disturbances.
- **Enhanced Scenario-Based and Stochastic Modeling** – Future studies can advance stochastic programming and scenario reduction techniques using deep learning for better uncertainty modeling in renewable generation, load demand, electricity pricing, and electric vehicle integration. This can improve the accuracy of predictive simulations and support risk-aware decision-making for operators and planners.
- **Integration of Emerging Technologies** – There is scope for incorporating electric vehicles, hydrogen-based storage and generation, sector-coupled resources, and smart grid infrastructures into optimization frameworks. AI-enabled co-simulation and predictive planning can help achieve more sustainable, low-carbon, and resilient energy systems that balance technical, economic, and environmental objectives in future power grids.

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