

Frequency Stability Assessment and Synthetic Inertia in Low-Inertia Power Systems: A Comprehensive Review

Jennifer Ugochukwu Njonu, Boyi Jimoh, Mohammed Musa, Sulaiman Haruna, Bashir Musa Umar,
and *David Enemali Abah

Ahmadu Bello University, Zaria, Kaduna State, Nigeria.

*Corresponding authors' email: deabah@abu.edu.ng

ABSTRACT

The rapid integration of inverter-based renewable energy sources (RESs), particularly solar photovoltaic (PV) and wind power, has significantly reduced the rotational inertia traditionally provided by synchronous generators, creating unprecedented challenges for frequency stability in modern power systems. Reduced system inertia results in higher rates of change of frequency (RoCoF), deeper frequency nadirs, and increased vulnerability to disturbances, necessitating advanced frequency assessment and synthetic inertia solutions. This paper presents a comprehensive review of frequency stability assessment methods and synthetic inertia techniques for low-inertia power systems. First, the fundamental principles of frequency dynamics, inertial response, and the impact of renewable energy penetration on system inertia are discussed. Subsequently, recent advances in deterministic and probabilistic frequency stability assessment methodologies are reviewed, followed by a critical evaluation of virtual synchronous machines, droop-based virtual inertia, model predictive control, battery energy storage systems, grid-forming converters, and intelligent control strategies for synthetic inertia provision. A comparative analysis of existing studies highlights their methodologies, performance metrics, advantages, and practical limitations. The review further identifies key research challenges, including uncertainty modeling, adaptive inertia allocation, converter operational constraints, computational complexity, and real-time implementation. Finally, future research directions toward uncertainty-aware frequency assessment, adaptive synthetic inertia, artificial intelligence-assisted control, and resilient converter-dominated power systems are discussed. This review provides a comprehensive reference for researchers and power system engineers developing reliable frequency stability enhancement strategies for future renewable-dominated electricity networks.

Received: 21 Sep. 2026

Accepted: 09 Oct. 2026

Published: 12 Oct. 2026

Keywords:

Frequency stability, Low-inertia power systems, Synthetic inertia, Virtual inertia, Grid-forming inverter, Grid-following inverter

INTRODUCTION

Global energy transitions have accelerated the integration of renewable energy sources (RES) to mitigate climate change and reduce fossil fuel dependency (Buire et al., 2026). Unlike conventional synchronous generators, which inherently provide rotational inertia through their kinetic energy storage, solar PV systems interface with the grid via power electronic inverters that decouple mechanical dynamics from electrical frequency response. Consequently, high PV penetration diminishes system inertia, amplifying frequency transients during generation-load imbalances (Al-azzawi, 2024). Traditional primary and secondary frequency control loops (governor droop and LFC) are increasingly strained under these conditions, as reduced inertia elevates ROCOF and deepens frequency nadirs (Saleem & Saha, 2024). While virtual inertia, energy storage systems, and AI-based controllers have been proposed, many suffer from high computational overhead, limited generalizability, or reliance on deterministic modeling that fails to capture real-world stochasticity.

The widespread adoption of RESs has surged due to the depletion of fossil fuel reserves and increasing environmental concerns (Ratnam et al., 2020). The transition from traditional synchronous generator-based energy sources (SGESs) to inverter-based RESs introduces fundamental changes to

power generation, creating distinct challenges for maintaining grid frequency stability (Ratnam et al., 2020). A key issue arises from the inherent absence of rotational inertia in inverter-based RESs, leading to a decline in overall system inertia as the penetration of these energy sources within power grids grows (Ratnam et al., 2020).

The inherent volatility and unpredictability of RESs, such as solar and wind, pose significant challenges to power system operations (Younis et al., 2017). Replacing conventional synchronous generators (SGs) with a large number of power electronic inverters enhances efficiency, stability, power quality, and operational flexibility. However, managing power among these sources presents considerable challenges in system design and monitoring (Younis et al., 2017).

In recent times, only a few countries like Denmark, Uruguay, Germany, India, Ireland, Portugal and Spain successfully integrated significant shares of RESs into their main power grids. Denmark led with nearly 53% RES penetration, followed by Uruguay at 28% and Germany at 26%. Other nations, including India, Ireland, Portugal, and Spain, also achieved RES penetration levels exceeding 20%. Figure 1 illustrates the RES power generation shares of various countries in 2017 and their respective targets for 2050 (Ratnam et al., 2020).

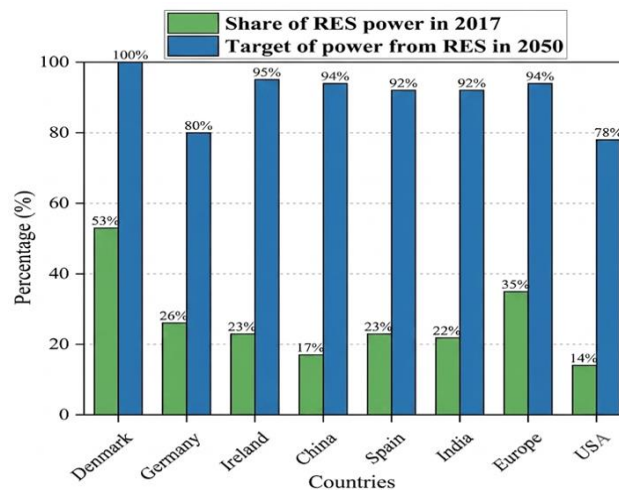


Figure 1: RES share for different countries in 2017 and 2050 (Ratnam et al., 2020)

The large-scale integration of renewable energy sources (RESs) into power grids introduces significant challenges related to frequency stability. Unlike conventional power systems, RESs typically provide little to no inertial response. For example, photovoltaic (PV) arrays rely on power electronic DC–AC inverters for grid integration, which do not contribute to grid inertia. Similarly, wind turbines use variable-frequency AC–DC–AC converters, effectively decoupling their mechanical inertia from the grid (Gulzar et al., 2022).

As a result, the overall inertia of the power system diminishes with higher RES penetration (Seneviratne & Ozansoy, 2016). This reduction in system inertia increases the rate of change of frequency (ROCOF) and exacerbates frequency deviations during power imbalances. Such rapid changes can significantly compromise the frequency stability of the grid, demanding advanced strategies to mitigate these effects (Seneviratne & Ozansoy, 2016).

The concept of power system stability is a significant focus in today's interconnected power systems. It refers to the ability of a power system to regain stability after disturbances are eliminated (Gulzar et al., 2022). In contrast, an unstable system loses control and can experience catastrophic consequences for the seamless operation of the power grid. Addressing stability issues has become an essential aspect of designing a dependable power system. Ensuring synchronicity between various components of the power system is a critical responsibility for power system engineers (Gulzar et al., 2022).

Generating electrical power must align with the demand on the load side, taking into account losses. A reliable power system operates within a specific range, but external factors can disrupt the system's frequency, pushing it into an unstable state (Gulzar et al., 2022). In contemporary power systems, frequency control is accomplished through a dual-loop approach. The primary loop focuses on averting frequency transients by employing governor droop, which can introduce steady-state errors. The secondary method, called automatic gain control or load frequency control, is responsible for maintaining the system's frequency at a stable level (Gulzar et al., 2022).

In power system, inertia is provided by the rotating masses of synchronous generators. When there is a sudden imbalance between generation and load, these rotating masses store kinetic energy and release it momentarily to slow down frequency changes. This inertial response helps maintain grid

stability by preventing rapid frequency deviations. However, RES such as solar and wind are typically connected to the grid through power electronics such as inverters, which lack physical rotating inertia. As a result, grids with high renewable penetration experience faster frequency changes, increasing the risk of instability and outages. Several researches provides a comprehensive exploration of strategies to enhance frequency stability in low-inertia power systems, particularly in the context of increasing RES penetration (Yang et al., 2020). Various methods, including artificial intelligence, virtual inertia emulation, energy storage systems, and advanced control algorithms, have been proposed and evaluated across different studies. Many advanced optimization methods and algorithms, such as eigen sensitivity-based optimization, genetic algorithms (GA), and artificial neural networks (ANNs), provide significant performance improvements in simulations but often suffer from high computational costs (Buraimoh et al., 2022). ANN-based approaches show great promise in optimizing controller gains for real-time frequency control, but their performance can degrade when the system operates outside of the training conditions. These methods require extensive training data covering all potential operating scenarios, which can be difficult to obtain or may not cover every possible disturbance (Yap et al., 2019). The major contributions of this review are summarized as follows:

- i. Provides a comprehensive review of frequency stability assessment methods in low-inertia power systems, covering both deterministic and probabilistic approaches.
- ii. Presents a systematic classification of synthetic inertia technologies, including virtual synchronous machines, droop-based virtual inertia, model predictive control, battery energy storage systems, and intelligent control techniques.
- iii. Critically compares existing frequency stability enhancement methods based on their operating principles, validation approaches, performance metrics, advantages, limitations, and practical implementation challenges.
- iv. Identifies current research gaps related to uncertainty modeling, adaptive synthetic inertia allocation, converter operational constraints, computational efficiency, and real-time implementation.

Proposes future research directions toward uncertainty-aware frequency stability assessment, adaptive synthetic inertia control, artificial intelligence-assisted energy management, and resilient converter-dominated power systems.

SYSTEMATIC REVIEW METHODOLOGY

This review adopts a systematic literature review (SLR) methodology based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure a transparent, rigorous, and reproducible synthesis of the existing literature on frequency stability assessment and synthetic inertia in low-inertia power systems (Page et al., 2021). The adopted methodology comprises six sequential stages: (i) formulation of research questions, (ii) literature search, (iii) study screening, (iv) eligibility assessment, (v) quality assessment, and (vi) data extraction and synthesis.

Literature Search Strategy

A comprehensive literature search was conducted using six major scientific databases, namely IEEE Xplore, Scopus, Web of Science, ScienceDirect, SpringerLink, and Wiley Online Library. To ensure comprehensive coverage of recent developments, publications from 2015 to 2026 were considered. Additional relevant studies were identified through backward and forward citation tracking using Google Scholar.

Boolean search operators were employed to combine relevant keywords associated with frequency stability and synthetic inertia. The primary search string is expressed as ("Frequency Stability" OR "Dynamic Frequency Response" OR "Frequency Assessment") AND ("Synthetic Inertia" OR "Virtual Inertia" OR "Virtual Synchronous Machine" OR "Grid-Forming Inverter") AND ("Low-Inertia Power System" OR "Renewable Energy" OR "Solar PV" OR "Wind Power" OR "Converter-Dominated Power System").

Study Selection

The retrieved publications were screened using a three-stage selection process. First, duplicate records obtained from different databases were removed. Second, titles and abstracts were examined to eliminate studies that were unrelated to the objectives of this review. Finally, the remaining articles underwent full-text assessment to determine their eligibility for inclusion. The study selection process follows the PRISMA 2020 framework and is summarized in the PRISMA flow diagram presented in Figure 2.

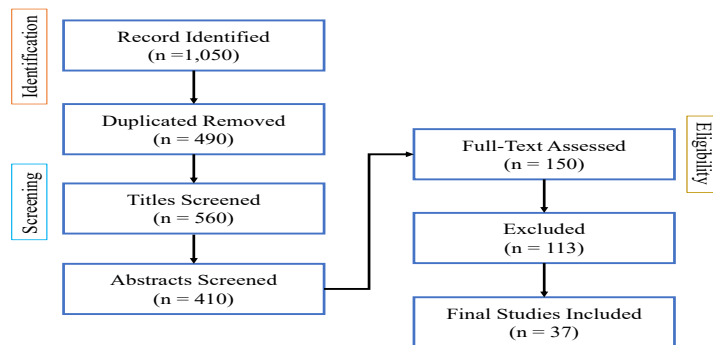


Figure 2: PRISMA 2020 flow diagram of the systematic review methodology for selecting studies Frequency Stability Assessment and Synthetic Inertia in Low-Inertia Power Systems

Inclusion and Exclusion Criteria

To ensure the relevance and quality of the reviewed literature,

predefined inclusion and exclusion criteria were established as shown in Table 1.

Table 1: Inclusion and Exclusion Criteria for the Systematic Literature Review

Category	Criterion	Description / Rationale
Inclusion Criteria	Research focus	Studies that investigated frequency stability issues in electrical power systems were included.
	System characteristics	Studies focusing on low-inertia power systems or renewable energy-dominated power systems were considered relevant.
	Technical contribution	Studies that proposed, analyzed, or evaluated synthetic inertia, virtual inertia, or other frequency support techniques were included.
	Validation approach	Studies presenting analytical analysis, simulation studies, experimental validation, or hardware-in-the-loop (HIL) testing were included.
	Publication type	Only studies published in peer-reviewed journals or conference proceedings were considered.
Exclusion Criteria	Language	Studies written in English were included to ensure consistent analysis and interpretation.
	Duplicate studies	Duplicate publications or multiple versions of the same study were removed to avoid redundancy.
	Research scope mismatch	Studies focusing exclusively on voltage stability, transient stability, or other stability aspects without addressing frequency stability were excluded.
	Publication quality	Editorials, book chapters, theses, technical reports, patents, and other non-peer-reviewed publications were excluded.
	Insufficient technical information	Studies lacking adequate methodological details, system descriptions, or validation results were excluded.
	Review articles	Review papers were excluded from the primary analysis; however, they were used only for identifying additional relevant references.

Frequency Stability

Dynamic model of the Load Frequency Control (LFC) loop, which plays a pivotal role in maintaining the stability of a power system (Kothari & Nagrath, 2003). The fundamental components of the power system encompass the generator, turbine, and the speed-governing framework. The LFC loop operates with two primary inputs: the controller input ΔP_{ref} , representing the reference power change, and the load disturbance ΔP_D , signifying external factors affecting the system load (Yang et al., 2020). The desired outcomes of the LFC loop are the variations in the generator frequency, denoted as $\Delta\omega$, and the Area Control Error (ACE). The transfer functions governing the turbine and governor dynamics are expressed through equations (1) and (2.2) (Lal & Barisal, 2019), providing a mathematical foundation for understanding the intricate interplay of these critical components in the power system's overall stability and control.

$$G_T(s) = \frac{\Delta P_T(s)}{\Delta P_V(s)} = \frac{1}{1 + sT_T} \quad (1)$$

In the context of the dynamic model for Load Frequency Control (LFC) discussed earlier, the turbine dynamics are characterized by the turbine time constant, denoted as T_T . This time constant plays a crucial role in determining the response time of the turbine to changes in input power. When there is a change in turbine power output, represented as ΔP_T , and a simultaneous alteration in the input power to the turbine, denoted as ΔP_V , the turbine time constant (T_T) governs the rate at which the turbine adjusts to these changes. Essentially, it reflects the time it takes for the turbine to reach a new steady-state condition in response to variations in the input power, providing insights into the dynamic behavior of the turbine component within the broader LFC framework (Lal & Barisal, 2019).

In addition to the turbine dynamics, the governor dynamics contribute significantly to the overall behavior of the Load Frequency Control (LFC) system. The governor time constant is denoted by T_G , and it represents the characteristic time for the governor to respond to changes in the system. When there is a change in governor power output, indicated by ΔP_G , the governor time constant (T_G) influences the rate at which the governor adjusts its output as in equation (2).

$$G_G(s) = \frac{\Delta P_V(s)}{\Delta P_G(s)} = \frac{1}{1 + sT_G} \quad (2)$$

Moreover, the rotating mass within the power system is highly sensitive to frequency changes. This sensitivity is analyzed through the speed-load characteristic, a crucial aspect of understanding the system's dynamic response. The speed-load characteristic provides insights into how the rotating mass responds to variations in the system frequency. This analysis is essential for comprehending the intricate interplay between the governor, turbine, and the overall power system dynamics, forming a critical foundation for effective Load Frequency Control as in equation (3).

$$\frac{\Delta\omega(s)}{\Delta P_T - \Delta P_D} = \frac{1}{2H + D} \quad (3)$$

The relationship between the change in frequency ($\Delta\omega$), the governor power output change (ΔP_G), and the reference input change (ΔP_{ref}) can be expressed through equation (4). This equation establishes a correlation that encapsulates the dynamics of the power system, specifically considering the inertia constant (H). The inertia constant represents the inherent ability of the power system to resist changes in its state.

Equation (4) serves as a key link in understanding how adjustments in the governor power output (ΔP_G), the reference input (ΔP_{ref}), and the resulting change in frequency ($\Delta\omega$) are interconnected. This correlation is fundamental in Load Frequency Control, as it provides a quantitative representation of how the system responds to external inputs and disturbances, offering valuable insights for effective control and stability measures in power systems.

$$\Delta P_G(s) = \Delta P_{ref}(s) - \frac{1}{R} \Delta\omega(s) \quad (4)$$

In the context of the governor dynamics discussed earlier, the speed regulation of the governor is denoted by R . The speed regulation (R) is a crucial parameter that characterizes the ability of the governor to maintain a steady speed in response to changes in load. It quantifies the change in speed for a unit change in load.

The frequency biased factor (B) is a key composite parameter in the analysis of the power system dynamics. It is expressed as the sum of the frequency-sensitive load change (D) and the speed regulation (R), providing a comprehensive representation of factors influencing the system's response to variations. Mathematically, the relationship is given by the equation (2.5):

$$B = \frac{1}{R} + D \quad (5)$$

This formulation encapsulates both the load-dependent and governor-dependent components contributing to the frequency biased factor (B), offering a concise representation for understanding the intricate interplay of these factors in the context of Load Frequency Control (Lal & Barisal, 2019).

Power System Inertia

Power system inertia refers to the ability of a power system to resist changes in frequency due to sudden imbalances between electricity supply and demand. It is primarily provided by the rotating masses of synchronous generators (like those in traditional power plants—coal, gas, hydro, etc.), which continue to spin and supply energy for a short time even when generation is interrupted (Lal & Barisal, 2019).

It also explores the effects of renewable energy sources (RESs) on system inertia. In conventional power systems, most electricity is generated by sources such as coal, nuclear, and hydroelectric power plants. These plants typically utilize synchronous generators (SGs), as depicted in Figure 3. The kinetic energy stored in the rotating parts of an SG is fundamental to frequency dynamics and stability. This inherent property, referred to as inertia, plays a vital role in responding to power imbalances caused by variations in load, generation, or grid faults (Dreidy et al., 2017).

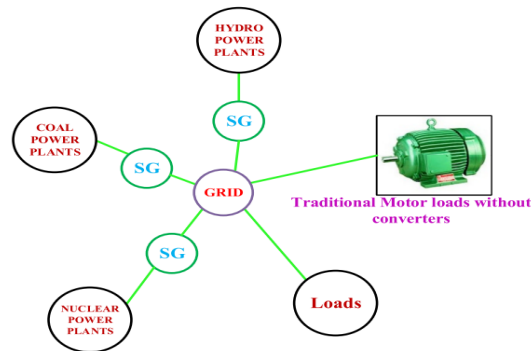


Figure 3: Traditional power system (Dreidy et al., 2017)

When the system frequency begins to decline, the synchronous generator (SG) responds by releasing the kinetic energy stored in its rotating mass. This release occurs almost instantaneously and serves as the first line of defense against frequency deviations (Dreidy et al., 2017). It provides a critical buffer until the primary frequency controllers, such as governor actions, are activated to stabilize the frequency, as illustrated in Figure 4 (Dreidy et al., 2017).

In any power system, the degree of frequency change resulting from a supply-demand mismatch is directly

influenced by the system's inertia. Higher inertia slows the rate of change of frequency (ROCOF), offering more time for control mechanisms to restore balance. Conversely, systems with lower inertia experience faster and larger frequency deviations, making them more susceptible to instability. This relationship underscores the essential role of inertia in maintaining grid stability during power imbalances (Miao et al., 2015).

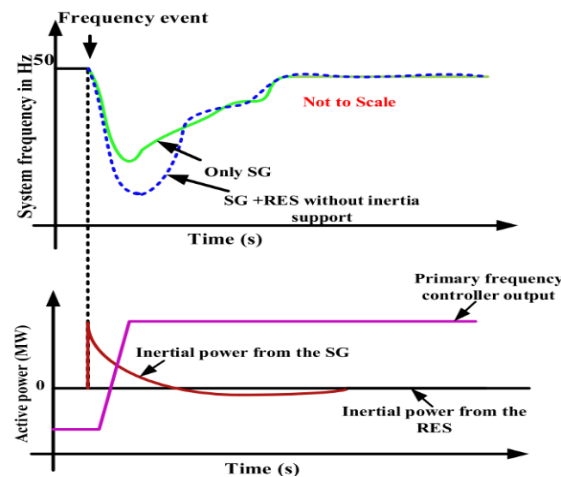


Figure 4: Effect of inertia of after tripping of the generator (Miao et al., 2015)

In traditional power systems, inertia is defined as the resistance to changes in the rotational speed of a synchronous generator (SG). It is a critical property that helps stabilize the grid frequency during disturbances by temporarily balancing the power mismatch using the kinetic energy stored in the rotating mass of the generator (Tielens & Van Hertem, 2016). The inertia of an SG is quantified using equation (6):

$$J = \int r^2 dm = r^2 m \quad (6)$$

r is the radius of the rotating part of an SG in m, and m is the mass in kg.

The kinetic energy of the SG (E_{KE}) expressed as equation (7):

$$E_{KE} = \frac{1}{2} J \omega_m^2 \quad (7)$$

Where J is the moment of inertia of the rotating body about the axis of rotation, ω_m^2 square of the angular velocity of the rotating body.

The swing equation is a fundamental equation in power system dynamics, representing the relationship between the rate of change of kinetic energy and the difference between mechanical and electrical power in a synchronous generator. It is used to analyze the rotor dynamics and frequency

stability of power systems (Tielens & Van Hertem, 2016), (Marco et al., 2026).

$$\frac{d}{dt} \left(\frac{1}{2} J \omega_m^2 \right) = P_m - P_e \quad (8)$$

Where P_m mechanical input power delivered to the shaft and P_e electrical output power delivered to the grid.

The swing equation (8) emphasizes that the stability of a power system is maintained when the average accelerating power is zero. This means that the mechanical power supplied to the generator matches the electrical power absorbed by the load. Any imbalance between the mechanical power input and the electrical power output results in a deviation of the rotor's angular speed from its steady-state value.

$$H = \frac{E_{KE}}{S} = \frac{\frac{1}{2} J \omega_m^2}{S} \quad (9)$$

The inertia constant H in equation (9) is a measure of how long a generator or power system can sustain nominal power output using only the kinetic energy stored in its rotating mass as shown in (4). This property plays a crucial role in frequency stability during disturbances by slowing down the rate of frequency change (ROCOF).

The inertia constant H can be expressed in terms of time (in seconds) as in (10):

$$H_{Total} = \frac{\sum_{i=1}^n H_i S_i}{\sum_{i=1}^n S_i} = \frac{\sum_{i=1}^n KE_i}{S_{Total}} \quad (10)$$

Where H_i is the inertia constant of a power system i , S_i is the generation capacity of the system i , and n is the total number of conventional plants. The total inertia in a traditional power system can be described as a resistance in the form of kinetic energy exchange from rotating machines, to compensate for the changes in frequency arising from power imbalances. Thus, short-term energy support under load fluctuations is called inertia (Younis et al., 2017). The amount of required kinetic energy during a power imbalance in the power system shown in Figure 2 can be expressed as in equation (11).

$$\Delta E_{KE} = \int (P_G - P_L) dt \quad (11)$$

ΔE_{KE} change in rotational kinetic energy of the generator, P_G generated power (mechanical input converted to electrical output by the generator) and P_L load power (electrical power demanded by the system or consumed by the load).

Impact of RES on Inertia of the Power System

In a traditional power system, the synchronous generators inherently provide inertia, which plays a crucial role in

limiting the Rate of Change of Frequency (ROCOF) following a contingency event. This inertia acts as a buffer, stabilizing the grid against sudden frequency changes caused by power imbalances.

In a future power system, where renewable energy sources (RES) and loads are predominantly integrated through power electronic converters (as illustrated in Figure 5), the system's inertia is significantly reduced compared to traditional systems (Bevrani et al., 2014). This reduction in inertia has several critical implications:

- Increased ROCOF:** With less inertia, the system's frequency responds more rapidly to power imbalances, resulting in higher ROCOF.
- Greater Frequency Deviations:** The frequency can deviate more significantly during disturbances, posing challenges for maintaining operational stability.
- Stability Threats:** The higher penetration of power electronic converters exacerbates the system's vulnerability to instability, as they decouple the rotating mass of generators from the grid.

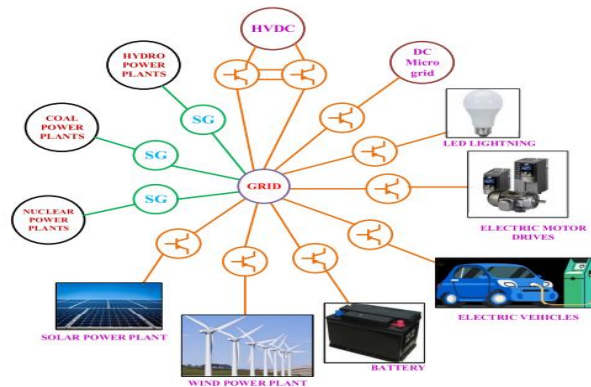


Figure 5: Modern Power system (Bevrani et al., 2014)

Frequency response model of RES dominated low inertia power grid

In power grids dominated by renewable energy sources (RESs), the inherent lack of rotational inertia poses significant challenges to frequency stability. Traditional synchronous generators, with their natural inertial response, are being replaced by inverter-based RESs such as wind and solar, which do not provide similar inertial support. To address this, frequency response models for low-inertia power grids with high-RES penetration have been developed

to analyze and mitigate stability issues (Saleem & Saha, 2024).

The frequency dynamics of the i -th area in an N -area power grid as shown in Figure 6, consisting of n synchronous generator-based energy sources (SGESs) and m inverter-based renewable energy sources (RESs), can be described using a differential equation (12) that models the relationship between power imbalance, system inertia, damping, and frequency deviation.

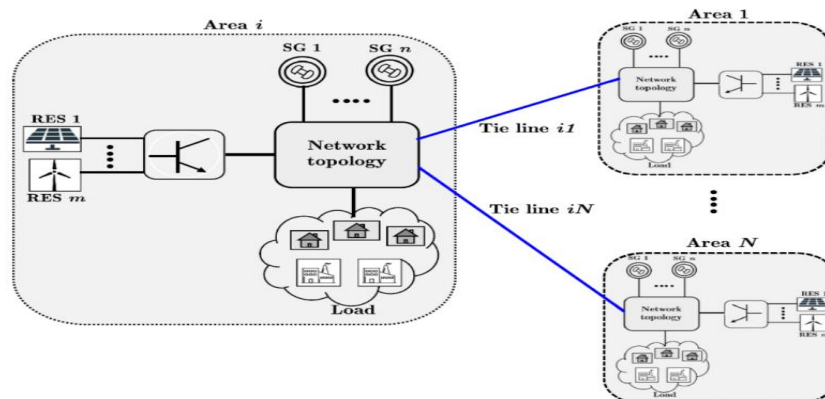


Figure 6: An N-interconnected power grid (Saleem & Saha, 2024)

$$\frac{d\Delta f_i}{dt} = \frac{f_i^0}{2H_i S_{Bi}} \left(-D_i \Delta f_i + \Delta P_{SGi} + \Delta P_{RESi} - \Delta P_{Li} - \sum \Delta P_{ij} - \Delta P_{Ci} \right) \quad (12)$$

Where $\Delta P_{SGi} = \sum_{sg=1}^n \Delta P_{SG,sg}$: deviation in SGES generation in the i_{th} area from the scheduled value, $\Delta P_{RESi} = \sum_{r=1}^m \Delta P_{RES,r}$: deviation in RES generation in the i_{th} area from the scheduled value, ΔP_{Li} : deviation in load demand in the i_{th} area from the scheduled value, $\sum \Delta P_{ij}$: variations in scheduled power exchange from the i_{th} area to interconnected areas, ΔP_{Ci} : a sudden change in the i_{th} area power generation or load demand due to a contingency event, Δf_i : deviation in the i_{th} area frequency from the nominal frequency f_i , 0, $E_i = H_i S_{Bi}$: aggregated inertia of the i_{th} area. Traditional power systems rely on the kinetic energy of rotating SG masses to buffer frequency transients. The swing equation governs this dynamics, where the inertia constant H dictates ROCOF and frequency recovery trajectories. With IB-RES replacing SGs, system inertia declines, leading to faster ROCOF and deeper frequency nadirs during contingencies. Studies (Thiesen, 2022) confirm that reduced inertia compromises primary frequency response, necessitating advanced control interventions.

Virtual and Synthetic Inertial Control Strategies

The progressive displacement of synchronous generators (SGs) by inverter-based resources (IBRs) has fundamentally altered the dynamic response of power grids. Traditional frequency stability relies on the physical kinetic energy stored in rotating masses, which inherently resists frequency deviations via the swing equation in (13) (Salam et al., 2026).

$$2H \frac{d\Delta f}{dt} = \Delta P_m - \Delta P_e - D\Delta f \quad (13)$$

In contrast, IBRs decouple mechanical dynamics from the electrical grid, resulting in near-zero natural inertia. To mitigate the resulting high Rate of Change of Frequency (ROCOF) and deep frequency nadirs, virtual and synthetic inertia control strategies have emerged as critical enablers of grid-forming capability (Khan et al., 2024). Unlike passive frequency support, synthetic inertia actively emulates the inertial response of SGs through fast power-electronic control loops, injecting or absorbing power proportional to the measured ROCOF and frequency deviation (Cicenas & Radziukynas, 2022).

Primary Control Architecture

Virtual inertia implementation can be broadly categorized into four dominant architectural paradigms:

Virtual Synchronous Machine (VSM) / Synchronverter

Pioneered by Zhong and Weiss (Sang et al., 2022), VSM explicitly replicates the complete electromechanical swing dynamics, field excitation, and stator impedance of SGs within inverter control firmware. By embedding virtual rotor inertia (H_{vir}) and damping (D_{vir}) coefficients, VSM enables IBRs to participate in primary frequency regulation and provide inherent grid strength (Yap et al., 2019). While highly effective in stability enhancement, VSM requires precise tuning to avoid control-loop oscillations and DC-link voltage instability during severe transients.

Droop Control Augmented with Virtual Inertia

A computationally lighter alternative, this approach superimposes a derivative-based inertial term ($K_{df} \frac{df}{dt}$) onto conventional active power-frequency droop control (Sati et al., 2025). The inertial gain is typically fixed or gain-scheduled based on operating point. Studies demonstrate significant ROCOF reduction and improved nadir performance; however, fixed coefficients often result in over- or under-compensation under varying PV penetration and contingency severity (Buraimoh et al., 2022).

Model Predictive Control (MPC) and Optimization-Based Inertia

MPC frameworks optimize virtual inertia and damping dispatch over a receding horizon by solving constrained optimization problems in real-time (X. Deng et al., 2023). These methods explicitly account for system topology, converter ratings, and forecasted renewable variability. While offering superior dynamic performance, MPC suffers from high computational latency and dependency on accurate short-term forecasting, limiting real-time applicability in large-scale networks (Buire et al., 2026).

Adaptive and Intelligent Control Schemes

Recent advances employ fuzzy logic, neural networks, and reinforcement learning to dynamically adjust H_{vir} and D_{vir} based on online frequency metrics. AI-driven controllers exhibit robust performance across wide operating ranges but face challenges in interpretability, training data requirements, and real-time deployment guarantees under unseen grid topologies (Han et al., 2025).

Grid-Forming vs. Grid-Following Inverter Dynamics

A critical distinction in synthetic inertia deployment lies in inverter operational mode. Grid-following (GFL) inverters synchronize to an external voltage/frequency reference and cannot establish grid strength independently; they only provide secondary frequency support via supplementary control loops (Khan et al., 2024). Conversely, grid-forming (GFM) inverters act as internal voltage sources, establishing frequency and voltage references autonomously while emulating inertial dynamics. Recent grid codes (IEEE 2800-2022, ENTSO-E RfG) increasingly mandate GFM capabilities for IBRs to ensure stability in low-inertia regimes. However, transitioning from GFL to GFM requires careful handling of converter current limits, DC-link energy buffers, and small-signal stability margins to prevent control saturation or cascading tripping (Salem et al., 2025).

Grid-following inverters lack inherent frequency support, prompting research into grid-forming controls that emulate SG dynamics. Virtual inertia algorithms, VSG architectures, and BESS-based fast frequency response have demonstrated ROCOF mitigation (Poolla et al., 2019; Pazmiño et al., 2021; Hussain & Shireen, 2021). However, many approaches assume idealized control responses, neglect hardware constraints, or lack adaptive tuning under varying grid topologies. In this exemplary microgrid, the internal control of GFM inverter is designed with voltage and current loops as described in Figure 7 (Cristaldi et al., 2024).

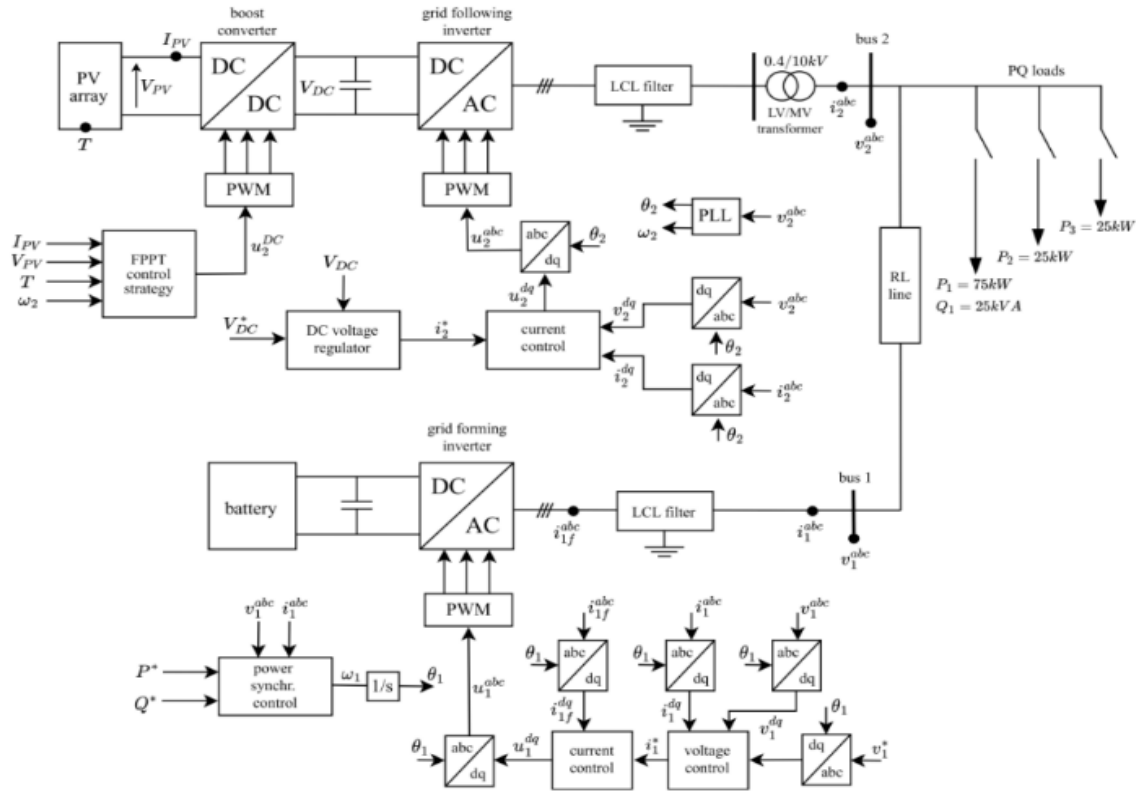


Figure 7: Grid-forming and grid-following inverter control (Cristaldi et al., 2024)

Implementation Constraints and Stability Challenges

Despite theoretical maturity, practical deployment of virtual inertia faces several unresolved engineering constraints:

- Power Electronics Limitations:** Inverters possess finite thermal and current ratings. Emulating high virtual inertia without respecting short-circuit current limits can trigger protective shutdowns during severe faults (Chand et al., 2025).
- DC-Link Voltage Dynamics:** Synthetic inertia relies on rapid power exchange between the DC-side and AC-grid. Insufficient DC-link capacitance or slow MPPT dynamics can cause voltage collapse during prolonged inertial response (Buonanno et al., 2022).
- Timescale Coupling:** Virtual inertia control operates on millisecond-to-second timescales, overlapping with primary frequency control and protection systems. Poorly coordinated dynamics can induce negative damping and sub synchronous oscillations.
- Deterministic Tuning Bias:** Most existing frameworks calibrate H_{vir} and D_{vir} using worst-case or average scenarios, neglecting stochastic variability in solar irradiance and load demand. This leads to either conservative inertia provisioning or frequent frequency limit violations under real-world uncertainty (Buonanno et al., 2022).

Overview of Existing Approaches

In (Kouba et al., 2017), proposed a hybrid Genetic Algorithm-Particle Swarm Optimization (GA-PSO) approach for optimizing Load Frequency Control (LFC) in interconnected power systems. The method minimizes performance indices (ISE, IAE, ITAE, and ITSE) to improve transient response. Compared with the conventional PI controller, the GA-PSO approach reduced maximum overshoot from 12.5% to 3.2% and shortened the settling time

to 3.1 s (a 62% improvement), resulting in enhanced frequency stability. However, its performance depends on proper parameter tuning and may deteriorate under abrupt load variations or highly dynamic operating conditions. In (Toma et al., 2018), investigated the use of battery energy storage systems (BESSs) to enhance frequency stability in low-inertia power systems by combining frequency deviation and RoCoF signals to provide synthetic inertia and primary frequency support. Simulation results on a two-area interconnected system demonstrated improved frequency regulation and dynamic response. However, the study employed an idealized BESS model that neglected battery degradation, efficiency losses, and state-of-charge constraints, while assuming fixed system parameters that did not account for renewable energy variability or interactions with other control mechanisms. In (Guo & Summers, 2019), investigates the performance and stability of low-inertia power systems under stochastic system inertia, where system dynamics are modeled using a linearized stochastic swing equation with multiplicative noise. The study employs the H_2 norm as a performance metric to evaluate system behavior in response to persistent disturbances and transient faults. A key contribution of the paper is the derivation of a generalized Lyapunov equation, which fundamentally differs from traditional systems influenced only by additive noise. For grids with uniform inertia and damping parameters, closed-form expressions for the H_2 norm of the stochastic swing equation are derived, offering insights into how system performance depends on: Network topology, System parameters, Distribution characteristics of disturbances. Additionally, a mean-square stability condition is established to assess the robustness of the system. Numerical simulations further validate the theoretical results, providing deeper insights into the performance and stability of low-inertia power grids with stochastic inertia variations. However, the

analysis is based on a linearized stochastic swing equation, which may not fully capture the nonlinear dynamics of real-world power systems, especially under extreme disturbances or large fluctuations.

In (Aziz et al., 2019), proposed a hybrid adaptive load frequency control (LFC) strategy combining Variable Fuzzy Logic Control (VFLC) and an Improved Genetic Algorithm (IGA). The two-loop framework uses VFLC for robust disturbance regulation and IGA for optimizing fuzzy parameters under varying operating conditions. Tested on a three-area LFC system with multiple load and climatic scenarios, the proposed method dynamically adjusts membership functions and fuzzy rules, achieving superior performance compared with conventional PI and adaptive fuzzy controllers. Its effectiveness was further validated using a 49-bus power system implemented on a Real-Time Digital Simulator (RTDS). However, the approach remains dependent on predefined search spaces and initial conditions for fuzzy rule optimization, which may limit adaptability under highly uncertain or unforeseen operating conditions. In (Poolla et al., 2019), developed explicit models of grid-following and grid-forming virtual inertia (VI) devices for inertia emulation and fast frequency response in low-inertia power systems. An optimization framework was proposed to determine the optimal placement and parameters of VI devices, with validation performed using a high-fidelity model of the South-East Australian power system. The results demonstrated improved frequency stability and system resilience. However, the approach relies on accurate system models and parameter estimation, which may not fully represent real-time uncertainties in renewable generation. Furthermore, idealized VI responses are assumed, neglecting practical constraints such as communication delays, converter limitations, and hardware constraints. The validation on a specific regional grid also limits its applicability to other network configurations. In (Chamorro et al., 2020), presents a method for predicting the timing of the frequency nadir using a Nonlinear Auto-Regressive (NAR) model based on an Artificial Neural Network (ANN). The proposed estimation approach is evaluated under conditions of gradually decreasing system inertia, allowing for the assessment of its adaptability across different prediction horizons. However, the accuracy of the model is highly dependent on the quality and diversity of the training data, which may limit its generalizability to unseen system conditions or rare disturbance events. Additionally, the model may struggle to maintain precision under highly nonlinear system behaviors or sudden, large disturbances not represented during training. The approach also assumes a consistent relationship between system variables and frequency response, which might not hold under rapidly changing grid topologies or high levels of renewable integration.

In (Paturet et al., 2020), investigates the Unit Commitment (UC) problem in power networks with low rotational inertia, addressing the challenges posed by reduced system stability due to high renewable energy penetration. The study focuses on incorporating frequency-related constraints into the UC formulation to ensure reliable grid operation. Key contributions include the derivation of constraints for Rate-of-Change-of-Frequency (RoCoF), Frequency Nadir, and Steady-State Frequency Error. These constraints are developed using a uniform system frequency response model that integrates the dynamics of both synchronous generators and grid-forming inverters. To address uncertainties from wind power variability and equipment contingencies, a stochastic UC formulation is implemented using a scenario-tree approach, enabling more robust decision-making in

scheduling generation resources. However, the study relies on a uniform system frequency response model, which may not fully capture the complex dynamics of large-scale power grids with diverse generation sources and load variations.

In (Yang et al., 2020), proposed a load frequency control (LFC) strategy based on a double equivalent-input-disturbance (EID) controller for photovoltaic-integrated multi-area power systems. The method employs two EID controllers to estimate and compensate for disturbances caused by PV output variations, load changes, and grid voltage fluctuations. MATLAB/Simulink simulations showed that the proposed approach significantly reduced frequency deviations compared with FA-PI and conventional PI controllers, achieving only 6% and 7% of their respective deviations. However, the performance depends strongly on accurate disturbance estimation, where modeling errors and detection delays may degrade compensation effectiveness. Moreover, the use of linearized system models may limit its ability to capture nonlinear dynamics during large disturbances and transient operating conditions. In (Chien et al., 2020), proposes an artificial neural network (ANN)-based controller that determines optimal controller gains for frequency regulation using load disturbance, wind penetration level, and wind speed as input variables. Once properly trained on a representative dataset, the ANN is capable of efficiently generating suitable gain values even for operating conditions not explicitly included in the training data making it well-suited for real-time frequency control applications. Simulation results obtained using MATLAB/SIMULINK on a local power system in Taiwan demonstrate that the proposed ANN-based controller achieves superior frequency response compared to a conventional fixed-gain controller. However, the effectiveness of the ANN is highly dependent on the quality and diversity of the training dataset; insufficient or unrepresentative data may lead to inaccurate gain predictions under unfamiliar conditions. The model assumes stable and consistent system dynamics, which may not hold during abrupt topology changes or severe disturbances. Moreover, the ANN operates as a black-box model, limiting interpretability and making it difficult to diagnose or validate its internal decision-making processes.

In (Qaid et al., 2021), investigated rotational inertia in conventional power systems, focusing on the relationship between generator ratings, inertia constants, and frequency response. Using the IEEE 9-bus system, the study evaluated multiple scenarios and showed that systems with smaller-rated generators achieved higher inertia levels and improved frequency recovery after disturbances. An optimal generator rating range of 100–400 MVA was identified for enhanced inertia performance. However, the analysis is limited by the simplified IEEE 9-bus model and does not consider practical factors such as governor dynamics, mechanical losses, or generator ramping constraints, which may affect real-world applicability. In (Hussain & Shireen, 2021), introduces a primary frequency controller (PFC) designed to rapidly compensate for power imbalances without contributing additional inertia to the system. The proposed method estimates real-time power imbalances caused by disturbances and addresses them through the coordinated operation of multiple small-scale distributed battery energy storage systems (BESSs). The power imbalance is inferred by monitoring the initial Rate of Change of Frequency (RoCoF) immediately following a disturbance. Based on this estimation and the rated capacities of the BESSs, appropriate reference power values are calculated to guide their response. Operating in grid-following mode, the BESSs are controlled

to inject or absorb power accordingly. The effectiveness of the proposed PFC is evaluated using the Typhoon real-time simulation platform under various disturbance scenarios and is benchmarked against the performance of a conventional virtual synchronous generator (VSG) controller. The controller operates in grid-following mode, which may limit its ability to provide grid-forming capabilities or contribute to system strength during severe disturbances. The accuracy of power imbalance estimation relies heavily on precise measurement of the initial RoCoF, which may be affected by noise, delays, or measurement errors in real-world deployments.

In (Pazmiño et al., 2021), investigates the impact of two virtual inertia-based control strategies—one utilizing battery energy storage systems (BESS) and the other incorporating a virtual inertia algorithm into wind generation units on frequency regulation within an electric power system. The analysis is conducted within the primary frequency control time frame under a high wind penetration scenario. Simulation results demonstrate that both control strategies significantly enhance system frequency response during disturbance events, particularly in terms of frequency nadir and Rate of Change of Frequency (RoCoF). Moreover, the improvement is markedly more pronounced when both strategies are implemented simultaneously, validating the study's hypothesis. The proposed model serves as a diagnostic and analytical tool for evaluating the dynamic behavior of key system variables, enabling grid operators to assess the frequency stability under various high-risk scenarios and proactively implement corrective or preventive measures. However, the models used for batteries and wind generation units assume ideal behavior and may not account for degradation, control delays, communication issues, or non-linearities in actual hardware. The combined strategy's effectiveness is shown under a specific high wind penetration scenario, and its generalizability across different grid topologies, load conditions, and renewable mixes remains to be validated.

A high-fidelity dynamic model of a generic low-inertia power system has been developed by (Markovic et al., 2021) to assess stability under varying operational conditions. This full-order model integrates state-of-the-art control schemes for both synchronous generators and converter-based generation, explicitly distinguishing between grid-forming and grid-following operational modes. Additionally, the model captures the dynamic behavior of transmission lines and loads, ensuring a comprehensive representation of system interactions. To identify stability vulnerabilities, modal analysis techniques including participation factors and parameter sensitivity are employed. These analyses highlight the system's most vulnerable segments and provide insights into the adverse effects of timescale coupling and control interference, which can degrade stability in low-inertia scenarios. However, the differentiation between grid-forming and grid-following converters relies on specific control implementations, which may not generalize across all converter designs used in actual power systems.

In (Venkatraman et al., 2021), a comprehensive framework for the performance-based allocation of virtual inertia and damping to converter-interfaced generators in a detailed low-inertia power system. The approach employs an iterative eigensensitivity-based optimization algorithm to determine optimal controller gains, ensuring both the preservation of small-signal stability and compliance with desired damping ratios and frequency response characteristics following disturbances. Two distinct problem formulations are introduced and validated using simulations on a modified

version of Kundur's classic two-area system and an extended 59-bus model of the South-East Australian network. However, the optimization process relies heavily on accurate linearized system models, which may not fully capture nonlinear dynamics during large disturbances or extreme operating conditions. Additionally, the eigen sensitivity-based approach assumes consistent modal behavior, which may vary under different system configurations or high levels of renewable penetration.

In (Vega et al., 2022), proposed a methodology for determining the control requirements that should be imposed on converter-interfaced generation to ensure frequency stability in low-inertia power systems. Using projections of the future Chilean power system, the authors analyzed the impact of high converter penetration levels and demonstrated that frequency-support-enabled converters significantly enhance system stability. Although the approach provided valuable insights into control requirements for converter-based generation, the analysis was deterministic and did not account for uncertainties associated with renewable generation variability or load fluctuations. In addition, adaptive synthetic inertia control was not investigated.

Deng and Fang (2022) developed a state-space model for grid-forming converters equipped with distributed virtual inertia to improve frequency regulation in low-inertia power systems. The study investigated the stability challenges associated with virtual inertia control and proposed a lead compensator to enhance converter stability without requiring additional energy storage systems. Simulation and experimental results demonstrated that the proposed strategy improved system inertia and frequency regulation performance. However, the work focused mainly on converter-level stability analysis and did not consider uncertainties in renewable generation and load demand. Furthermore, the study did not provide a framework for evaluating frequency stability or determining inertial support requirements at the power system level.

In (Saleem et al., 2024), the development and application of novel stability indices that offer critical insights into grid frequency sensitivity, resiliency, and permissibility under varying levels of RES penetration was presented. These indices serve as effective tools for evaluating frequency stability and highlighting the increasing vulnerability of grid frequency to disturbances as RES integration rises. The proposed frequency stability assessment framework incorporates system uncertainties through MCS, accounting for the stochastic nature of load demand and RES generation. Furthermore, a methodology is introduced to quantify the required level of inertial support necessary to maintain frequency reliability in the presence of high-RES penetration. A comprehensive case study based on a modified IEEE 39-bus test system reflecting the characteristics of a real-world power grid with heterogeneous load profiles and renewable sources demonstrates the effectiveness of the proposed indices and methodology in assessing frequency stability and determining inertial support requirements. However, the accuracy of the results also depends heavily on the quality and representativeness of the probabilistic input data for load demand and RES generation. Additionally, the approach assumes fixed control strategies for RES and does not fully account for dynamic interactions between multiple ancillary services or evolving grid codes.

In (Al-azzawi, 2024) a PV-based power system comprising a boost converter, battery energy storage system (BESS), bidirectional converter, three-phase inverter, droop control, and adjustable load is investigated. The study demonstrates that PV fluctuations directly affect frequency deviations,

while BESS integration effectively reduces frequency variations and improves system reliability. However, increased PV penetration can introduce higher frequency instability. Although droop control enhances frequency response under moderate disturbances, its effectiveness under severe or rapid load changes remains limited without supplementary control. The study also does not fully address scalability under high PV penetration and the complex interactions among multiple distributed energy resources. In (Saleem & Saha, 2024) developed a comprehensive methodology for assessing frequency stability and determining required inertial support in power grids with high renewable energy penetration. The study introduced three stability indices for quantifying frequency sensitivity, resiliency, and permissibility and employed Monte Carlo Simulation (MCS) to incorporate uncertainties associated with load demand and renewable generation. The proposed methodology was validated on a modified IEEE 39-bus test system and further verified through OPAL-RT real-time simulation studies. Despite its effectiveness, the framework relied on computationally intensive conventional Monte Carlo Simulation and did not incorporate adaptive synthetic inertia control or detailed inverter operational constraints such as current limits and DC-link voltage dynamics. In (Khan et al., 2024) presented a comprehensive review of grid-forming control strategies for inverter-based resources in modern power systems. The study examined major grid-forming techniques, including virtual synchronous machines, droop control, and matching control, and analyzed their effects on system frequency stability and operational performance. The review highlighted the increasing

importance of grid-forming technology in future inverter-dominated power systems. However, the work was largely theoretical and did not propose a practical framework for probabilistic frequency stability assessment or inertial support estimation.

In (Marco et al., 2026) evaluated the impact of increasing grid-forming inverter penetration on frequency transient behavior in renewable-dominated power systems. The authors investigated improvements in frequency nadir and ROCOF under different penetration levels and demonstrated that grid-forming inverters can significantly improve frequency stability in low-inertia networks. However, the study focused principally on penetration analysis and did not incorporate uncertainty modeling, adaptive inertia control strategies, or optimization of inertial support requirements.

Buire et al. (2026) investigated the tuning of grid-forming converters for the optimal allocation of virtual inertia and damping in low-inertia power systems. The study proposed strategies for improving dynamic performance through optimal allocation of control parameters and demonstrated the effectiveness of grid-forming converters in supporting frequency stability. While the proposed approach provided significant improvements in converter performance, it did not incorporate probabilistic assessment of renewable generation uncertainty or evaluate power-system-wide inertial support requirements under varying PV penetration levels.

Table 2 provides a comprehensive summary and comparative analysis of the key contributions in this domain, highlighting the methodologies employed, system models considered, performance metrics utilized, and the associated limitations.

Table 2: Comparative Analysis of Frequency Stability and Inertial Support Strategies in Low-Inertia Power Systems

Ref.	Methodology Technique	System Model Case Study	Performance Metrics	Major Findings	Limitations
(Kouba et al., 2017)	Hybrid GA-PSO optimized PI for LFC	Interconnected multi-area system	Overshoot, settling time, ISE, IAE, ITAE, ITSE	Reduced overshoot (3.2%) and settling time (3.1 s); 62% improvement over PI	Sensitive to tuning; reduced robustness under abrupt load variations
(Toma et al., 2018)	BESS-based virtual inertia using frequency + RoCoF signals	Two-area system	Frequency deviation, RoCoF, response time	Effective synthetic inertia provision and improved dynamic response	Idealized BESS model; ignores degradation, SoC, and efficiency losses
(Guo & Summers, 2019)	Stochastic swing equation with H ₂ norm analysis	Low-inertia stochastic system	H ₂ norm, mean-square stability	Derived Lyapunov-based stability conditions; quantified inertia uncertainty impact	Linearization limits nonlinear dynamic representation
(Aziz et al., 2019)	Hybrid VFLC-IGA adaptive LFC	Three-area system + 49-bus RTDS	Frequency deviation, robustness	Superior dynamic response vs PI and AFLC; adaptive rule generation	Dependence on initial conditions and fuzzy rule design
(Poolla et al., 2019)	Optimization of grid-forming & grid-following virtual inertia	South-East Australian grid	Frequency nadir, resilience	Optimal placement enhances system stability and inertia support	Assumes ideal device response; limited generalizability
(Chamorro et al., 2020)	ANN-based NAR model for frequency nadir prediction	Low-inertia scenarios	Prediction accuracy, nadir timing	Accurate nadir prediction under varying inertia levels	Data-dependent; poor extrapolation for unseen disturbances
(Paturet et al., 2020)	Stochastic Unit Commitment with frequency constraints	Low-inertia grid with RES	RoCoF, nadir, steady-state frequency	Integrates frequency constraints into UC for stability assurance	Uniform frequency model oversimplifies system dynamics
(Yang et al., 2020)	Double EID-based LFC control	PV-integrated multi-area system	Frequency deviation	Reduced deviation to ~6–7% of PI-based methods	Relies on accurate disturbance estimation; linear model assumption
(Chien et al., 2020)	ANN-based adaptive gain controller	Taiwan power system	Frequency deviation	Improved real-time gain tuning and frequency control	Black-box nature; requires extensive training data

Ref.	Methodology Technique	System Model Case Study	Performance Metrics	Major Findings	Limitations
(Qaid et al., 2021)	Inertia analysis based on generator ratings	IEEE 9-bus system	RoCoF, frequency recovery	Smaller generators improve inertia and recovery; optimal 100–400 MVA range	Simplified system; ignores practical generator constraints
(Hussain & Shireen, 2021)	RoCoF-based BESS primary frequency control	Real-time Typhoon simulation	Frequency deviation, response speed	Fast imbalance compensation without inertia provision	Measurement noise affects RoCoF accuracy; no grid-forming capability
(Pazmiño et al., 2021)	Hybrid virtual inertia (BESS + wind)	High wind penetration system	RoCoF, frequency nadir	Combined approach yields best frequency support	Assumes ideal devices; limited validation across scenarios
(Markovic et al., 2021)	High-fidelity dynamic modeling with modal analysis	Low-inertia system (full-order model)	Eigenvalues, participation factors	Identifies instability sources and control interactions	Model complexity; limited generalization across converter types
(Venkatraman et al., 2021)	Eigen-sensitivity-based inertia allocation	Kundur system + 59-bus grid	Damping ratio, frequency response	Optimized inertia improves stability and damping	Relies on linear models; limited nonlinear applicability
(Vega et al., 2022)	CIG penetration and control requirement analysis	Chilean grid (2046 projection)	Frequency stability limits	Up to 99% penetration achievable with frequency support	Does not consider extreme disturbances
(Abah et al., 2022)	GOA-optimized PDF + (0.85+PI) LFC	Two-area nonlinear system	Overshoot, settling time, ITAE	Significant improvement over SSA-PID and GA-PID	Heuristic tuning may converge to local minima
(Al-azzawi, 2024)	Probabilistic frequency stability indices (MCS-based)	Modified IEEE 39-bus	Frequency sensitivity, inertia requirement	Quantifies inertia needs under RES uncertainty	Dependent on probabilistic data quality

CONCLUSION

The transition toward renewable-dominated power systems has significantly reduced the rotational inertia traditionally provided by synchronous generators, creating major challenges for frequency stability. Reduced system inertia leads to higher RoCoF, deeper frequency nadirs, and increased vulnerability to disturbances, making frequency stability a critical concern in future low-inertia power systems. This review has presented a comprehensive assessment of frequency stability analysis methods and synthetic inertia technologies for modern power systems. The fundamental concepts of power system inertia and frequency dynamics were discussed, followed by a critical review of deterministic and probabilistic frequency stability assessment methods. Various synthetic inertia strategies, including virtual synchronous machines, droop-based control, model predictive control, battery energy storage systems, artificial intelligence-based controllers, and grid-forming converters, were examined with respect to their operating principles, advantages, and limitations. A comparative analysis of existing studies revealed substantial progress in enhancing frequency stability through advanced control strategies. Despite these advances, several challenges remain. Most existing approaches rely on deterministic analyses, assume ideal converter operation, and employ fixed synthetic inertia parameters, while uncertainty associated with renewable generation, converter operational constraints, and real-time implementation are often overlooked. Furthermore, issues such as converter current limits, DC-link voltage dynamics, communication delays, and computational complexity continue to hinder practical deployment. Overall, future frequency stability solutions should integrate uncertainty-aware assessment, adaptive synthetic inertia control, and coordinated operation of grid-forming converters and energy storage systems. Such integrated frameworks will be essential

for enhancing the resilience, stability, and reliability of future renewable-dominated low-inertia power systems.

Future Research Directions

Despite the significant progress achieved in frequency stability assessment and synthetic inertia technologies, several important research challenges remain open.

- Probabilistic frequency stability assessment should receive greater attention. Future studies should move beyond deterministic analyses by incorporating uncertainties associated with renewable energy generation, load demand, equipment outages, and weather variability through advanced stochastic modeling techniques.
- Adaptive synthetic inertia control should replace fixed-parameter virtual inertia schemes. Intelligent adaptive controllers capable of adjusting inertia and damping parameters in real time according to changing operating conditions can substantially improve system resilience while reducing unnecessary power injections.
- Grid-forming converter technologies require further investigation. Future research should address practical implementation issues, including converter current limits, DC-link voltage dynamics, fault ride-through capability, synchronization stability, and coordinated operation with conventional synchronous generators.
- Artificial intelligence and machine learning offer promising opportunities for improving frequency stability. Reinforcement learning, deep neural networks, digital twins, and physics-informed machine learning have the potential to enable predictive frequency assessment, adaptive inertia allocation, and autonomous converter control while reducing computational complexity.
- Coordinated frequency support from distributed energy resources should be investigated through the

integration of battery energy storage systems, electric vehicles, microgrids, demand response, and distributed renewable generators to provide fast and flexible frequency regulation services.

- vi. Hardware validation and real-time implementation: Although many synthetic inertia strategies have demonstrated excellent simulation performance, relatively few have been validated using hardware-in-the-loop platforms or field demonstrations. Bridging the gap between simulation and practical deployment will be essential for the reliable operation of future converter-dominated power systems.

By addressing these challenges, future research can establish robust, adaptive, and uncertainty-aware frequency stability frameworks capable of supporting the continued integration of renewable energy while maintaining the security and resilience of modern power systems.

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