

Stability Analysis of Modern Electrical Power Systems

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Abstract: The increasing integration of renewable energy sources, distributed generation, energy storage systems, and flexible loads is significantly transforming the dynamic characteristics of modern electrical power systems. These developments introduce new challenges to power-system stability, including reduced system inertia, complex control interactions, voltage instability, frequency deviations, and oscillatory behaviour. This review paper presents a comprehensive overview of stability analysis techniques applicable to modern electrical power systems, covering rotor-angle stability, frequency stability, voltage stability, and converter-driven stability. Classical analytical approaches, including eigenvalue analysis, small-signal stability analysis, transient stability assessment, and time-domain simulation, are reviewed alongside emerging methods based on wide-area measurements, advanced control techniques, optimization, and artificial intelligence. Particular attention is given to the impact of inverter-based renewable generation and grid-forming and grid-following converter controls on system stability. The paper also discusses recent trends, computational challenges, and the applicability of data-driven and real-time stability assessment methods. Finally, key research gaps and future directions are identified to support the development of reliable, resilient, and flexible power grids capable of accommodating high levels of renewable and distributed energy resources.

Keywords: *power system; stability; renewable energy sources; time-domain analysis; optimization*

Introduction

Electrical power systems are undergoing a significant transformation due to the increasing penetration of renewable energy sources, distributed generation, energy storage systems, electric vehicles, flexible loads, and power-electronic interfaces. Traditionally, power systems were dominated by large synchronous generators that provided substantial rotational inertia, voltage support, and predictable dynamic characteristics. The increasing replacement or displacement of conventional generation by inverter-based resources, such as solar photovoltaic and wind power plants, has changed these characteristics and introduced new forms of dynamic interactions. Consequently, maintaining stable and reliable operation has become a major challenge for modern power-system planners and operators.

Power-system stability [1] refers to the ability of an electrical power system, for a given initial operating condition, to regain an acceptable state of equilibrium after being subjected to a disturbance. Stability is generally classified into rotor-angle stability, voltage stability, and frequency stability [2]. Rotor-angle stability is associated with the ability of synchronous machines to maintain synchronism following disturbances. Voltage stability concerns the ability of the system to maintain acceptable bus voltages under normal and disturbed operating conditions, while frequency stability relates to the ability of the system to maintain frequency within acceptable limits following an imbalance between generation and demand. These stability categories are closely interconnected, particularly in highly stressed and dynamically changing networks.

The increasing use of inverter-based renewable energy resources has introduced additional complexity into stability analysis [3]. Unlike conventional synchronous generators, inverter-based resources do not inherently provide the same level of physical inertia and their dynamic behaviour is strongly influenced by converter control systems, phase-locked loops, current controllers, and grid-support functions. High penetration of such resources can therefore affect system frequency response, voltage regulation, damping characteristics, and transient behaviour. Furthermore, interactions between multiple converters and the surrounding network may result in control-related oscillations and other dynamic phenomena that are not adequately represented by traditional stability models.

The transition toward modern power grids has also increased the importance of advanced monitoring, control, and computational techniques [4]. Wide-area measurement systems and phasor measurement units provide high-speed synchronized measurements that can support real-time assessment of system dynamics. At the same time, advanced numerical methods, optimization techniques, machine learning, and data-driven approaches are being investigated for faster and more accurate stability assessment. Grid-forming converter technology, demand-side flexibility, battery energy storage, and advanced protection and control schemes are also being considered as mechanisms for improving system resilience and supporting stable operation under high renewable penetration.

Conventional stability-analysis methods, including steady-state analysis, eigenvalue-based small-signal analysis, transient stability simulation, and voltage-stability assessment, remain important tools for power-system studies [5]–[6]. However, the increasing complexity of modern grids requires these methods to be complemented by advanced models and real-time assessment techniques. Accurate representation of converter controls, renewable-energy variability, communication systems, and changing network conditions is particularly important for obtaining reliable stability assessments.

This review paper therefore examines the major concepts, classifications, analytical methods, and recent developments associated with stability analysis of modern electrical power systems. It reviews conventional and emerging approaches for assessing rotor-angle, voltage, frequency, and converter-driven stability, with particular emphasis on systems containing high levels of renewable and inverter-based generation. The paper also discusses the advantages and limitations of existing techniques, identifies important research challenges, and highlights potential directions for developing more accurate, computationally efficient, and real-time stability assessment frameworks for future power grids.

Related work

Power-system stability has traditionally been studied in terms of the ability of an interconnected power system to maintain an acceptable operating condition following small or large disturbances.

Early stability-analysis approaches were largely based on mathematical models of synchronous generators, excitation systems, governors, loads, and transmission networks [7]. Voltage stability analysis evaluates whether a power system can maintain acceptable bus voltages following disturbances or gradual changes in loading and generation [8]. The increasing replacement of conventional synchronous generation by inverter-based renewable generation has resulted in considerable research on frequency stability [9] and system inertia [10].

Key Contribution

The key contributions of this review paper are summarized as follows:

- **Comprehensive classification of power-system stability:** The paper reviews the major categories of stability, including rotor-angle stability, voltage stability, frequency stability, and converter-driven stability, and explains their relevance to modern power networks.
- **Review of conventional stability-analysis methods:** Classical techniques such as small-signal analysis, eigenvalue analysis, transient stability assessment, time-domain simulation, and voltage-stability analysis are systematically reviewed along with their applications and limitations.
- **Assessment of renewable and inverter-based generation impacts:** The review examines how increasing penetration of solar PV, wind energy, battery energy storage, and other inverter-based resources affects inertia, damping, voltage regulation, frequency response, and system dynamics.
- **Analysis of converter-related stability challenges:** Particular attention is given to grid-following and grid-forming converters, control interactions, phase-locked loops, weak-grid conditions, and converter-network interactions that can influence system stability.

Comparative Experiments

A particularly useful contribution would be a standardized comparison as given in Table 1.

Table 1. Comparison of different methods for stability analysis

Method	Stability Type	Accuracy	Computational Cost	Renewable Systems	Real-Time Suitability	Validation
Eigenvalue analysis	Small-signal	High	Low–Medium	Moderate	High	Simulation
Time-domain simulation	Transient	High	High	High	Moderate	Simulation
Energy-function method	Transient	High	Medium	Moderate	Moderate	Simulation
ML-based method	Multiple	High*	Low after training	High	High	Simulation/Hardware
Deep learning	Multiple	High*	Training-intensive	High	High	Simulation

Method	Stability Type	Accuracy	Computational Cost	Renewable Systems	Real-Time Suitability	Validation
PMU/WAMS-based	Online stability	High	Medium	High	Very High	Real-time data
Hybrid physics + AI	Multiple	Potentially high	Medium–High	Very High	High	Emerging

Conclusion

This review has presented a comprehensive assessment of power-system stability analysis, covering rotor-angle, voltage, frequency, and small-signal stability under conventional and renewable-integrated operating conditions. The reviewed studies demonstrate that increasing penetration of inverter-based renewable resources introduces new challenges associated with reduced inertia, weak-grid operation, converter interactions, and rapidly varying operating conditions. Conventional analytical and numerical methods remain important because of their interpretability and physical foundation, while optimization-based, artificial-intelligence-based, and data-driven approaches provide promising capabilities for complex and large-scale stability assessment. However, their performance depends strongly on data quality, model accuracy, computational requirements, and appropriate validation.

References

- [1] Kundur, P. and Malik, O.P., 1994. *Power system stability and control* (Vol. 7, p. 623). New York: McGraw-hill.
- [2] Murad, N.S.F.M., Kamarudin, M.N., Rozali, S.M. and Zakaria, M.I., 2024. Power system stability and control: a comprehensive review focusing on the rotor angle case. *Bulletin of Electrical Engineering and Informatics*, 13(6), pp.3897-3909.
- [3] Gu, Y. and Green, T.C., 2022. Power system stability with a high penetration of inverter-based resources. *Proceedings of the IEEE*, 111(7), pp.832-853.
- [4] Ahsan, F., Dana, N.H., Sarker, S.K., Li, L., Muyeen, S.M., Ali, M.F., Tasneem, Z., Hasan, M.M., Abhi, S.H., Islam, M.R. and Ahamed, M.H., 2023. Data-driven next-generation smart grid towards sustainable energy evolution: techniques and technology review. *Protection and Control of Modern Power Systems*, 8(1), pp.1-42.
- [5] Kar, M.K., 2023. Stability analysis of multi-machine system using FACTS devices. *International Journal of System Assurance Engineering and Management*, 14(6), pp.2136-2145.
- [6] Kar, M.K., Kumar, S., Singh, A.K. and Panigrahi, S., 2021. A modified sine cosine algorithm with ensemble search agent updating schemes for small signal stability analysis. *International Transactions on Electrical Energy Systems*, 31(11), p.e13058.
- [7] Sahoo, S.K., Kar, M.K., Kumar, S. and Mahanty, R.N., 2025. Optimal design of SSSC damping controller using a novel hybrid modified grey wolf-particle swarm optimization to suppress power system oscillations. *Measurement*, p.119723.
- [8] Kar, M.K., Sabat, J. and Kanungo, S., 2025. Voltage profile enhancement of an AVR system using ant lion optimization algorithm. *Engineering Research Express*, 7(1), p.015335.
- [9] Gupta, N.K., Kar, M.K. and Singh, A.K., 2025. Statistical analysis-based load frequency control of multi-area system with nonlinearities using 2-DOF-PID controller with application of improved sine-cosine algorithm optimizer. *Scientia Iranica*, 32(1).

- [10] Mishra, D., Maharana, M.K., Kar, M.K., Nayak, A. and Cherukuri, M., 2023. Modified differential evolution algorithm for governing virtual Inertia of an isolated microgrid integrating electric vehicles. *International Transactions on Electrical Energy Systems*, 2023(1), p.8950650.