

Status review on stability analysis of solar and wind electrical energy resource based microgrids integration into a multi-machine power system

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Abstract:

The global push to generate significant amounts of electrical energy from renewable sources is primarily driven by concerns over global warming. Solar photovoltaic (PV) and wind energy are among the most promising renewable sources for large-scale power production, largely due to advancements in converter technologies. If the current rate of installation continues, wind and solar PV power could significantly alter the electrical grid and potentially affect its stability. This paper offers a comprehensive analysis of the technological challenges, focusing on stability issues related to the large-scale integration of wind and solar PV into the power system. It also explores stability studies for solar PV, as well as the role of HVDC, DFIG, FACTS devices, and dynamic models of generators. In conclusion, the paper summarizes research findings on technical solutions to address power system stability challenges. The study supports power system engineers and policymakers in enhancing grid stability amid high solar PV and wind integration. It guides the use of technologies like HVDC, DFIGs, and FACTS for building resilient, renewable-driven power systems.

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1. Introduction

Electrical power system stability plays a crucial role in modern electrical grids by ensuring that they can absorb disturbances and maintain reliable operation. As electricity demand increases and renewable energy sources are more widely integrated, keeping the system stable becomes both more challenging and more necessary. Effective understanding and management of power system stability are essential for ensuring dependable grid operation, accommodating the rising incorporation of renewables, and meeting the evolving requirements of consumers and industries [1]. As these power systems continue to develop, the focus on stability will grow, spurring further research and development in this important area.

In recent decades, solar and wind energies have emerged as some of the most commonly used renewable sources compared to others [2]. However, unlike wind energy, solar energy is only available during daylight hours. Although both wind and solar energy are inherently variable, wind energy tends to exhibit greater uncertainty due to its less predictable nature. This is in contrast to solar energy, which typically follows a repetitive daily irradiance pattern. Additionally, both wind and solar resources are subject to seasonal fluctuations and can be significantly influenced by weather conditions [3]. While the impact of solar and wind generators on power system

stability may be minimal at low levels of deployment, their increasing penetration can affect the dynamic performance of the power system

Demand of electricity is increasing swiftly, while the huge amount of fossil fuel like gas coupled with the operational and maintenance required to produce sufficient electricity to meet the ever-increasing demand results in an enormous cost. As time passes, the operational and maintenance cost may increase exponentially resulting at higher electricity production cost. In this regard, the hunt for alternative energy sources has been sparked by environmental concerns, the exhaustibility of fossil fuels, and rising energy demands [4]. Renewable energy resources now have more chances for integration into power system networks due to the recent advancements in renewable energy technologies and a decline in the cost of their unit energy production. Moreover, renewable energy resources are everywhere, unlike conventional energy sources, which are concentrated in a small number of places throughout the globe [5]. Renewable energy is clean, reusable, sustainable, and beneficial to the environment. Examples of renewable energy sources include wind, sun, tidal, small hydro, geothermal, refuse-derived fuel, and fuel cells. Renewable energy has grown in importance as a result of pollution issues and the growing scarcity of fossil fuels [6]. Wind and solar energy have shown to be two of the most cost-effective renewable

energy sources. Because fossil fuels produce power at a low cost per unit, a sizable portion of the world's electricity is still produced in this way. Due to the negative effects of this dependence on the environment, such as pollution and global warming, it is now necessary to explore and develop clean energy alternatives in order to produce electricity [6].

The wind and solar renewable resource uncertainty may result in higher loss of load probability (LOLP), especially during longer load demand supply periods. In the presence of critical loads, conventional non-renewable energy sources such as fossil fuel based generating systems are required to cover the base loads. Looking at the nature of each of the two sources, it is clear that each of them complements the other, so they are among the most common integrated energy systems [7, 8]. Despite the merging of the wind and solar energy together, there are still some problems in eliminating fluctuations in the produced energy completely, especially with systems that are not connected to the grid, where the integration process cannot be completely controlled. Due to the aforementioned issues associated with wind and solar renewable energy sources, their integration into conventional grid system gives rise to questions on transient stability problem which is due to small signal stability and also due to weather conditions [7, 8].

2. Renewable energy outlook

Renewable energy is derived from naturally replenishing sources that cannot be exhausted. This type of energy not only ensures energy security and fosters national economic growth but also helps reduce or eliminate greenhouse gas emissions, conserves non-renewable resources, and lowers energy costs [9]. Africa, including Nigeria, holds significant yet largely untapped renewable energy potential. Since the Kyoto Protocol was established in 1992 [10, 11], the global emphasis has been on securing safe, sustainable, and environmentally friendly energy sources. In response to increasing energy demands and the need to reduce GHG emissions, governments have begun shifting away from conventional fossil fuels toward alternative renewable sources. Additionally, renewable energy resources (RER) enhance energy security and bolster the global energy economy [12, 6]. As a result, energy production based on RER has grown rapidly in recent years—a trend expected to continue in the coming decades [13, 14, 15]. Research by the Renewable Energy Policy Network for the 21st Century [16] indicates that between 2007 and 2020, global capacity for key renewable sources such as solar PV and wind energy increased by more than 95-fold and 8-fold, respectively. Notably, in terms of overall installed capacity, solar PV technology surpassed wind technology in 2020, as shown in Figure 1.

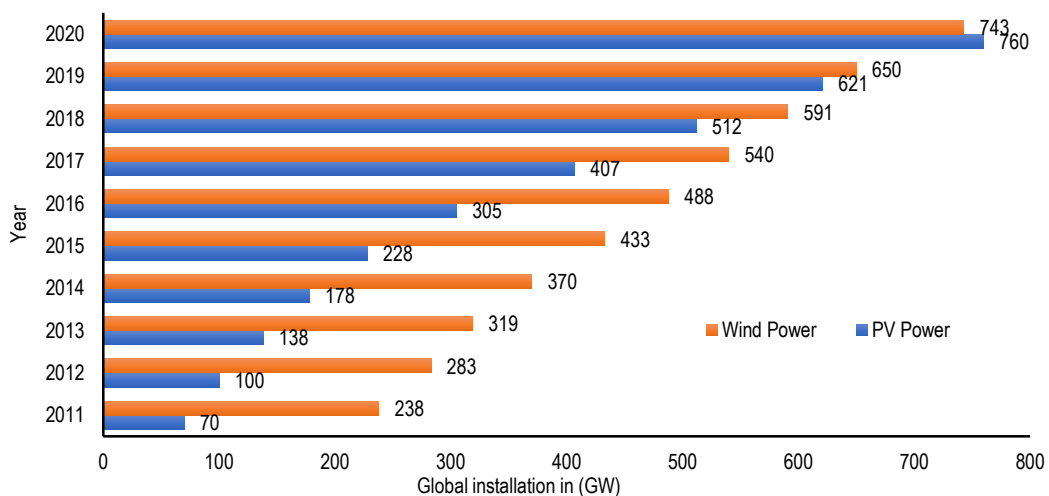


Figure 1: Global PV and Wind installed capacity for 2011 – 2020, [16]

3. Power system stability

Power system stability refers to a system's ability to operate steadily under normal conditions and to swiftly reestablish a stable equilibrium following disruptions in the network [17]. These disruptions can vary widely from minor events such as gradual load changes and routine control actions to major incidents like the sudden loss of a significant generator or load, or a short circuit occurring on a power line [18].

3.1 Classification of Power System Stability

Power system stability may appear to be a single concern, but it cannot be addressed in isolation. Its instability can manifest in various forms and is affected by

numerous factors. As illustrated in Figure 2, categorizing stability into distinct groups significantly aids in the analysis of stability issues. This categorization helps identify the key factors contributing to instability and supports the development of strategies for maintaining stable operations [19]. The approach is based on the following aspects:

- The physical characteristics of the instability in relation to the primary system parameter where it is observed.
- The magnitude of the disturbance, which is crucial for determining the most effective way to calculate and predict stability.
- The instruments, procedures, and time frame necessary for assessing stability.

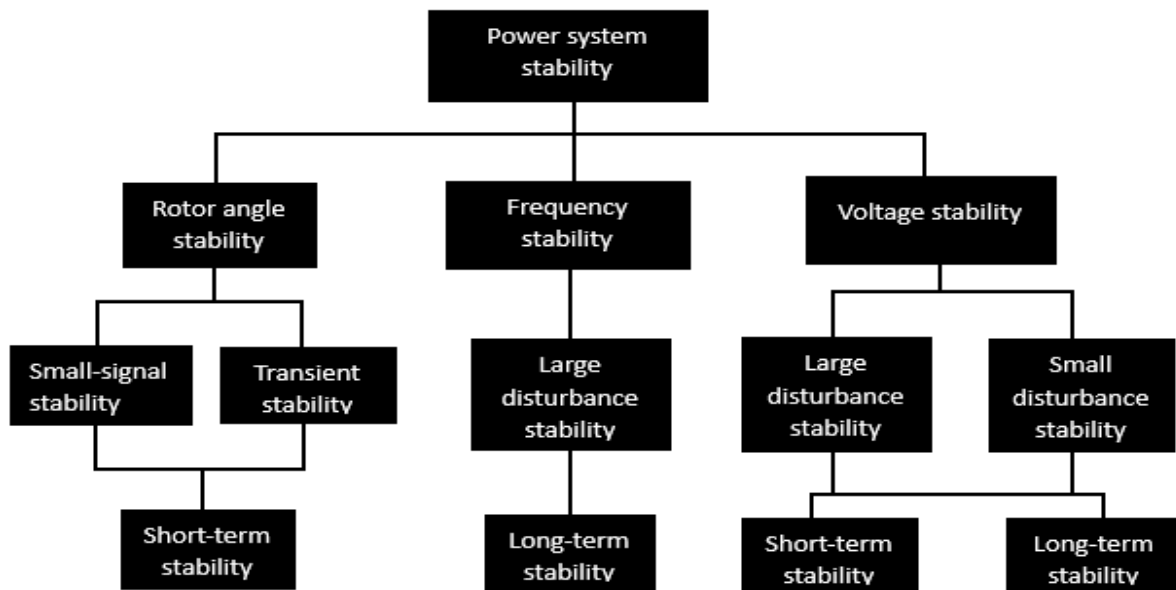


Figure 2: Power system stability Classification [19]

3.1.1 Rotor Angle Stability

Rotor angle stability refers to the capacity of interconnected synchronous machines in a power system to remain synchronized both during normal operation and after experiencing a disturbance [19]. This stability hinges on each machine's ability to keep or re-establish a balance between electromagnetic torque and mechanical torque. One type of instability that may occur is when certain generators experience increasing angular swings, causing them to fall out of sync with others. A critical factor in this aspect of system stability is how the power output of synchronous machines changes with variations in their rotor angles. This issue, often termed the "rotor angle stability problem," involves analyzing the electromechanical oscillations that naturally occur within power systems. When forces act to either accelerate or decelerate one or more machines relative to the others, restoring forces work to bring the machines back into synchronism [19].

Under steady-state conditions, each machine maintains a constant speed because its input mechanical torque and output electrical torque are in balance. However, if a disturbance occurs, this balance is disrupted, and the machine rotors begin to speed up or slowdown in line with the laws governing rotating bodies. For example, if one generator temporarily runs faster than another, its rotor will advance relative to the slower machine. This relative shift leads to a transfer of part of the load from the slower machine to the faster one, a process that is governed by the power-angle relationship. Consequently, the differences in angular separation and speed tend to diminish. The change in electrical torque following a disturbance can be broken down into two parts [19]:

- a. Synchronizing torque component: This component is in phase with the rotor angle disturbance.
- b. Damping torque component: This component is in phase with the speed deviation.

For the system to remain stable, every synchronous machine must have both torque components. Insufficient synchronizing torque can lead to non-oscillatory or

aperiodic instability, while a lack of damping torque may cause oscillatory instability. Rotor angle stability can be classified into two subcategories: small disturbance (or small-signal) rotor angle stability and large disturbance (transient) rotor angle stability [19].

3.1.2 Voltage Stability

Voltage stability is the ability of a power system to keep the voltages at all its buses steady under normal conditions and during disturbances. Instability may occur when the voltage at certain buses gradually falls or rises. Such instability can lead to a loss of load in areas where the voltage becomes too low or compromise the overall integrity of the power system. A continuous decline in bus voltages can also be linked to rotor angles losing synchronism. For instance, if the rotor angles between two groups of machines gradually approach or exceed 180° , this loss of synchronism can cause very low voltages at intermediate network points near the electrical centre where rotor angle stability is not typically an issue—resulting in a prolonged voltage drop characteristic of voltage instability [17].

High levels of active and reactive power flowing through the transmission network's inductive reactance limit the system's power transfer capacity, which in turn causes increased reactive power losses and voltage drops. When some generators hit their field current limits, both power transfer and voltage support become even more restricted. According to Grigsby [19], voltage stability can be classified into two subcategories:

- a. Large Disturbance Voltage Stability: This concerns the system's ability to control voltages following significant disturbances—such as system faults, loss of generation, or circuit contingencies. This ability depends on the characteristics of the system load as well as the interactions between continuous and discrete controls and protection schemes [19].
- b. Small Disturbance Voltage Stability: This deals with the system's response to minor perturbations like

incremental changes in load. It is determined by the properties of the loads and the continuous and discrete controls at any given moment. This concept helps predict how the system voltage will react to small changes. A key criterion for small disturbance voltage stability is that, for every bus in the system at a given operating condition, the bus voltage magnitude should increase when the reactive power injection at that bus is increased. Conversely, if for any bus the voltage magnitude decreases with an increase in reactive power injection, the system is considered unstable. In simpler terms, the system is voltage stable if all buses exhibit positive $V-Q$ sensitivity and unstable if any bus shows negative $V-Q$ sensitivity [19].

Voltage stability phenomena are also classified by the duration of their dynamics:

- a. Short-term Voltage Stability: This involves fast-acting components such as induction motors, electronically controlled loads, and HVDC converters. A typical scenario occurs during hot weather when the system is stressed by high air-conditioning loads and a disturbance, like equipment malfunction, occurs near a load centre [19].
- b. Long-term Voltage Stability: This relates to slower-acting elements such as tap-changing transformers, thermostatically controlled loads, and generator field current limiters. For example, in a heavily loaded EHV network with minimal reactive power reserves, the loss of a heavily loaded transmission line could trigger a significant voltage drop at nearby EHV buses, which would then impact the distribution system [19].

This comprehensive view of voltage stability highlights the importance of maintaining proper voltage control across different timescales and operating conditions to ensure the reliability of the power system.

3.1.3 Frequency Stability

Frequency stability refers to a power system's ability to maintain a steady frequency within an acceptable range after a significant system fault, which creates a major imbalance between power generation and load [20]. Achieving stability requires restoring equilibrium between generation and load while minimizing load loss.

Severe faults in the system often lead to large variations in frequency, power flow, voltage, and other key variables, triggering processes, control mechanisms, and protective actions that are not typically considered in

traditional transient or voltage stability studies. Some of these processes operate at a slow pace, such as boiler dynamics, while others only activate under extreme conditions, like volts/hertz protection that disconnects generators. In large, interconnected networks, such events often lead to islanding, where stability is determined by whether each isolated section (island) of the system can reach a sustainable operating state with minimal loss of load. The overall frequency response of the island dictates its stability rather than the relative movement of individual machines.

Frequency stability issues typically arise from inadequate equipment performance, poor coordination of control and protection systems, or insufficient generation reserves. Studies by Kundur [20], Kundur, *et al.* [21], Chow *et al.* [22] have documented such challenges. During frequency instability, the time scales of responses from various system components vary significantly, ranging from a few seconds (e.g., generator control actions) to several minutes (e.g., responses from prime mover energy supplies and load voltage regulators).

According to Chang [23], the main factors contributing to frequency stability issues include:

- a. A reduction in system inertia, leading to angular and frequency instability.
- b. Decline in voltage stability due to lower energy distribution.
- c. Oscillations at lower frequencies resulting from shifts in power-sharing ratios.

4. Wind Energy Conversion Systems

Unlike conventional power systems, which can be controlled to regulate power output, wind-based energy systems depend on naturally fluctuating wind resources. However, advancements in technology and economic competition have positioned wind power as a major energy source. Its advantages over other renewable sources make it a preferred option for large-scale electricity generation. A wind energy conversion system (WECS) converts wind's kinetic energy into electrical energy or other useful forms of energy. Over the past decade, wind power has expanded significantly due to its environmental benefits and advantages over traditional energy sources [24]. Innovations in technology have not only reduced electricity production costs but also improved the efficiency and reliability of wind turbines [25]. A typical WECS consists of a wind turbine, an electric generator, power transmission lines, and connected loads as shown in Figure 3.

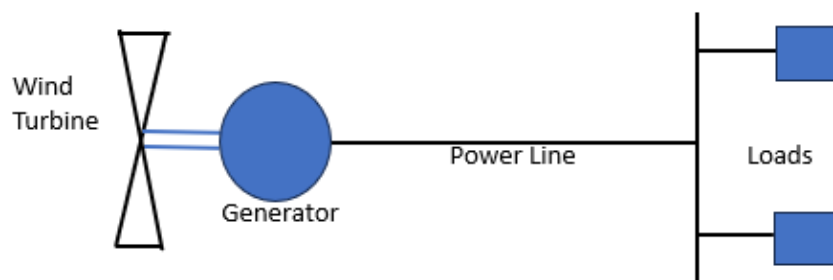


Figure 3: Conversion system of wind energy

Wind turbines can be categorized into horizontal and vertical types based on their axis of rotation. Horizontal-axis wind turbines are the most commonly used in grid-connected wind farms, whereas vertical-axis turbines have their rotor shafts positioned vertically.

The mechanical components of a WECS include the rotor, main shaft, gearbox, mechanical brakes, nacelle, pitch and yaw control systems, and wind measurement instruments. On the electrical side, the system comprises a generator, power converter, step-up transformer, and wind farm collection points or points of common coupling [25].

Wind turbines can be categorized into fixed-speed and variable-speed types. In fixed-speed wind turbines, the rotor is directly linked to the generator, with the stator winding connected to the grid. Examples of wind farms using this setup include those employing squirrel cage induction generators (SCIG) and wound rotor induction generators. These turbines are relatively inexpensive and have a simple design. However, they are unable to adjust to changing wind speeds, making them less efficient than variable-speed turbines.

Conversely, variable-speed wind turbines adjust their operating speed based on wind conditions, optimizing energy capture. However, they require a complex power electronics converter, making them more costly than fixed-speed turbines [26]. Variable-speed systems commonly utilize permanent magnet synchronous generators, DFIG-based generators, and wound rotor synchronous generators [27]. While they offer superior energy efficiency,

cost remains a key consideration, with DFIG-based generators being a widely adopted choice for variable-speed wind technology.

5. Solar-Grid Integration

Solar-grid integration is a method that facilitates the large-scale introduction of solar power from photovoltaic (PV) systems into the existing electrical grid. This process requires extensive planning, covering aspects such as solar component production, installation, and utilization. Understanding how different levels of solar energy integration affect the grid is crucial for effective implementation [28].

The inverter is one of the most critical components in a grid-connected photovoltaic system, as it converts the direct current (DC) generated by PV modules into alternating current (AC), which is used by most electrical devices. Inverters must ensure stable voltage and frequency despite load fluctuations and manage reactive power if needed [28].

A solar-grid integration network enables substantial PV power penetration into the national utility grid. This is a key technological advancement as it enhances energy efficiency in buildings, improves PV system economics, reduces operational costs, and benefits both consumers and utilities [29]. With the increasing shift toward renewable energy sources over fossil fuels, many countries have widely adopted solar-grid integration [30].

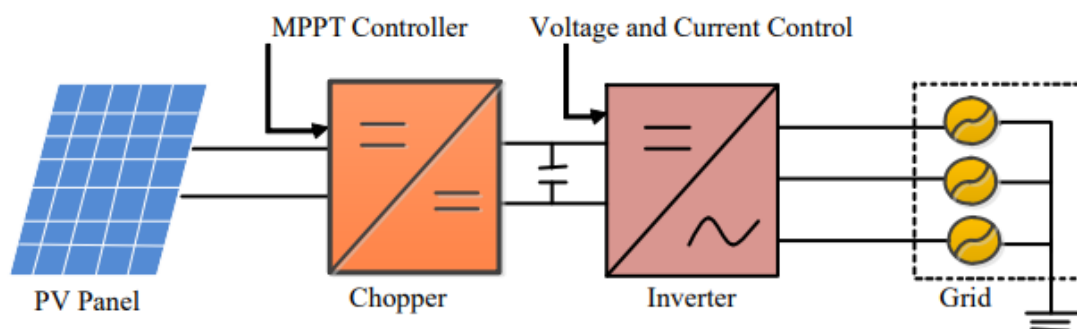


Figure 4: Grid connected solar system (GCSS) main component [30]

In a conventional power distribution system, electricity flows from centralized generators to substations and then to consumers. However, solar energy generation introduces bidirectional power flow, which traditional electrical distribution systems were not designed to handle. In areas with long feeder circuits serving rural or developing regions, mismatches between PV generation and load demand can impact system parameters [31]. If PV generation surpasses local energy demand, excess energy may flow back through the distribution feeder and even the substation, potentially affecting the stability of the utility grid and other connected consumers [31].

6. Components of Power System

Key components of a power system include traditional synchronous generators, doubly fed induction generator (DFIG)-based wind generators, loads, flexible AC transmission system (FACTS) devices, high-voltage

direct current (HVDC) links, and power oscillation damping controllers. A detailed mathematical representation of these components is necessary for stability analysis [27, 64].

When analysing power system stability through model-based approaches, the system is represented as a mathematical model, and its stability is determined using eigenvalues. Several indicators—such as participation factors, mode forms, polarity, controllability, observability, and sensitivity—are used for eigenvalue assessment. Since power system eigenvalues typically have an imaginary component, their real part indicates stability: negative values represent stable states with damping oscillations, while positive values indicate instability. If the eigenvalues are conjugate, the real part determines the damping magnitude, with a positive value signifying stability. The imaginary component represents oscillation frequency [32]. When an eigenvalue is less than, equal to,

or greater than zero, it respectively signifies a stable state, a critical state, or an unstable system.

7. Fundamental Concepts Review

This section presents a review of research on various topics, including wind and solar power generation, renewable energy micro grids (comprising solar, wind, and storage systems), large-scale renewable energy integration into utility grids, power system stability analysis, cost reduction strategies, and performance optimization.

The global shift towards sustainable energy systems has increased the focus on Distributed Generation (DG), particularly solar photovoltaic (PV), due to rising environmental concerns and energy demands. According to Ackermann, *et al.* [33], DG refers to small-scale power generation located close to the load centre, which helps reduce transmission losses and improves overall system reliability. Shukla, *et al.* [34] highlighted the role of solar PV in promoting low-carbon energy transitions, while the International Energy Agency [35] stressed its growing relevance in meeting global electricity needs. Distributed energy solutions are increasingly considered vital in reducing carbon emissions and enhancing grid resilience, especially in developing regions.

Despite extensive literature on DG, gaps remain in integrating technical, economic, and policy aspects into a single framework. Al Abri, *et al.* [36] and Hung, *et al.* [37] provided insight into optimal sizing and siting of DG to reduce power losses and improve voltage profiles. However, many studies, such as Hiremath, *et al.* [38], have focused primarily on rural electrification potential without incorporating cost-effectiveness or policy feasibility. Ghosh, *et al.* [39] examined regulatory challenges in India, revealing how policy bottlenecks hinder DG adoption. In similar lines, Chauhan and Saini [40] explored barriers related to financial viability, technical expertise, and regulatory infrastructure. Furthermore, Ghosh, and Ghosh [41] and Rizwan, *et al.* [42] emphasized the need for integrated models to support evidence-based decision-making for DG integration.

To address these multidimensional gaps, this study adopts a mixed-methods approach combining technical simulation and economic analysis. Singh and Parida [43] implemented hybrid models to analyze the effect of DG on distribution networks, supporting the integration of HOMER Pro and MATLAB/Simulink for comprehensive assessments. Niknam, *et al.* [44] demonstrated the effectiveness of multi-objective optimization in DG planning. Meanwhile, Adefarati, *et al.* [45] advocated for incorporating reliability and economic indices in the planning process. The methodological framework in this study is designed to model real-world conditions through case-based simulations to assess the effectiveness of solar PV integration under various operating scenarios.

The data used for simulations are drawn from both primary and secondary sources. Reddy, *et al.* [46] and Khan, *et al.* [47] stressed the significance of using accurate load and irradiance profiles for modeling purposes. Inputs like solar radiation, load curves, and system configurations are gathered to evaluate system responses across

different DG penetration levels. NREL [48] and Adefarati, *et al.* [49] also provided valuable secondary data for resource mapping and demand profiles. These simulations are configured to measure voltage stability, system losses, and network performance under dynamic loading conditions.

The results reveal substantial improvements in voltage regulation and a significant reduction in technical losses when DG is optimally located and properly sized. Nikna, *et al.* [50] and Abidin, *et al.* [51] validated these technical benefits, while Adeuyi, *et al.* [52] reported favourable cost-benefit ratios in Nigeria. Mutarraf, *et al.* [53] further confirmed improved reliability metrics in DG-enabled micro grids. From an economic perspective, studies by Rauf, *et al.* [54], Das, *et al.* [55] and Wamukonya [56] showed that the high initial investment cost of solar PV is compensated by long-term energy savings, government incentives, and environmental benefits. Additionally, Afonaa-Mensah, *et al.* [57] demonstrated the importance of tariff structures and financial models in determining the economic viability of solar PV systems.

The integration of solar PV-based DG presents compelling technical and economic advantages. However, supportive policy frameworks and institutional capacities are crucial for realizing these benefits. As highlighted by Aliyu, *et al.* [58], inadequate regulatory support remains a major barrier to solar PV deployment in Sub-Saharan Africa. Rauf, *et al.* [54] and World Bank [59] proposed reforms in grid codes, incentives, and training programs to promote DG integration. Finally, IRENA [60], IEA [61] and World Bank [62] emphasized the importance of cross-sectoral collaboration and public-private partnerships in scaling distributed energy solutions. Therefore, this study recommends an integrated policy, technical, and economic approach tailored to local conditions for successful solar PV deployment in power distribution networks.

The integration of renewable energy sources into power systems has prompted significant research interest in improving voltage and small signal stability. Abhinav, and Ratnesh [63] explored the use of Static Var Compensator (SVC) to dampen power system oscillations, demonstrating its effectiveness through eigenvalue analysis. Similarly, Karthikeyan [64] assessed the role of STATCOM in shifting system eigenvalues, thus enhancing small signal stability. These findings emphasize the value of Flexible AC Transmission System (FACTS) devices in improving system dynamics.

Wind power integration introduces complex challenges due to its variability and asynchronous nature. Abhinav and Pindoriya [65] provided a comprehensive review of grid integration of wind turbines with battery energy storage systems, discussing the need for robust converter control strategies to manage active/reactive power and enhance voltage stability. Bi and Gao [66] supported this view by analyzing voltage stability under different fault conditions, highlighting the need for coordinated control of multiple renewable sources for maintaining system integrity.

The evolving structure of power systems has also driven attention toward analytical methods for voltage

stability. Liang, *et al.* [67] reviewed various approaches such as L-index, modal analysis, and V-Q sensitivity analysis, and underlined the necessity of improving coordination between asynchronous and synchronous generation to manage the increased complexity of renewable-dominated grids.

Despite these advancements, further work is still necessary. Abhinav and Ratnesh [63] called for future studies to investigate the impact of renewable penetration on system modes. Karthikeyan and Dhal [64] suggested exploring optimization algorithms beyond the PSAT platform. Furthermore, Abhinav and Pindoriya [65] recommended focusing on the dynamic behaviour of wind systems, emphasizing efficient dispatch and frequency regulation.

In conclusion, the literature highlights gaps in analytical precision and controller optimization. Lian, *et al.* [67] noted limitations in the accuracy of stability margin calculations due to the complexity of modern systems. Bi and Gao [66] identified that while wind energy enhances voltage support, effective control must consider various operating conditions and fault scenarios to prevent instability.

8. Conclusion

The literature review indicates that several factors influence the high penetration of solar PV and wind energy, including system size, location, type, reserves, displacement of conventional generators, reactive power compensation, and control mechanisms. Considerable efforts have been made to address stability challenges associated with integrating large-scale solar and wind-based micro grids into the power grid. However, most studies focus on specific stability issues rather than adopting a unified approach.

Beyond stability, dispatching strategies and spinning reserves are also essential for future power systems with high renewable energy penetration, highlighting the need for further research in these areas. The integration of these energy sources into the grid presents challenges due to their inherent variability, which raises stability concerns, particularly in off-grid systems.

Globally, there is a strong shift toward renewable energy to minimize greenhouse gas emissions and enhance energy security. Over the past decade, the capacity of renewable energy sources, especially solar PV and wind, has grown significantly. To facilitate large-scale integration in future power systems, it is essential to address stability concerns related to voltage, frequency, and rotor angle while also developing standardized integration practices. Overall, the document emphasizes the necessity of a comprehensive approach and further research to ensure the stable and reliable incorporation of renewable energy into power grids.

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