Proceedings of the 3rd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/147/2025.22914

Stability Analysis and Optimization of Power Grids with High Penetration of Renewable Energy: A Comprehensive Review

Jingda Hu

School of Engineering, University of Birmingham, Birmingham, United Kingdom
jxh1676@student.bham.ac.uk

Abstract: The growth of renewable energy capacity has transformed global power systems. However, with this trend, grid stability is facing increasing challenges, especially due to reduction in system inertia. This comprehensive review investigates the impacts of high renewable energy penetration on power grid stability, focusing on small-signal stability analysis and the Lyapunov method. With case studies, it highlights how the reduced inertia affects stability of the grids. By combining the advantages of small signal analysis and Lyapunov method, a hybrid approach is proposed to improve grid resilience, offering a pathway to optimize stability in low-inertia systems.

Keywords: Renewable energy, Power grid stability, Small-signal, Lyapunov.

1. Introduction

The environmental pollution caused by power generation receives more attention with the increasing global environmental issues. Fossil fuels contribute the most to global climate change, accounting for over 75% of global greenhouse gas emissions and nearly 90% of all carbon dioxide emissions. The emissions need to be reduced by almost 50% by 2030 and reach net zero by 2050 to avoid the worst impacts of climate change [1]. With the support of the polices of most countries and the lower cost, the growth in renewable energy capacity is expected to rise with wind power and solar PV making up a record 96% of this increase over the next five years [2]. While renewable energy offers both environmental and economic benefits, its integration brings challenges to the inertia of the power system. The power system inertia refers to the capacity of a power system to oppose system frequency changes caused by resistance provided by rotating masses. The level of inertia in a system depends on the kinetic energy stored in the rotating components of synchronously interconnected machines, including different types of generators and synchronously operating motor loads [3]. A larger inertia means better stability of the power system. Since wind and solar systems are connected to the grid through non-synchronous inverters, these systems do not provide inertia inherently [4]. If the scale of integration of renewable energy is large, synchronous generators will be replaced, resulting in a reduction in system inertia. Insufficient inertia of the power system will affect its stability and even cause the collapse of the system. The '8.9' Blackout in Britain and the '2.15' Blackout in Texas, USA are both major electrical accidents caused by low inertia in recent years [5]. Small-signal analysis and the Lyapunov method are both widely used in the stability analysis of power systems. This paper presents a comparative study of the two methods for stability analysis of power grids with high penetration of renewable energy. This paper reviews the stability challenges introduced by high renewable penetration. Two major

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DOI: 10.54254/2755-2721/147/2025.22914

analytical methods—small-signal and Lyapunov—are critically examined, and then a combined framework is proposed.

2. Small-signal Analysis

A method for analyzing small-signal stability in power systems is proposed by optimizing an eigenvalue objective function along parameter rays [6]. Eigenvalues determine the stability of the system. When the eigenvalues are complex values, the damping refers to the real part of the eigenvalues, and the frequency of oscillation refers to the imaginary part [7]. It identifies key stability points, such as oscillation damping limits and load flow boundaries, using constraints from load flow equations and dynamic state matrix properties. With results dependent on initial guesses and numerical methods, the approach provides a comprehensive stability characterization.

Small-signal stability analysis is an important method for evaluating the dynamic behavior of a power system under perturbations around an operating point. This approach provides critical insights into the oscillations and inertia of the system. With the rising integration of renewable energy sources, grids with traditional synchronous generators are facing new stability challenges due to reduced inertia and increased variability. Low inertia affects the frequency stability and weakens damping, necessitating robust analytical methods to ensure grid reliability. Small-signal analysis has been widely used to study stability in power systems with reduced inertia due to renewable energy system integration.

In microgrids with wind and PV sources, small-signal stability and low inertia arises from the lack of traditional rotating masses [8]. The approach, which is based on eigenvalues, reveals risks of oscillation, establishing small-signal analysis as a key method for low-inertia microgrid studies. Small-signal stability is examined in a wind and PV generation system using modal analysis [9]. Critical modes are exacerbated by low inertia is identified, and the ability of the method to access frequency stability in decentralized and renewable energy systems is demonstrated. Small-signal analysis is applied to systems with significant renewable generation with low inertia [10]. The linearized model shows that a controlled renewable energy system can improve damping, underscoring the role of the method in mitigating low-inertia effects. A synchronous motor generator pair is proposed to improve stability in low inertia systems with high renewable energy penetration [11]. Eigenvalue analysis indicates enhanced damping compared to standalone generators, validated experimentally, highlighting small-signal analysis's utility in evaluating inertia-augmentation strategies. The adaptability of small-signal to hybrid, renewable energy-dominated configurations is shown by time-domain simulations with simplified transfer functions confirming power-frequency balance despite low inertia [12]. By analyzing small-signal stability in a wind and PV power system with low inertia, renewable energy system contributions enhance damping and frequency recovery are shown via eigenvalue analysis using the New England test system [13]. The effectiveness of small-signal analysis in a low inertia system is illustrated. For a 100% renewable energy system, small-signal analysis is brought into low-inertia grids by exploring small-signal synchronous stability in a fully renewable, converter-domain system lacking traditional inertia [14].

3. Lyapunov Method

In renewable energy systems with low inertia, traditional small-signal analysis falls short in capturing large transient events. The Lyapunov method provides a robust framework for analyzing the large signal stability of nonlinear systems.

For inverter stability, the model of a DC/AC inverter as an electrostatic machine is proposed, deriving a Lyapunov function using Popov's theorem to assess its stability when feeding an infinite

DOI: 10.54254/2755-2721/147/2025.22914

bus [15]. The study quantifies the inverter's ability to maintain synchronously under large disturbances, critical in low-inertia microgrids. An energy function for a droop-controlled inverter in a single micro source infinite bus system is developed, by estimating critical clearing times under voltage drops, the adaptability of the method in evaluating transient stability in low inertia systems is highlighted [16].

For converters, the large signal stability of the three-phase AC/DC rectifier is analyzed using a singular perturbation approach and Lyapunov function, showing inductance ensures stability in a low-inertia system [17]. The study related to DC microgrids with renewable inputs addressing large transients in a low-inertia environment [18].

For loads and systems, the Takagi-Sugeno multi-modeling approach is used to generate a Lyapunov function for a DC/AC motor drive system, assessing stability under load transients [19]. Through the investigation of the large signal stability of a hybrid AC-DC aircraft power system with constant power load, the stability in low inertia, converter-dominated systems is highlighted [20]. The study of applying Lur'e's method to develop a Lyapunov function for a microgrid comprising a synchronous generator and a DC motor load evaluates critical clearing times under faults, relevant for hybrid renewable systems with partial inertia [21].

For traditional adaptations, the Boundary Controlling Unstable Equilibrium Point (BCU) method for transient stability analysis is introduced [22]. The principles of the method are adaptable to renewable microgrids, addressing low inertia transient events. The energy function methods for transient stability are reviewed, applicable to low-inertia renewable systems where synchronism is challenged by intermittent renewable energy system inputs [23]. The approach uses Lyapunov methods and offers insights into modeling renewable microgrids while retaining critical low inertia dynamics [24].

4. Comparative Analysis

Small-signal analysis excels at identifying oscillation modes and damping ratios in low inertia environments [8,10,12,14]. This precision is important for diagnosing stability risks arising from reduced rotational mass. By linearizing dynamics around operating points, the method simplifies the study of low-inertia systems, enabling efficient computation despite renewable energy system variability [9-11]. The applicability of small-signal analysis spans microgrids [8], distribution networks [9], hybrid systems [13], and fully converter-based grids [14], demonstrating versatility in addressing diverse low inertia scenarios. Despite its strengths, the method also faces significant challenges in low-inertia environments. It can be inferred that, limited to small disturbances, the method cannot predict stability under large signal events, which is common in low-inertia systems [8-14]. In low-inertia systems with fluctuating renewable energy system outputs, accurate linearization is difficult [9-10]. The wrong selection of operating point can misrepresent stability when inertia is low. By focusing on linear approximations when using small-signal analysis, nonlinear interactions amplified by low inertia are overlooked [13,14]. Current studies usually assume network models are static and ignore dynamic interactions that are pronounced in low inertia grids, limiting real-world applicability [11-12].

The Lyapunov method assesses stability under large disturbances, which is important for renewable energy systems' variability [15,16,20]. The method captures converter nonlinearity can be captured by the Lyapunov method [17,18], prevalent in low inertia grids. To enhance the low-inertia system resilience, with analyzed stability boundaries from the method, the component sizing can be improved [19,21]. The region of attraction is often underestimated [19,20], potentially over-constraining designs in low-inertia systems with variable RES inputs. Constructing Lyapunov functions for multi-converter systems [21,24] is computationally intensive, particularly in low-inertia microgrids with numerous nonlinear elements. Simplified assumptions (e.g., infinite bus)

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may not hold in fully islanded, low inertia microgrids, limiting real-world applicability [15,16]. As system order increases, methods like Takagi-Sugeno scale exponentially, posing challenges for complex, low-inertia renewable networks [19]. Some studies lack extensive simulation or experimental validation, reducing confidence in applying results to dynamic, low-inertia systems [17].

Building on the complementary strengths and limitations of these methods, a hybrid approach emerges as a promising solution to address the multifaceted stability challenges of low-inertia systems. By integrating small-signal analysis's precision in steady-state monitoring with the Lyapunov method's robustness in transient analysis, this framework not only bridges their analytical gaps but also enables practical innovations. These include optimizing control parameters for virtual synchronous generators (VSGs) to emulate traditional inertia and implementing real-time monitoring to dynamically stabilize grids under renewable variability, offering grid operators comprehensive tools to ensure reliability in renewable-dominated networks.

5. Future Prospects for Innovation

5.1. Hybrid stability Framework

Small-signal analysis excels in linear dynamics with eigenvalue and modal analysis, while the Lyapunov method is more suitable for nonlinear systems. The combination of the two methods can be used as a hybrid stability framework, suitable for both small perturbations and large transients. According to research, with small-signal analysis, the oscillation modes is identified in a renewable energy system, and the tolerance to large disturbances drops or load steps is quantified through Lyapunov methods [14-16]. In low-inertia systems with reduced traditional rotating mass by renewable energy, this framework reduces oscillation risks and transient instability by combining steady-state precision with large-disturbance robustness [5]. This framework addresses small-signal analysis's limitation to large signals and makes the modeling process using Lyapunov easier. In this hybrid approach, ritical frequency and damping characteristics is determined by using small-signal analysis, stability boundaries under specific conditions are estimated by Lyapunov function. With linear and nonlinear analysis, such a combination bridges their analytical gap.

5.2. Control Parameter Optimization

Virtual Synchronous Machines (VSGs) is an important solution in renewable energy systems, emulating the inertia and damping of conventional synchronous generators to enhance grid stability [25]. Small-signal analysis can efficiently optimizes control parameters under steady-state conditions, such as tuning virtual synchronous generator parameters to enhance damping [14], while Lyapunov methods ensure robustness under large perturbations, as in inverter stability design post-fault [15]. Combining them enables control optimization across steady-state and transient regimes. For example, in high-RES penetration systems, small-signal analysis can adjust frequency regulation gains [12], and the Lyapunov methods [21] can validate these parameters. In low-inertia grids, where the lack of physical inertia weakens frequency stability [4], this approach directly compensates by fine-tuning VSGs to mimic traditional generators. Theoretically, this provides a multi-objective optimization foundation, balancing damping and transient tolerance. Practically, it enhances frequency and voltage stability in low-inertia grids. Grid operators rely on this innovation to maintain stability as renewable penetration grows, mitigating risks like the Texas '2.15' blackout, where insufficient inertia led to collapse [5].

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5.3. Real-Time Monitoring and Implementation

Small-signal analysis's efficiency suits real-time monitoring, such as assessing system state from frequency data [12], while Lyapunov's analytical solutions (e.g., BCU method) provide stability thresholds. Their combination enables dynamic stability monitoring [22]. For example, in a low-inertia microgrid, small-signal analysis can compute damping ratios and oscillation frequencies in real-time, while Lyapunov functions update the region of attraction based on current conditions (e.g., PV output changes), predicting tolerance to upcoming disturbances. This can be data-driven: sensors collect real-time states (e.g., voltage, power), small-signal models analyze rapidly, and Lyapunov functions adjust dynamically, offering warnings and control suggestions. In a 100% RES system, this monitoring can assess GFL and GFM converter synchronism in real-time, guiding dynamic adjustments (e.g., increasing virtual inertia) to prevent instability [14]. In low-inertia systems, where RES variability heightens instability risks, this directly addresses rapid fluctuations by providing continuous stability insights [5]. Theoretically, this extends stability analysis from static to dynamic, introducing time dependency. For grid operators, this is vital to avert cascading failures, offering real-time tools to stabilize grids under unpredictable renewable behavior.

6. Conclusion

The global shift toward decarbonization accelerates the integration of renewable energy sources (RES) into the power grids, reducing system inertia and introducing significant stability challenges. This review addressed these issues by comparing small-signal analysis and the Lyapunov method. With the result of the comparative analysis, it can be found that small-signal analysis is not suitable for large-signal events but it provides efficient calculation, while the Lyapunov method lacks in efficiency but suitable for large perturbation.

Based on this, the study proposes a hybrid framework that integrates small-signal and Lyapunov methods, bridging linear and nonlinear stability analysis to improve the resilience in low-inertia systems. This innovation finds practical grounding in the China Southern Grid (CSG), managing high renewable integration in five provinces. Small-signal analysis detects frequency oscillations, while Lyapunov-based approaches evaluate transient stability, highlighting the hybrid approach's strengths. Additionally, the framework supports more applications, such as optimizing virtual synchronous generators (VSGs) and real-time stability monitoring, addressing both steady-state and transient stability [25]. Future research is recommended to focus on simplifying Lyapunov function construction and developing efficient algorithms for real-time use. CSG's Yunnan asynchronous grid pilot, could be a validation scenario.

In conclusion, with the rise of renewable integration, advanced stability analysis becomes more and more important. This review demonstrates that the hybrid framework, supported by method comparison and practical relevance in systems like CSG, offers a robust solution, combining technical innovation with the a carbon-neutral energy future.

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