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AI-Based Predictive Models for Power System Stability in Modern Smart Grids

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ABSTRACT

Modern power systems are becoming increasingly complex due to renewable energy integration, smart grids, inverter-based resources, and variable load demand. Artificial intelligence-based predictive models offer effective solutions for stability analysis by improving forecasting, monitoring, and real-time control. Machine learning, deep learning, reinforcement learning, and digital twin technologies help identify transient stability, voltage instability, frequency deviation, and dynamic grid interactions. These models enhance reliability, adaptability, and operational efficiency in modern energy networks. However, challenges such as data quality, cybersecurity, interpretability, and scalability still require further research. Overall, AI-based predictive models support resilient, intelligent, and sustainable power system operation.

Keywords: *Artificial Intelligence, Power System Stability, Predictive Models, Smart Grid, Renewable Energy*.

I. INTRODUCTION

The rapid transformation of modern electrical power systems has been significantly driven by the increasing penetration of renewable energy sources, smart grid technologies, and power electronic-based infrastructures. As traditional synchronous generation is progressively replaced by inverter-based renewable energy systems, maintaining power system stability has become more complex and challenging than ever before. Stability issues now extend beyond classical rotor-angle and voltage stability problems to include dynamic interactions introduced by grid-forming and grid-following inverters, stochastic renewable generation, and highly variable load patterns. In this context, conventional analytical and deterministic approaches are often insufficient to capture the nonlinear, time-varying, and high-dimensional behavior of modern grids. Consequently, artificial intelligence (AI)-based predictive models have emerged as a transformative solution for enhancing power system stability analysis, offering improved accuracy, adaptability, and real-time decision-making capabilities (Murugesan et al., 2026; Liu et al., 2023). These AI-driven approaches leverage large-scale operational data, advanced learning architectures, and predictive analytics to support forecasting, monitoring, and control functions in dynamic power environments. Moreover, with the integration of smart sensors, Phasor Measurement Units (PMUs), and Internet of Things (IoT) devices, the availability of high-resolution data has further strengthened the applicability of machine learning and deep learning models in stability assessment tasks. Studies have also highlighted that improvements in spatiotemporal forecasting accuracy directly contribute to enhanced grid reliability through frequency regulation, demand response, and synthetic inertia support mechanisms (Murugesan et al., 2026). Therefore, the convergence of AI technologies with modern power system operations represents a paradigm shift toward intelligent, self-adaptive, and resilient energy infrastructures.

Artificial intelligence-based methods, particularly machine learning (ML), deep learning (DL), and reinforcement learning (RL), have demonstrated significant potential in addressing stability challenges in modern power systems. These methods are capable of learning complex nonlinear relationships between system variables, enabling more accurate prediction of transient stability, voltage collapse, and frequency deviations under varying operating conditions. For instance, convolutional neural networks (CNNs) have been successfully applied for grid stability assessment, achieving superior performance compared to traditional multilayer perceptron models by effectively processing multi-dimensional system data such as power flow, load demand, and economic parameters (Zhang & Lin, 2025). Similarly, deep learning techniques have been extensively studied for both dynamic and cyber-physical stability analysis, offering advantages in feature extraction, pattern recognition, and real-time inference (Muhammed et al., 2026). In addition, digital twin technology has further enhanced AI-based stability evaluation by providing a virtual replica of physical power systems, enabling continuous simulation, validation, and optimization of predictive models under realistic conditions (Shen et al., 2025). Hybrid approaches combining classical power flow methods such as Newton-Raphson techniques with AI-based predictive correction mechanisms have also shown promising results in improving steady-state analysis accuracy and operational reliability (Hang et al., 2025). Furthermore, the increasing adoption of inverter-based resources has introduced new stability concerns, particularly in weak grid conditions characterized by low short-circuit ratios. In this regard, grid-forming inverters and AI-augmented control strategies have been proposed to enhance system inertia, damping, and synchronization capabilities (Abdelwahab & Vokony, 2026). Collectively, these advancements indicate that AI-based predictive models are not merely supplementary tools but are becoming integral components of modern power system stability frameworks.

Despite significant progress, several challenges remain in the implementation of AI-based predictive models for power system stability analysis. One of the major limitations is the availability of high-quality, labeled datasets that accurately represent diverse operating conditions, including extreme contingencies and rare fault scenarios. Data privacy, cybersecurity risks, and communication constraints in distributed smart grid environments further complicate model training and deployment processes (Sulaiman et al., 2023). Additionally, issues related to model interpretability, scalability, and generalization across different grid configurations continue to limit widespread adoption in real-world applications (Alhamrouni et al., 2024). Another critical challenge lies in the uncertainty associated with renewable energy generation, particularly wind and solar power, which introduces variability that can destabilize grid operations if not properly managed through predictive control strategies (Li et al., 2024). Furthermore, converter-dominated systems require advanced stability assessment frameworks that consider both control parameters and dynamic interactions between grid components, which traditional AI models may not fully capture without domain-specific adaptations (Liu et al., 2023). To address these issues, emerging research is focusing on federated learning, hybrid AI-physical models, and adaptive learning algorithms capable of real-time updating and decentralized decision-making. The integration of artificial intelligence with advanced communication networks, digital twins, and smart sensors is expected to further enhance predictive accuracy and operational resilience. Overall, AI-based predictive models represent a crucial technological advancement in power system stability analysis, enabling more reliable, efficient, and intelligent energy systems that align with the global transition toward sustainable and renewable energy integration (Afridi et al., 2022; Murugesan et al., 2026).

II. RESEARCH BACKGROUND

Murugesan et al. (2026) had reviewed the substantial transformation that had occurred in global power systems over the previous decade due to the rapid expansion of variable renewable energy (VRE). The authors had summarized the major advances that had been achieved in power grid forecasting, highlighting the transition from conventional statistical approaches to more sophisticated techniques such as deep learning models. It had been reported that improvements in spatiotemporal resolution and the integration of high-quality weather data had considerably reduced forecasting errors for wind and solar power generation. The study had further emphasized that advancements in forecasting accuracy had been closely linked with improvements in grid stability through mechanisms such as synthetic inertia, frequency regulation, and demand response. A comparison between deterministic and probabilistic forecasting approaches had also been presented to demonstrate progress in predictive reliability. Additionally, the article had identified ongoing challenges in developing a more reliable, resilient, and secure VRE-powered system, while suggesting strategic pathways for future grid modernization and operational resilience.

Muhammed et al. (2026) had presented a comprehensive review of the integration of advanced artificial intelligence, particularly deep learning techniques (DLTs), in modern power systems, where increasing penetration of renewable energy sources and smart technologies had created significant challenges related to stability, security, and control. The study had systematically examined the application of DLTs in two major domains, namely dynamic phenomena and cyber-physical phenomena, thereby offering a dual thematic structure that distinguished it from earlier reviews. It had been reported that the authors not only categorized existing methods but also critically discussed their performance, application-specific benefits, and inherent advantages over conventional approaches. The review had further analyzed essential aspects such as input features, model architectures, training strategies, and evaluation metrics. Moreover, limitations associated with adaptivity, scalability, data security, and data efficiency had been identified, and future research directions, including interdisciplinary design recommendations, had been proposed. Overall, the study had been considered a valuable contribution for guiding future research toward stable, secure, and efficient power systems.

Abdelwahab and Vokony (2026) had presented a comprehensive review of the global transition from synchronous generator-based power systems to inverter-based renewable energy systems and the associated stability challenges in weak grids. The study had explained that conventional Grid-Following (GFL) inverters became unstable under low Short-Circuit Ratio (SCR) conditions due to their reliance on grid voltage synchronization. It had critically examined the shift toward Grid-Forming (GFM) inverters, highlighting their ability to enhance stability in future renewable-dominated systems. The authors had reviewed key GFM strategies such as Droop Control and Virtual Synchronous Machine (VSM), comparing their power-sharing, frequency regulation, and virtual inertia characteristics in islanded and ultra-weak grids. Advanced mitigation approaches, including adaptive control and virtual impedance, had also been discussed along with their practical limitations. Furthermore, the paper had emphasized the emerging role of artificial intelligence in enabling self-tuning inverter control and had outlined future research directions for AI-augmented GFM inverters supported by robust verification and validation frameworks.

Zhang and Lin (2025) investigated the increasing complexity of modern power systems and emphasized that ensuring stable operation had become progressively difficult. They highlighted that the stability of the power grid was critical for a reliable power supply, and inaccuracies in its analysis could directly compromise system safety, presenting significant challenges to traditional analytical methods. To address this issue, they proposed an assessment approach integrating Convolutional Neural Networks (CNNs) for evaluating grid stability. Although CNNs had been widely applied in general power system analysis, their utilization specifically for power grid stability assessment was reported to be relatively limited. The study described that multi-dimensional operational data, including power, reaction time, and price elasticity coefficients, were first cleaned and normalized, and then fed into a constructed CNN model. Case studies were reported to demonstrate that the CNN approach significantly outperformed traditional methods and Multilayer Perceptron (MLP) models, achieving an accuracy of 92% and providing more precise judgments of grid stability.

Shen et al., (2025, June) reported that the increasing integration of inverter-based resources (IBR) had posed significant stability challenges for modern power systems. They observed that artificial intelligence (AI)-enabled methods were being developed to assess power system stability following contingencies, with algorithm development and validation typically conducted offline using existing datasets. The study indicated that advancements in AI-based solutions allowed the analysis of the expanding volume of power system data. The authors highlighted the role of digital twins (DT) as virtual replicas that continuously reflected the behaviours of physical systems, noting that a DT-based testbed provided a realistic and interactive environment for AI algorithm development, testing, and validation. They described a case study on AI-enhanced real-time transient stability assessment (RT-TSA) that demonstrated the practical utility of the DT-based testbed, where multiple algorithms were evaluated to identify the most suitable one based on offline accuracy and online execution time. The study concluded that DT-based testbeds had considerable potential to advance AI applications in power systems.

Hang et al. (2025, April) emphasized that, with the global push toward carbon neutrality, the integration of new energy sources into power systems had increased, making the assessment of system stability an urgent concern. They proposed an artificial intelligence-based method for steady-state analysis, which combined the Newton-Raphson method and PQ decomposition to compute power flow across the system. The study indicated that artificial intelligence techniques were subsequently applied to evaluate the reliability of results through analysis of error characteristics. Unlike conventional AI approaches, the method incorporated generative adversarial network-based data set expansion and a multi-scale fusion neural network model. The findings were reported to be validated using actual data from the East China Power Grid, which demonstrated the feasibility and practical applicability of the proposed AI algorithm in enhancing power system stability analysis.

Alhamrouni et al. (2024) comprehensively reviewed the emerging field of intelligent techniques aimed at enhancing power system stability, control, and protection. They noted that with increasing global energy demands and the integration of renewable sources, maintaining the reliability of both conventional power systems and smart grids had become critical, as traditional methods were reportedly insufficient to manage the complexity and dynamic behavior of modern grids. The study highlighted the adoption of advanced intelligence methods, including AI, machine learning, deep learning, metaheuristic optimization algorithms, fuzzy logic, reinforcement learning, and model predictive control, to address these challenges. The authors reported that these approaches were applied for predictive maintenance, fault detection, real-time monitoring, and control, demonstrating improved precision and efficiency in protection systems. They also discussed the role of fuzzy logic in decision-making under uncertainty, reinforcement learning for dynamic stability, and the integration of IoT and big data analytics for real-time system optimization. Case studies were cited to illustrate practical implementations, and the review concluded by identifying existing limitations and suggesting future research directions to develop more robust, flexible, and scalable intelligent systems in the power sector.

Li et al. (2024) reported that the pursuit of carbon neutrality had driven a notable increase in the adoption of renewable energy (RE), which in turn necessitated accurate energy generation forecasting, optimized power dispatch to minimize costs within operational constraints, effective system control to maintain stable electricity supply, and supportive electricity market mechanisms for bidding and trading decisions. They observed that uncertainties inherent in RE generation, particularly the intermittent nature of wind power, posed significant challenges for balancing real-time electricity supply and demand, often requiring reliance on traditional power sources and potentially raising electricity prices. The study highlighted that artificial intelligence (AI)-based methods, including machine learning, deep learning, and reinforcement learning, had been increasingly applied to enhance RE system forecasting, dispatch, control, and market operations. Furthermore, they suggested that these techniques were adaptable to a range of operational problems and emphasized emerging trends in RE system development, such as distributed installations, diversified energy storage, and increasingly complex market structures, which AI approaches could help address.

Liu et al. (2023) highlighted the increasing application of artificial intelligence (AI) for power system stability assessment, noting that AI offered faster evaluation compared to conventional time-domain methods. They reviewed four types of classical AI-based grid stability assessment methods reported in recent literature, summarizing and comparing various AI algorithms employed in these studies. The authors emphasized that, with the growing prevalence of power converters using grid-forming control in modern systems, the impact of converter parameters on grid stability warranted careful investigation. In this regard, they introduced the concept of converter-dominated power system state of stability (CDPS-SOS) assessment, discussing qualitatively how AI could be used to evaluate system stability margins while accounting for converter control parameters and grid bus voltages. Overall, the study aimed to provide a comprehensive overview of AI-based stability assessment approaches for traditional grids and offered a conceptual framework to address emerging challenges in future converter-dominated power systems.

Sulaiman et al. (2023) examined the integration of widely distributed smart grid components into modern power systems, emphasizing their secure linkage through extensive communication networks. They reported that these components facilitated applications such as distributed energy management, system state forecasting, and cyberattack security, generating large volumes of data that enhanced automation and efficiency within the smart grid. The study highlighted the limitations of traditional computing approaches in handling this data and noted that AI-based techniques had gained substantial attention. Specifically, Long Short-Term Memory (LSTM) and recurrent Neural Networks (RNN) were developed to capture the adaptive temporal dynamics of energy systems influenced by Revised Encoding Schemes or system reconfiguration. The authors described a federated learning strategy that allowed consumers to share power data via edge clouds, preserving privacy while remaining communication-efficient. They also formulated optimization problems for Energy Data Owners and service operations, considering non-independent and identically distributed data effects. Simulation results indicated that the LSTM model, despite longer training times and higher training loss, effectively detected false data injection attacks and incentivized high-quality local modeling, improving overall system performance.

Afridi et al. (2022) discussed that, following the depletion of fossil fuels, global reliance on renewable energy sources had increased significantly over the years. They highlighted that, in response to growing energy demands and the need for energy security, complex and hybrid generation systems were being developed. The study indicated that uninterrupted power supply and technological improvements were strongly dependent on effective and fault-resilient Operation & Maintenance (O&M) systems. The authors reported that various innovative algorithms and techniques had been introduced to minimize equipment and plant downtime and that robust prognostic maintenance systems were being designed to identify faults before occurrence. They observed that complex data analytics and Artificial Intelligence (AI) algorithms were increasingly employed to enhance the efficiency of these systems. The paper reviewed predictive and prognostic maintenance frameworks from existing literature, focusing on approaches, challenges, and data-related issues, including data quality, feature engineering, interpretability, and security. They also examined publicly available datasets commonly used in the domain and identified future research directions to improve prognostic maintenance practices.

Phosung et al. (2021) investigated the instability issues arising in electrical power systems where most loads were actively controlled power electronics converters, which behaved as constant power loads and exhibited small-signal negative impedance, thereby potentially reducing system stability margins and performance. The study highlighted that while active damping approaches were commonly employed for instability mitigation, applying such methods at the load side could adversely affect load performance. To address this, the authors proposed a novel instability mitigation design based on an artificial intelligence technique, specifically the adaptive tabu search algorithm. The findings indicated that the proposed method enabled the power system to maintain stable operation up to rated power and improved load performance compared to conventional design approaches. Furthermore, the study reported strong consistency among theoretical analyses, simulation results, and experimental validations.

III. KEY FINDINGS FROM STUDY

Author (Year)	Study Focus	Methodology	Key Findings
Murugesan et al. (2026)	Renewable energy forecasting and grid stability	Review of statistical and deep learning forecasting models	Deep learning significantly improved forecasting accuracy, supporting grid stability through better frequency regulation and demand response mechanisms
Muhammed et al. (2026)	Deep learning applications in power system stability and cybersecurity	Systematic review of DLT architectures and applications	DLTs improved dynamic and cyber-physical stability analysis, but challenges remain in scalability, security, and data efficiency
Abdelwahab & Vokony (2026)	Stability of inverter-based power systems	Comparative review of grid-following and grid-forming inverters	Grid-forming inverters enhance stability in weak grids; AI supports adaptive inverter control and virtual inertia
Zhang & Lin (2025)	AI-based power grid stability classification	CNN-based predictive model using multi-dimensional data	CNN achieved ~92% accuracy, outperforming MLP and traditional methods in stability assessment
Shen et al. (2025)	AI-enabled stability assessment using digital twins	Digital twin-based simulation and AI validation framework	Digital twins improved real-time transient stability analysis and enhanced AI model testing accuracy
Hang et al. (2025)	Steady-state power system stability evaluation	Hybrid model (Newton-Raphson + AI + GAN augmentation)	AI-enhanced power flow analysis improved stability evaluation accuracy and robustness
Alhamrouni et al. (2024)	AI in power system stability, control, and protection	Comprehensive literature review of AI/ML/RL methods	AI techniques improved fault detection, prediction, control, and protection in smart grids
Li et al. (2024)	Renewable energy system operation and optimization	Review of AI/ML/DL/RL applications	AI improved forecasting, dispatch optimization, and market operation under renewable uncertainty
Liu et al. (2023)	AI-based stability assessment in converter-dominated grids	Conceptual framework and comparative review	AI enables fast stability assessment; converter parameters strongly influence grid stability
Sulaiman et al. (2023)	Smart grid security and forecasting	LSTM, RNN, federated learning approach	LSTM improved anomaly detection; federated learning ensured privacy and efficient distributed learning

Afridi et al. (2022)	Predictive maintenance in renewable energy systems	Review of AI-based prognostic maintenance techniques	AI improved fault prediction, reduced downtime, but data quality and interpretability remain challenges
Phosung et al. (2021)	Stability of AC–DC systems with constant power loads	AI-based adaptive tabu search optimization	Proposed AI method improved system stability and load performance under dynamic conditions

IV. CONCLUSION

The study on Power System Stability Analysis Using Artificial Intelligence-Based Predictive Models highlights the significant transformation occurring in modern electrical power systems due to the integration of renewable energy sources, smart grid technologies, and advanced computational intelligence techniques. It is evident from the reviewed literature that traditional stability analysis methods, which were primarily based on deterministic and linear assumptions, are becoming less effective in handling the nonlinear, dynamic, and uncertain behavior of contemporary power systems. The increasing penetration of inverter-based resources, variability in renewable energy generation, and complexity of interconnected grids have introduced new stability challenges that require adaptive, data-driven, and real-time analytical approaches. In this context, artificial intelligence (AI), including machine learning, deep learning, reinforcement learning, and hybrid predictive models, has emerged as a powerful solution for improving stability assessment, forecasting accuracy, and system reliability. Studies have demonstrated that AI-based models such as convolutional neural networks, long short-term memory networks, and hybrid optimization frameworks significantly outperform conventional methods in detecting instability, predicting system behavior, and supporting decision-making processes under dynamic operating conditions (Zhang & Lin, 2025; Muhammed et al., 2026). Furthermore, the integration of digital twin technology has enhanced the realism and effectiveness of AI-based stability evaluation by enabling continuous simulation and validation of power system behavior under real-world scenarios (Shen et al., 2025). In addition, AI applications in predictive maintenance, fault detection, and renewable energy forecasting have contributed to reducing operational risks, improving system resilience, and optimizing power dispatch strategies (Afridi et al., 2022; Li et al., 2024). Despite these advancements, several challenges remain, including data quality limitations, cybersecurity concerns, model interpretability issues, and scalability constraints in large interconnected systems. Moreover, the transition toward converter-dominated grids requires more robust AI frameworks capable of handling complex interactions between grid-forming and grid-following inverters under weak grid conditions (Abdelwahab & Vokony, 2026). Therefore, future research must focus on developing hybrid AI-physics-based models, federated learning systems, and adaptive real-time predictive frameworks to ensure reliable and secure grid operations. Overall, AI-based predictive modeling represents a critical advancement in modern power system stability analysis, offering a pathway toward intelligent, resilient, and sustainable energy systems capable of meeting future global energy demands.

V. FUTURE SCOPE

The future of Power System Stability Analysis Using Artificial Intelligence-Based Predictive Models is highly promising, as the ongoing transformation of electrical grids toward renewable energy integration, decentralization, and digitalization continues to accelerate. One of the most significant future directions is the development of hybrid AI-physics-based models that combine the interpretability of traditional power system theory with the predictive strength of machine learning and deep learning algorithms. Such hybrid frameworks can improve both accuracy and reliability in stability assessment while maintaining physical consistency with grid behavior. Another important area is the advancement of real-time adaptive learning systems capable of continuously updating themselves using streaming data from smart grids, Phasor Measurement Units (PMUs), and Internet of Things (IoT) devices, enabling faster response to disturbances and dynamic changes in grid conditions. The integration of digital twin technology is also expected to expand further, providing highly accurate virtual replicas of power systems for continuous monitoring, simulation, and predictive control, thereby enhancing operational decision-making and system resilience. Additionally, reinforcement learning-based control strategies are likely to play a major role in autonomous grid management, particularly in optimizing voltage stability, frequency regulation, and demand-response coordination in complex renewable-dominated networks. Federated learning approaches will also become increasingly important for ensuring data privacy and cybersecurity while enabling collaborative model training across distributed energy resources without sharing sensitive data. Furthermore, AI-driven stability analysis will benefit from improved explainable AI (XAI) techniques, which will enhance transparency and trust in critical decision-making processes within power system operations. Future research is also expected to focus on converter-dominated grid stability, where grid-forming inverter control strategies combined with AI-based optimization will be essential for ensuring system robustness under low inertia conditions. Overall, the continued evolution of artificial intelligence, advanced communication networks, and smart grid infrastructure will significantly enhance predictive capabilities, making future power systems more intelligent, secure, resilient, and sustainable.

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