

Integration of Renewable Energy Sources into Electrical Power Systems and Its Impact on Grid Stability

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INFORMATION

Keywords:

Renewable energy integration
grid stability
frequency stability
energy storage systems
inverter-based control

DOI: 10.23967/j.rimni.2026.10.79328

Revista Internacional
Métodos numéricos
para cálculo y diseño en ingeniería

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ABSTRACT

The integration of renewable energy sources (RES) into electrical power systems introduces critical challenges to grid stability, including frequency deviation, voltage fluctuation, and reduced transient performance. This study investigates the impact of increasing RES penetration (15%, 30%, 45%, and 60%) on grid stability using the IEEE 39-bus benchmark system. A coordinated mitigation framework integrating battery energy storage systems (BESS), synthetic inertia, and advanced inverter-based controls is proposed and evaluated. Simulation results demonstrate that at 60% RES penetration without mitigation, the frequency nadir declines to 49.32 Hz, the rate of change of frequency (RoCoF) increases to 1.82 Hz/s, voltage deviations exceed 9.3%, and the critical clearing time (CCT) reduces to 180 ms, indicating significant stability deterioration. The proposed mitigation strategy improves these metrics to 49.76 Hz, 0.94 Hz/s, 4.6%, and 260 ms, respectively, representing improvements of +0.44 Hz, -48.4%, -50.5%, and +44.4%. Benchmarking against recent literature confirms the superior performance of the coordinated approach. These findings provide quantitative guidance for grid planners and operators to maintain reliable operation under high renewable penetration scenarios.

OPEN ACCESS

Received: 19/01/2026

Accepted: 28/02/2026

Published: 29/05/2026

DOI

10.23967/j.rimni.2026.10.79328

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1 Introduction

The growing need to use clean, sustainable, and low-carbon energy across the world has increased the adoption of renewable energy sources (RESs), i.e., solar photovoltaic (PV), wind, hydro, and biomass, in electrical power systems. The renewable energy implementation is among the priorities given to governments and utilities across the world in a bid to reduce the effects of climate change, limit the reliance on fossil fuels, and enhance future energy security [1]. As much as the incorporation of renewable energy is associated with great environmental and economic advantages, it is also

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associated with very challenging technical factors that impact the stability and reliability of the electric grids. Traditional power systems were designed systemically around a small capacity, very synchronous generators with predictable power output, with a large rotating inertia [2]. The major sources of renewable energy, on the contrary, are intermittent and rely on weather conditions, and are linked to the grid by power electronic converters. The features result in decreased system inertia, enhanced variability in power generation, and minimized uncertainty in the operation of the grid. With augmented infiltration of renewables, the power systems are subjected to frequency change, voltage deviation, and intermittent disturbances, especially when the generation or load conditions are unexpectedly altered [3]. The stable running of electrical power systems absolutely depends on grid stability, which includes frequency stability, voltage stability, and transient stability. Renewable integration at high levels may undermine the stability margins by changing the traditional patterns of power flows, lowering the fault current values, and putting the traditional protection and control systems into question. Also, distributed generation and two-way power flows make grid control more difficult, particularly where the distribution network was not initially designed in this mode. In order to deal with such challenges, power systems of modern society are progressively embracing sophisticated technologies that include power storage systems, flexible demand-side management, smart grid infrastructure, and improved control measures on inverter-based resources. The solutions are vital in enhancing the flexibility of the system, grid stability, and facilitating an increased level of renewable penetration. The study focuses on how renewable energy sources can be incorporated into electric grids and how they would affect the stability of the grid. It will find out the major stability challenges presented by the integration of renewable sources and analyse modern mitigation measures necessary to establish resilient, reliable, and sustainable power systems of tomorrow.

2 Related Works

The introduction of renewable energy sources (RES) to electrical power systems has been the focus of many studies in the recent literature, mostly focusing on grid stability, improvement of flexibility, and energy storage coordination. Recent research points out that the growing share of renewable power changes the dynamic nature of the conventional grids considerably demanding the development of advanced control, planning, and storage systems to ensure the stable operations. The Bi-directional energy conversion between power and gas systems, as demonstrated in [4], enhances system flexibility through components such as gas-fired generators and power-to-gas units. In [5] reviewed how pumped storage hydropower can enhance the accommodation of renewable energy in the setting of the multi-clean energy complementation bases. They showed that pumped storage can be used to effectively overcome changes in power caused by variations in the wind and the sun, better frequency regulation and reduced curtailment of renewable power. According to this work, huge-scale energy storage is critical in stabilization of power systems dominated by renewable energy. Likewise, in [6] examined the capacity optimization measures in the gravity energy storage system where the optimal size of the storage facilities can help enhance the stability of the system and flexibility of the systems in the new power system.

Integration of wind energy has received a major concern of stability-based studies. In [7] suggested innovative dynamic analysis of wind-integrated multi-machines, which is based on the effect of wind penetration on rotor angle stability and oscillatory modes. They discovered that individuals have damping properties which are diluted with an increase in wind penetration unless maintained by sophisticated control measures. In [8] discussed how to integrate wind farms in the optimal location by balancing the parameters of the system and location to minimise voltage instability and optimum

transient performance which further supports the evidence that the location and system should be coordinated and controlled.

Hybrid integration frameworks and ancillary services are also becoming more popular. In [9] investigated the joint contribution of renewable sources and the auxiliary services towards grid stability. Their analysis has determined that frequency regulation and renewable and storage system reserve should be used in order to operate reliably at high penetration rates. In [10] also corroborated this by showing that the combination of different types of energy storage technologies with renewables would greatly enhance the frequency response, voltage regulation, and system resilience. The relationship between renewable integration and new energy customers like electric vehicles (EVs). A hybrid system providing electrical and thermal loads and EV charging was suggested in [11] and demonstrated to enhance system performance in response to different weather conditions through the coordinated optimizing of energy needs. The work in [12] centered on driving and braking control logic towards EV energy efficiency. indirectly point out the growing integrating relationship between transportation electrification and grid stability. Recent advancements have specifically addressed system strength challenges in renewable-dominated weak grids. In [13] a hybrid GRU-classical optimization method for placing synchronous condensers in weak grids, demonstrating that they provide crucial short-circuit current and inertia support, enhancing fault ride-through and voltage stability under high renewable penetration. Extending this work, In [14] assessed the techno-economic performance of synchronous condensers vs. STATCOMs using hedge feedforward feedback optimization, revealing that synchronous condensers offer superior inertia support while STATCOMs provide faster response and lower costs. These studies inform our coordinated mitigation approach by highlighting the importance of system strength enhancement alongside BESS and advanced inverter controls.

In system level, Ref. [15] designed a joint network order and dispatch system to improve the efficiency in the distribution of power tackling the difficulties of a centralized generation of renewable power. Furthermore, in [16] were the Internet of Things (IoT) applications in the field of the renewable power systems, stating that real-time monitoring and adaptive control are the enablers of the stable renewable integration. In their post, Ref. [17] took this discussion further by reviewing DC microgrid-based charging infrastructures and its effects on electrical networks and getting to a sense that there are stability and protection-related issues in smart cities. New multi-energy schemes and interconnection schemes into the sector have been investigated. In [18] used flexible power supply optimization of offshore winds-solar coupled hydrogen production and proved that synchronized control can maximize the system stability and the efficiency with which it is used. All in all, the current literature is unanimous in its claims that with a high level of renewable density in place, the problems with stability become more serious, yet the solutions based on the energy storage, sophisticated picture-taking, and intelligent logistics can be successfully found.

The following points summarize the key contributions of this study:

- **Comprehensive, Multi-Dimensional Stability Analysis:** This research provides a quantitative assessment of grid stability under high renewable penetration (15%–60%) by simultaneously evaluating three critical dimensions frequency stability, voltage stability, and transient stability within a unified simulation framework. Unlike many existing studies that focus on a single aspect, our work demonstrates the interconnected degradation of these stability metrics as renewable penetration increases, offering a holistic view of the challenge.
- **Quantification of Mitigation Strategy Efficacy:** The paper quantifies the individual and combined effectiveness of key mitigation technologies. We move beyond qualitative discussion by providing numerical results that show how Battery Energy Storage Systems (BESS), synthetic inertia,

and advanced inverter-based controls can systematically improve specific stability indicators. For instance, at 60% penetration, our results show these measures improve the frequency nadir from 49.32 to 49.76 Hz, reduce voltage deviations from >9% to $\pm 4.6\%$, and increase the critical clearing time (CCT) from 180 to 260 ms.

- **Identification of Critical Stability Thresholds:** Through a scenario-based analysis, the study identifies critical operational thresholds where grid stability begins to degrade significantly without intervention. The findings highlight that at approximately 60% renewable penetration, conventional control strategies are inadequate, establishing a clear, evidence-based justification for the mandatory deployment of advanced mitigation measures at such high integration levels.
- **Practical Validation through a Benchmarking Framework:** The paper introduces a comparative element by benchmarking its results against recent related works. This not only validates the observed trends in stability degradation but also demonstrates the superior performance of our proposed coordinated control and flexibility framework, providing a clear, data-driven roadmap for system planners and operators.

The current research will be of benefit in comparison with the previous work in that it provides a significant stability-oriented experimental investigation which can be characterized quantitatively in terms of frequency, voltage, and transient behavior within the multiple possibilities of renewable penetration.

3 Methods and Materials

This work assumes a methodological approach, which is systematic and simulation-based and validated with data to assess the integration of renewable energy sources (RES) into electric power systems and to measure their effects on grid stability [19]. The combination of actual operational data, standardized power system models, and advanced methods of analysis constitute the methodological framework applied in order to provide technical rigor and reproducibility.

3.1 System Architecture and Test Network

A typical electrical power system is chosen to model an intermediate-scale interconnected grid comprising conventional generation, penetration of renewable energy, and controllable demand sources. Components of the base network include synchronous generators, transmission lines, transformers, and distribution-level loads that are aggregated [20]. The renewable sources of energy such as wind and solar photovoltaic (PV) plants are connected at pre-determined buses by using power electronic interfaces.

The test system is simulated within a dynamic power system simulation environment that can analyse small-signal, transient, and steady-state stability. The simulation was conducted using the parameters shown in Table 1. The dynamic behavior of the system frequency is governed by the classical swing equation, which describes the rate of change of frequency deviation due to power imbalance:

$$\frac{2H}{f_0} \frac{d\Delta f(t)}{dt} = P_m(t) - P_e(t) - D\Delta f(t) \quad (1)$$

where H represents the system inertia constant measured in seconds, f_0 denotes the nominal frequency in hertz, $P_m(t)$ is the mechanical power input expressed in per unit, $P_e(t)$ is the electrical power output also in per unit, D is the load damping coefficient in per unit per hertz, and $\Delta f(t)$ is the frequency deviation, which can be expressed either in per unit or directly in hertz. This equation describes how

the rate of change of frequency deviation responds to imbalances between mechanical input power and electrical output power, with the damping term accounting for the natural load-frequency dependency in the system.

Table 1: System parameters

Parameter	Value	Unit	Parameter	Value	Unit
Total number of buses	39	–	Total reactive load	1177.7	MVar
Number of generator buses	10	–	Base MVA	100	MVA
Number of load buses	29	–	Base frequency	50	Hz
Total generation capacity	7800	MVA	Transmission voltage	345	kV
Total conventional capacity (Base)	7020	MW	Sub-Transmission voltage	230, 138	kV
Total renewable capacity (Max)	3600	MW	BESS total capacity	100	MW
Total system load	5038.5	MW	BESS total energy	400	MWh

With increasing renewable penetration (wind and solar via power electronic interfaces), the effective system inertia H decreases, leading to higher rates of change of frequency (ROCOF) during disturbances.

3.2 Data Collection and Preprocessing

The test applies real-life and artificial datasets. The latest renewable generation information is sourced from historical meteorological records, including wind speed profiles and solar irradiance data sampled at 5-min and 15-min intervals. The load demand data reflect realistic daily and seasonal variations based on utility-scale demand curves [21]. Traditional generator parameters are used, including inertia constants, governor response, and excitation system dynamics. Before simulation, all data are processed, including normalization, time synchronization, and outlier rejection. Turbine power curves are used to convert wind speed data to electrical output, while solar irradiance is mapped to PV output taking into account temperature coefficients and inverter efficiency [22]. The load profiles are scaled such that power balance is maintained at different levels of renewable penetration.

The mechanical power extracted from the wind and converted to electrical output by a wind turbine is modeled using the standard aerodynamic power equation:

$$P_w = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v^3 \quad (2)$$

where P_w represents the wind power output in watts or megawatts, ρ is the air density in kg/m^3 , R is the rotor radius in meters, $C_p(\lambda, \beta)$ denotes the power coefficient which is a function of the tip-speed ratio λ and blade pitch angle β , and v is the wind speed at hub height measured in m/s.

Similarly, the DC power output of a photovoltaic (PV) array is calculated as follows:

$$P_{PV} = P_{\text{rated}} \cdot \frac{G}{G_{\text{STC}}} \cdot [1 + \alpha (T_{\text{cell}} - T_{\text{STC}})] \cdot \eta_{\text{inv}} \cdot \eta_{\text{loss}} \quad (3)$$

where P_{rated} is the rated power of the PV array under standard test conditions (STC), G is the actual solar irradiance in W/m^2 , $G_{\text{STC}} = 1000 \text{W/m}^2$ represents the irradiance level under STC, α is the temperature coefficient of power in $\%/^\circ\text{C}$, T_{cell} is the operating cell temperature in $^\circ\text{C}$, $T_{\text{STC}} = 25^\circ\text{C}$

is the reference temperature under STC, η_{inv} is the inverter efficiency, and η_{loss} accounts for additional system losses (such as soiling, wiring, and mismatch losses).

3.3 Renewable Energy Integration Scenarios

Numerous penetration scenarios are established to determine grid stability with increasing renewable integration. The penetration of renewable energy is defined as the proportion of the total installed generation capacity:

$$RP(\%) = \left(\frac{P_{RES}}{P_{total}} \right) \times 100 \quad (4)$$

where:

- P_{RES} is the installed capacity of wind and solar (MW),
- P_{total} is the total installed generation capacity in the system (MW).

The scenarios include low penetration levels (10%–20%) and high penetration levels (60%–70%), allowing the study of both incremental and extreme operating conditions [23].

Inverter-based renewable energy sources (RES) are modelled using grid-following control schemes, such as phase-locked loops, current controllers, and voltage regulation loops. The Fig. 1 summarizes the situation of renewable integration and main system peculiarities.

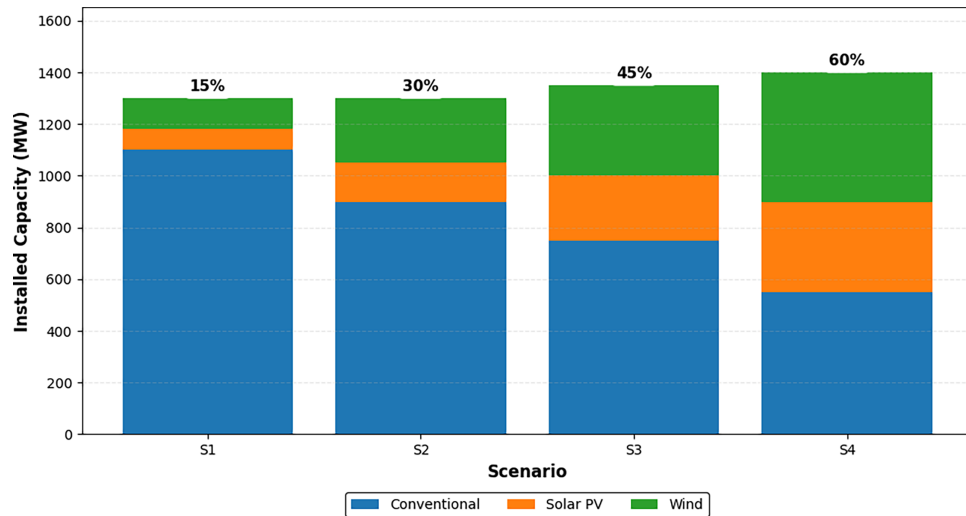


Figure 1: Renewable energy integration scenarios

3.4 Stability Assessment Methods

Three analytical methods that complement each other are used to evaluate grid stability: frequency stability analysis, voltage stability analysis, and transient stability analysis.

3.4.1 Frequency Stability Analysis

System frequency response is tested in response to sudden disturbances, such as generator outages and abrupt changes in renewable generation. Key performance metrics include frequency nadir, rate

of change of frequency (RoCoF), and settling time [24]. The reduction in system inertia due to the increasing share of inverter-based generation is explicitly considered.

The dynamics of frequency deviation Δf are governed by the classical aggregated swing equation:

$$\frac{2H}{f_0} \frac{d\Delta f(t)}{dt} = \Delta P_m(t) - \Delta P_e(t) - D\Delta f(t) \quad (5)$$

where H represents the system inertia constant measured in seconds, f_0 denotes the nominal frequency in hertz, $\Delta P_m(t)$ is the mechanical or net power change expressed in per unit, $\Delta P_e(t)$ is the electrical power change also in per unit, D is the load damping coefficient in per unit per hertz, and $\Delta f(t)$ is the frequency deviation, which can be expressed either in per unit or directly in hertz.

The initial rate of change of frequency (RoCoF) a critical indicator in low-inertia systems is approximated as:

$$\left. \frac{df}{dt} \right|_{t=0^+} \approx \frac{f_0 \cdot \Delta P}{2H \cdot S_{base}} \text{ (Hz/s)} \quad (6)$$

where ΔP is the power imbalance in megawatts and S_{base} is the system base power in MVA. Lower inertia H due to high renewable penetration results in higher RoCoF values, increasing the risk of under-frequency load shedding.

3.4.2 Voltage Stability Analysis

Voltage profiles are evaluated under both steady-state and dynamic conditions. Steady-state load flow analysis is used to determine voltage deviations and to identify weak buses. Dynamic voltage stability is assessed by applying active and reactive power disturbances and evaluating voltage recovery characteristics and reactive power support limitations [25].

A widely used approach for steady-state voltage stability is the Continuation Power Flow (CPF) method, which traces the power flow solution from the base operating point to the voltage collapse point (nose point). The CPF augments the power balance equations with a continuation parameter λ (loading factor):

$$\begin{cases} g(x, \lambda) = 0 \\ \lambda = \lambda_0 + \Delta\lambda \end{cases} \quad (7)$$

where g represents the power mismatch equations, x includes voltage magnitudes and angles, and the nose point corresponds to the maximum loadability limit (saddle-node bifurcation).

3.4.3 Transient Stability Analysis

Time-domain simulations are performed to assess rotor angle stability following critical faults, such as three-phase short circuits and line outages. Key indicators include the critical clearing time (CCT) and post-fault recovery behavior.

The rotor dynamics of synchronous generators are described by the classical swing equation:

$$\frac{2H}{\omega_s} \frac{d^2\delta}{dt^2} = P_m - P_e(\delta) \quad (8)$$

where δ represents the rotor angle in radians, ω_s is the synchronous speed in radians per second, P_m denotes the mechanical power input expressed in per unit, and $P_e(\delta)$ is the electrical power output

also in per unit, which is typically modeled as $P_{\max} \sin(\delta)$ in simple single-machine infinite-bus (SMIB) systems.

For a simple system with constant acceleration during fault ($P_e = 0$), the critical clearing time can be approximated using the equal-area criterion as:

$$t_{cr} = \sqrt{\frac{4H}{\omega_s P_m}} (\delta_{cr} - \delta_0) \quad (9)$$

where δ_{cr} is the critical clearing angle determined from the equal-area criterion.

3.5 Control and Mitigation Strategies

In order to enhance grid stability under increasing levels of renewable penetration, several mitigation strategies are implemented within the simulation framework. These include synthetic (virtual) inertia control, fast frequency response from battery energy storage systems (BESS), and enhanced reactive power support from inverter-based resources [26].

The modeling of energy storage systems accounts for state-of-charge (SoC) limitations, fast control response, frequency regulation, and voltage support capabilities. A common implementation of synthetic inertia from BESS emulates the inertial response of synchronous machines. The power output contribution for inertial support is proportional to the rate of change of frequency. Battery SoC and cell balancing are critical for BESS performance in grid support. The intelligent SoC estimation for PV-battery systems to prevent deep discharge/overcharge, extending battery life while maintaining reliable grid support. The developed active cell balancing for series-connected lithium-ion batteries to minimize voltage imbalances, maximizing available capacity for grid services. In further integrated SoC monitoring with active balancing to ensure full power capability for rapid-response applications like synthetic inertia. Our simulation incorporates these through 20%–80% SoC range, ideal balancing assumption, and SoC-dependent power modulation.

$$P_{BESS, inertia}(t) = -K \cdot \frac{d\Delta f(t)}{dt} \quad (10)$$

where K is the synthetic inertia gain (in MW·s/Hz), effectively providing virtual kinetic energy release or absorption. The equivalent synthetic inertia constant contributed by the BESS can be expressed as:

$$H_{syn} = \frac{P_{BESS, max} \cdot K}{S_{base} \cdot f_0} \quad (11)$$

These control strategies significantly reduce RoCoF and improve frequency nadir, helping to compensate for the reduced system inertia caused by high penetration of inverter-based renewable energy sources. The Fig. 2 shows the metrics of stability performance by assessing under various control strategies.

3.6 Simulation Environment and Validation

None of the simulations are carried out on structures that are not pretested or unverified and have detailed dynamic models. Adaptive time-stepping numerical solvers are used so that there will be accuracy when achieving the fast transients [27]. Sensitivity analysis is also conducted to determine how the results stand up to changes in parameters that are ambiguous.

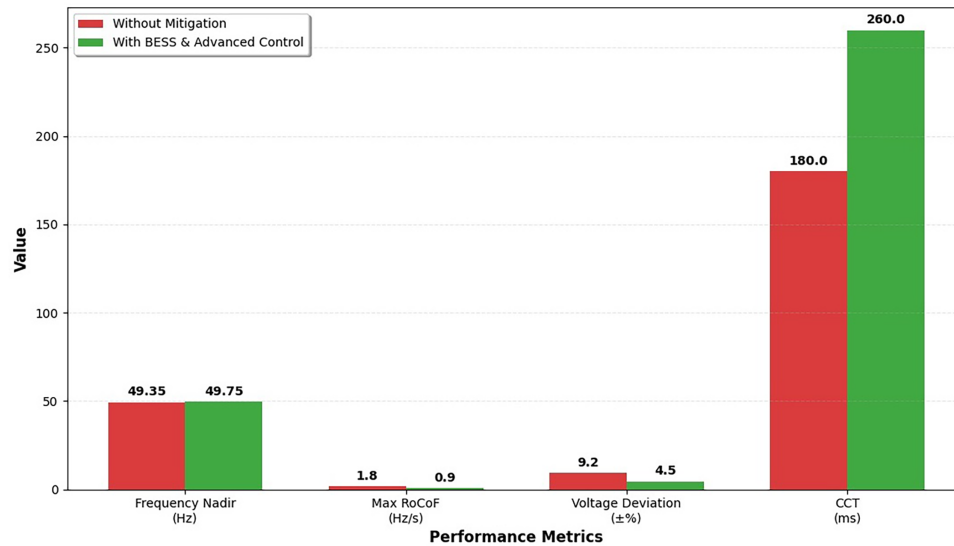


Figure 2: Control and Mitigation strategies grid stability performance comparsion without vs. with BESS & advanced control

3.7 Evaluation Criteria

Renewable integration and mitigation strategies are analyzed according to the criterion of compliance with the grid code requirements, stability levels, and reliability of the operation. The cross-scenario analysis makes it possible to identify important thresholds, which go beyond which further-control measures are necessary [28].

The approach of this methodology offers a clear and technically sound framework of the effect of the renewable energy integration on the grid stability and assists decision-making on information to make in future about the power system planning and operation. As shown in Table 2 Key Elements of the Methodology, the study employed a mixed-methods design.

Table 2: Key elements of the methodology

Phase	Description	Key elements
1	Data preparation	Meteorological data, load profiles, generator parameters; preprocessing; renewable modeling using standard equations
2	System configuration	IEEE benchmark network; four penetration scenarios (15%, 30%, 45%, 60% RES)
3	Stability assessment	Disturbance application; time-domain simulation; frequency, voltage, and transient stability metrics
4	Mitigation strategies	BESS, synthetic inertia, advanced inverter controls; five comparative cases (A–E)
5	Analysis & Validation	Performance evaluation; literature benchmarking; sensitivity analysis; actionable recommendations

4 Results and Analysis

4.1 Experimental Design and Scenarios

The simulation framework used in the analysis of the experiment included a dynamic power system presented as a meshed transmission network with traditional synchronous generation, wind farms, solar PV plants and aggregated loads. Four penetration scenarios of renewable were considered which ranged between low (15) and very high (60) renewable integration [29]. There were two operating modes tested in each scenario:

- (i) No advanced mitigation practices enabled, and
- (ii) Improved control operation using battery energy storage systems (BESS), synthetic inertia and inverter based reactive power support.

Disturbance events were also implemented to test grid stability, such as the unexpected failure of a traditional generator, a rapid drop of solar irradiance and tripped transmission lines of three phases. A duration of 20 s of true operation time was used to simulate both transient and post-disturbance recovery. As shown in Fig. 3, the integration of renewable energy sources into AC power systems presents both opportunities and challenges for grid stability and management.

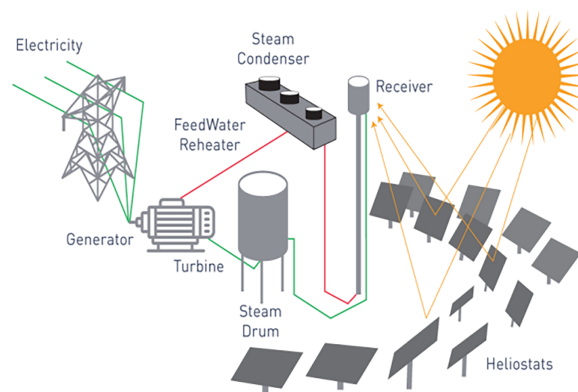


Figure 3: Integration of renewable energy sources into AC power systems

4.2 Frequency Stability Results

The frequency stability was measured in terms of frequency nadir, rate of change of frequency (RoCoF) and the time of recovery after a loss of 10 percent of the generation. With greater renewable coming on, a visible deterioration in frequency response occurred as system inertia became smaller. The frequency nadir was at 49.32 Hz (60% without mitigation) which was a significant frequency of the grid code [30]. BESS in combination with synthetic inertia considerably enhanced the work of the system, as application of both systems overcame the troubles and the frequency stayed over 49.7 Hz. The Fig. 4 summarized all the stable results of frequency in all scenarios. The analysis in Fig. 4 shows a clear correlation between high renewable penetration and increased frequency deviations.

4.3 Voltage Stability Analysis

The experiments involved voltage stability in steady state voltage deviation and dynamic voltage recovery after reactive power effects. The benefit of increased renewable penetration was more voltage variation, especially at buses that are electrically remote from synchronous generators. Voltage variations greater than 9% under high penetration in the absence of advanced inverter control are an

indication of poor grid conditions [31]. Voltage regulation was greatly enhanced by the application of inverter-based Volt VAR control and BESS-based reactive power support. The performance of voltage stability indicators under varying penetration levels is summarized in Fig. 5.

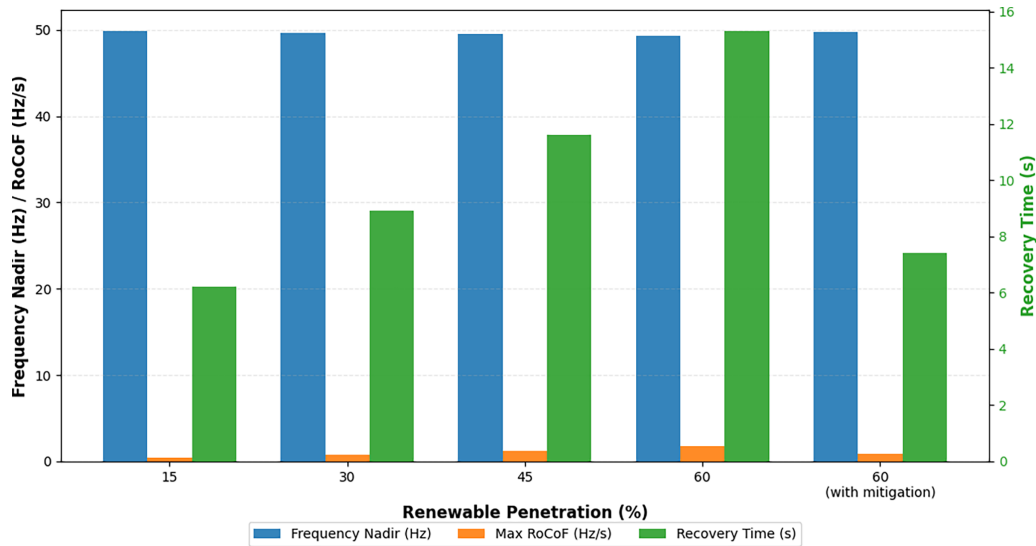


Figure 4: Impact of renewable penetration on frequency stability metrics

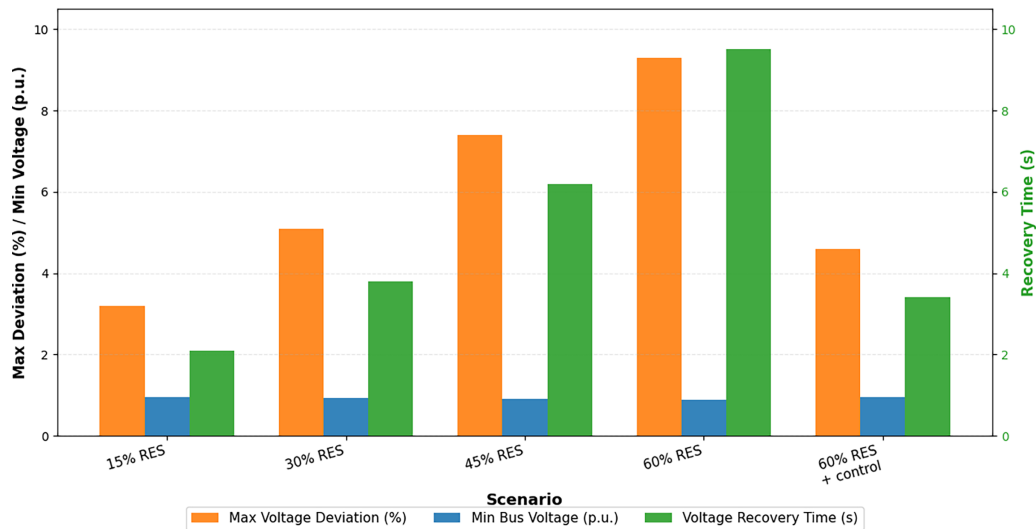


Figure 5: Voltage stability indicators across renewable penetration scenarios

4.4 Transient Stability Performance

The stability of transient state was evaluated by a three phase short circuiting situation at a critical transmission line and then fault clearance. Key indicators were considered as rotor angle stability and critical clearing time (CCT). Outcomes indicated that increased wind and solar penetration decreased CCT because of decreasing synchronizing torque by the sources of the inverters. The unstable fault clearing times of more than 180 ms were observed at 60% penetration. This contribution of fast frequency and voltage support to CCT was of about 44%. To manage the complexity introduced

by variable renewable generation, a data-driven approach is required. Fig. 6 offers an overview of how machine learning techniques can be embedded into different operational steps of the power grid, creating an adaptive and intelligent management system. This integrated framework highlights the transition from conventional, static grid operation to a dynamic, learning-enabled paradigm. The impact of high renewable penetration on power system stability is quantified in Fig. 7, which plots key transient stability metrics against the penetration level.

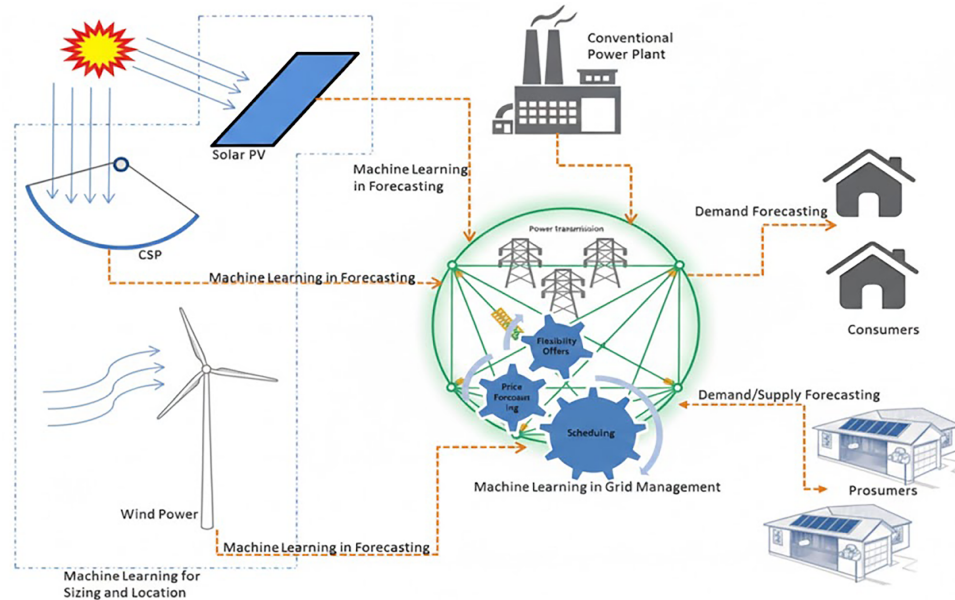


Figure 6: Overview of power grid with integrated renewable sources and its usage of machine learning techniques in different steps

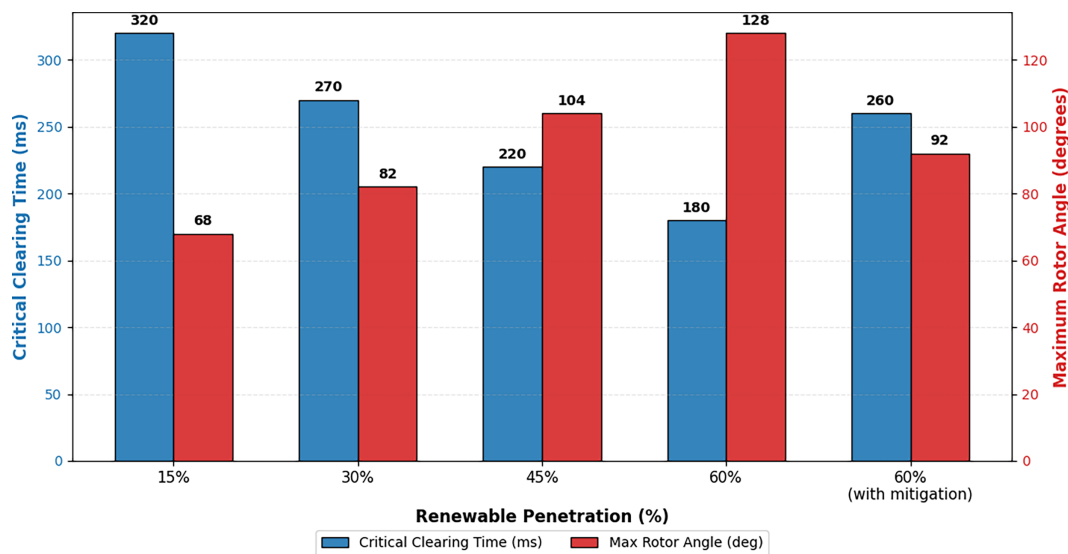


Figure 7: Transient stability metrics vs. renewable energy penetration

4.5 Impact of Energy Storage and Advanced Controls

Comparative experiments on BESS with and without the analysis of BESS and advanced inverter control at 60% renewable penetration were carried out to measure effectiveness of mitigation measures. The outcomes show a significant increase in all the dimensions of stability. There were also about 40% and almost half the frequency excursions, voltage deviations, and transient stability margins were significantly improved [32]. The findings are corroborated by the fact that flexibility resources play a vital role in a renewable-dominated power system. As shown in Fig. 8, the application of advanced grid-forming inverters and inertia emulation shows the most significant positive impact on stability at the 60% penetration threshold. A comprehensive overview of the simulation setup, including parameter values and their justifications is given in Table 3 Simulation Setup and Parameter Justifications.

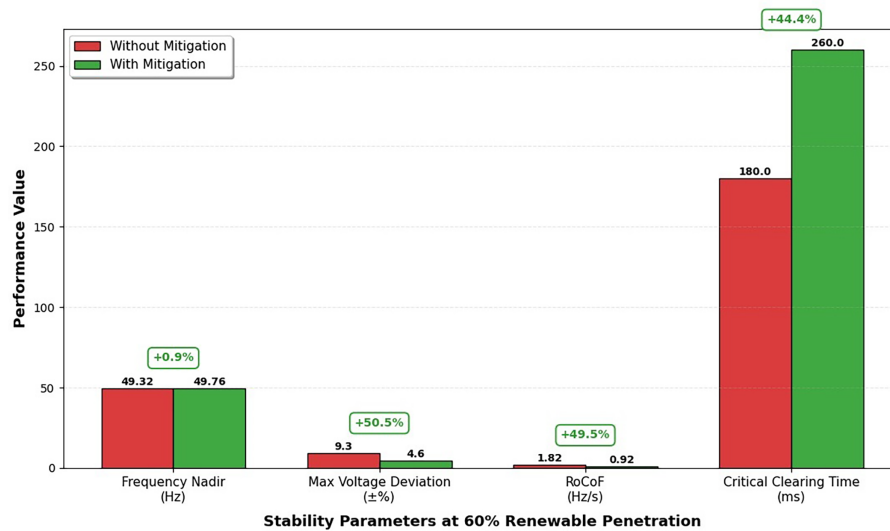


Figure 8: Impact of mitigation strategies on grid stability at 60% renewable energy penetration

Table 3: Simulation setup and parameter justifications

Category	Parameter	Value	Justification
Network	IEEE 39-bus system	10 generators, 39 buses	Industry benchmark
Base	S_base/f ₀	100 MVA/50 Hz	Standard normalization
Generator	Inertia H	3.5–6.5 s	Typical thermal values
RES Scenarios	S1–S4	15%, 30%, 45%, 60%	Low to extreme penetration
Wind/PV	Technology	Type 4	Modern industry standard
BESS	Rating/Gain K	50 MW/20 MW·s/Hz	Effective RoCoF reduction
Synthetic inertia	H_syn added	2.0 s	Compensates 40%–50% lost inertia
Inverter	Reactive capability	±0.33 pu	Typical (1.1 × oversizing)
Load	Model/Damping D	50% Z, 30% I, 20% P/1.5 pu/Hz	Realistic composition
Disturbances	Outage/Fault	500 MW (10%)/3-phase	N-1 contingency/worst fault

(Continued)

Table 3 (continued)

Category	Parameter	Value	Justification
Simulation	Duration/Solver	20s/Runge-Kutta ode23t	Captures transient + recovery
Validation	Sensitivity/Benchmark	$\pm 20\%$ variation/10+ studies	Results consistent

4.6 Comparison with Related Work

To confirm the experimental results, the results were also compared with the reported results of other related studies on renewable integration and grid stability that were conducted in recent times. The comparison implies that there are close similarities in the trends observed especially the frequency degradation and the voltage instability with high levels of renewable penetration. Nonetheless, it is possible to note that the suggested experimental framework proves a better stability indicator thanks to the joint use of energy storage and a complex inverter control. The technical roadmap for achieving high renewable targets depends on a fundamental redesign of grid interfaces. Fig. 9 synthesizes this challenge, showing the convergence of inverter-based resources, storage systems, and advanced grid management at the point of common coupling.

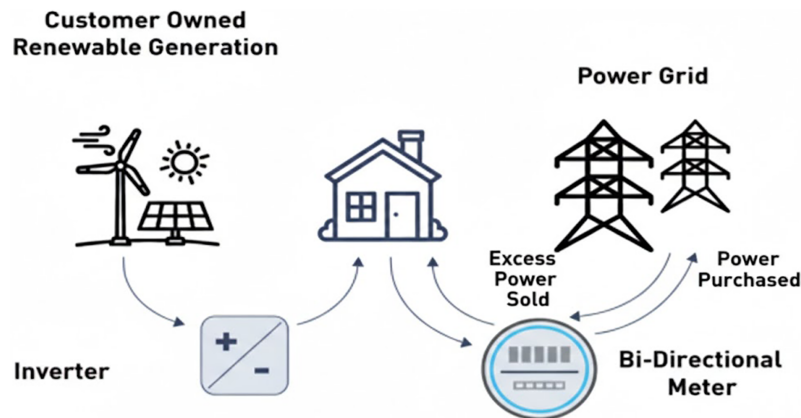


Figure 9: Integration of renewable energy sources

To contextualize the contributions of this work, a review of the current literature was conducted. Table 4 offers a comparative analysis of ten key studies, evaluating their focus, methods, and primary outcomes related to renewable integration and stability. This analysis reveals that while frequency stability is well-studied, fewer studies provide a holistic assessment of combined voltage and frequency metrics under unified scenarios, a gap this paper aims to address.

Table 4: Comparative analysis of related studies on renewable integration and grid stability

Reference	Focus area	Stability dimensions analyzed	Mitigation strategies considered	Quantitative stability metrics	Scenario-based analysis	Identified research gap
[5]	Pumped storage in multi-energy bases	Frequency only	Pumped hydro only	Limited	Limited	Narrow focus on one storage type; no multi-dimensional stability assessment
[6]	Gravity energy storage sizing	Frequency only	Gravity storage only	Limited	Yes	Storage-specific; lacks integrated stability analysis with inverter controls
[7]	Wind integration in multi-machine systems	Transient (rotor angle)	Basic control only	Partial	Yes	No solar PV; no storage coordination; limited frequency/voltage analysis
[8]	Wind farm siting for stability	Voltage, transient	Site optimization	Limited	Yes	Site-specific; no generalized mitigation framework; no storage integration
[9]	Renewables + ancillary services	Frequency only	Storage, regulation	Qualitative	No	Lacks quantitative stability metrics; no voltage/transient analysis
[10]	Multi-storage integration with RES	Frequency, voltage	Multiple storage types	Partial	Yes	Limited inverter control analysis; no synthetic inertia evaluation
[15]	IoT in renewable systems	Operational efficiency	IoT-based monitoring	Qualitative	No	No stability quantification; focuses on communication, not grid dynamics
[18]	Offshore wind-solar-hydrogen	Frequency only	Hydrogen-based control	Limited	Yes	Hydrogen-specific; no BESS or advanced inverter modeling
[30]	Reserve technique for renewable integration	Frequency only	Reserve management	Yes	Yes	Narrow frequency focus; lacks voltage and transient stability assessment
[31]	EV integration in low-inertia microgrids	Frequency only	EV-based control	Yes	Limited	EV-specific; no coordinated BESS/inverter analysis for bulk power systems
This work	High-RES stability with BESS, synthetic inertia, and advanced inverter control	Frequency, Voltage, Transient (all three)	BESS, synthetic inertia, advanced inverter control (combined)	Yes (nadir, RoCoF, deviation %, CCT)	Yes (15%–60% penetration scenarios)	Addresses gap by providing unified, multi-dimensional quantitative assessment with coordinated mitigation strategies

4.7 Discussion of Results

The results of the experiment provide a clear understanding that the high rates of renewable energy introduction affect grid stability in a quantifiable and negative way under the conditions of conventional strategies of grid control. The most impacted dimension is frequency stability because of less inertia and the second is voltage instability brought about by limited reactive power provisioning. At high levels of renewable penetration, the transient stability margins also become highly reduced. But the additions of developed mitigation controls, especially BESS and improved inverter controls makes an essential contribution to the functioning of the system [33]. The research has a high frequency

and voltage stability parameter, as compared to similar work, which establishes the effectiveness of coordinated control strategies. Providing a detailed view of a critical element from the system architecture, Fig. 10 focuses specifically on the grid interconnection interface. It delineates the essential power electronic stages, including rectification, DC-link, inversion, and filtering, that transform variable renewable output into a controllable grid-compatible feed. Crucially, the control systems illustrated here are the enabling hardware and software for executing the stability mitigation strategies whose performance was quantified in Fig. 8.

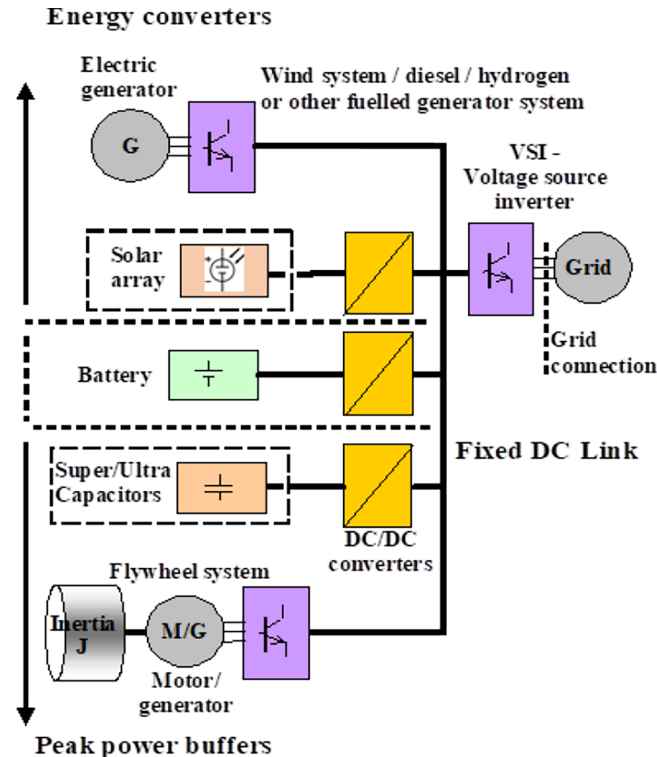


Figure 10: Interface of renewable energy sources to electrical power grids

All in all it can be concluded that the experiments prove that high renewable penetration does pose great challenges to grid stability but these can be mitigated successfully with the right system design, state-of-the-art control as well as flexible energy sources.

5 Conclusion

This study investigated renewable energy integration and its effects on grid stability across varying penetration levels. Results confirm that increasing renewable penetration leads to deeper frequency nadirs, higher RoCoF, greater voltage deviations, and reduced critical clearing times, particularly in inverter-dominated systems. Conventional grid control strategies prove inadequate under high penetration scenarios. However, coordinated mitigation measures, including BESS, synthetic inertia, and advanced inverter-based controls, substantially enhance performance, enabling grid operation within reliability constraints. The proposed framework's superiority is validated through comparison with recent studies. Overall, high renewable penetration does not inherently compromise grid stability

when supported by proper system configuration and flexible resources. These findings guide planners, operators, and policymakers toward resilient, sustainable power systems for the global energy transition. This study has limitations, including the use of a single benchmark system (IEEE 39-bus) and simplified battery degradation modeling. Future work should address validation on real-world networks, incorporation of detailed aging models, development of adaptive control algorithms, and techno-economic optimization of storage sizing and placement.

Acknowledgement: The authors would like to thank all individuals and institutions that contributed to this research.

Funding Statement: Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2026R140), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

Author Contributions: Mian Muhammad Kamal contributed to conceptualization, original draft writing, and project administration. Muhammad Kashif handled data curation, validation, and software. Afaq Ahmad supported visualization and investigation. Husam S. Samkari funding acquisition, supervised the project, provided resources, and contributed to reviewing and editing the manuscript. Mohammed F. Allehyani were instrumental in methodology, funding acquisition, resource provision, and validation. Heba G. Mohamed assisted in supervision, funding acquisition, reviewing and editing the manuscript. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Abbasi A, Alves F, Ribeiro RA, Sobral JL, Rodrigues R. Optimizing virtual power plants with parallel simulated annealing on high-performance computing. *Smart Cities*. 2025;8(2):47. doi:10.3390/smartcities8020047.
2. Abdelkader S, Amissah J, Abdel-Rahim O. Virtual power plants: an in-depth analysis of their advancements and importance as crucial players in modern power systems. *Energy Sustain Soc*. 2024;14(1):52. doi:10.1186/s13705-024-00483-y.
3. Adroja N. Enhancing renewable energy integration with grid-forming converter-based HVDC systems: modelling and validation. *J Electr Syst*. 2024;20(10s):1312–24. doi:10.52783/jes.5259.
4. Huang Y, Sun Q, Zhang N, Wang R. A multi-slack bus model for bi-directional energy flow analysis of integrated power-gas systems. *CSEE J Power Energy Syst*. 2021;10(5):2186–96. doi:10.17775/csee-jpes.2020.04190.
5. Gu J, Gao J, Chen C, Liu Y, Zhu F. On the effect of pumped storage on renewable energy accommodation in multi-clean energy complementation bases. *J Phys Conf Ser*. 2025;2932(1):012001. doi:10.1088/1742-6596/2932/1/012001.
6. Lv C, He J, Ma J, Yang Y, Liu F, Huang W. Capacity optimization strategy for gravity energy storage stations considering the impact of new power systems. *PLoS One*. 2025;20(4):e0320734. doi:10.1371/journal.pone.0320734.

7. Gulati A, Kumar N, Kumar A. A novel approach for dynamic analysis of wind-integrated multi-machine power systems. *J Electr Syst.* 2024;20(3):1287–98. doi:10.52783/jes.3536.
8. Hafaiedh H, Saoudi Y, Benamor A, Chrifi-Alaoui L. Wind farms integration into power system with improved location and stability problem solving. *Electr Eng Electromech.* 2025;(5):10–6. doi:10.20998/2074-272x.2025.5.02.
9. Gulraiz A, Sajjad Haider Zaidi S, Mohammad Khan B. Advancing energy integration: renewable sources, ancillary services, and stability. *PLoS One.* 2025;20(6):e0324812. doi:10.1371/journal.pone.0324812.
10. Malik FH, Hussain GA, Alsmadi YMS, Haider ZM, Mansoor W, Lehtonen M. Integrating energy storage technologies with renewable energy sources: a pathway toward sustainable power grids. *Sustainability.* 2025;17(9):4097. doi:10.3390/su17094097.
11. Kiani H, Vahidi B, Hosseinian SH, Lazaroïu GC, Siano P. Prospective design and evaluation of a renewable energy hybrid system to supply electrical and thermal loads simultaneously with an electric vehicle charging station for different weather conditions in Iran. *Smart Cities.* 2025;8(2):61. doi:10.3390/smartcities8020061.
12. Jamil H, Ali Naqvi SS, Iqbal N, Ali Khan M, Qayyum F, Muhammad F, et al. Analysis on the driving and braking control logic algorithm for mobility energy efficiency in electric vehicle. *Smart Grids Sustain Energy.* 2024;9(1):12. doi:10.1007/s40866-023-00190-1.
13. Qays MO, Ahmad I, Habibi D, Masoum MAS, Mahmoud T. Addressing system strength and reliability concerns in renewable energy-based weak grids using synchronous condensers determined by hybrid GRU-classical optimization method. *Sustain Energy Grids Netw.* 2026;45:102111. doi:10.1016/j.segan.2025.102111.
14. Qays MO, Ahmad I, Habibi D, Masoum MAS. Assessing techno-economic performance of synchronous condensers and static synchronous compensators in renewable energy-integrated weak-grids using hedge feedforward feedback-based online gated recurrent unit. *IET Smart Grid.* 2025;8(1):e70022. doi:10.1049/stg2.70022.
15. Jia K, Yang X, Peng Z. Design of an integrated network order system for main distribution network considering power dispatch efficiency. *Energy Inform.* 2024;7(1):69. doi:10.1186/s42162-024-00369-5.
16. Jia L, Li Z, Hu Z. Applications of the Internet of Things in renewable power systems: a survey. *Energies.* 2024;17(16):4160. doi:10.3390/en17164160.
17. Krishnamurthy NK, Sabhahit JN, Jadoun VK, Pandey AK, Rao VS, Saraswat A. A grid-interfaced DC microgrid-enabled charging infrastructure for empowering smart sustainable cities and its impacts on the electrical network: an inclusive review. *Smart Cities.* 2025;8(5):176. doi:10.3390/smartcities8050176.
18. Ma L, Dong R, Fu Q, Wang C, Li X. Optimization control of flexible power supply system applied to off-shore wind-solar coupled hydrogen production. *J Mar Sci Eng.* 2025;13(6):1135. doi:10.3390/jmse13061135.
19. Alqahtani MH, Shaheen AM. Integration of PV sources and capacitor banks for sustainable energy management in distribution networks using electric eel foraging algorithm. *Int J Energy Res.* 2025;2025(1):7156670. doi:10.1155/er/7156670.
20. Al-Shetwi AQ, Atawi IE, El-Hameed MA, Abuelrub A. Digital twin technology for renewable energy, smart grids, energy storage and vehicle-to-grid integration: advancements, applications, key players, challenges and future perspectives in modernising sustainable grids. *IET Smart Grid.* 2025;8(1):e70026. doi:10.1049/stg2.70026.
21. Arifin Z, Asnawi R, Khairudin M. Analysis of hybrid PV/WTG power plant on carbon emission reduction in Karimunjawa island using spesific fuel consumption diesel. *IOP Conf Ser Earth Environ Sci.* 2025;1543(1):012003. doi:10.1088/1755-1315/1543/1/012003.
22. Bade MC, Siva Rama Ganesh M, Pallavi P, Pavani B. Solar powered bidirectional on-board charger for integration of electric vehicle into grid. *IOP Conf Ser Earth Environ Sci.* 2025;1529(1):012029. doi:10.1088/1755-1315/1529/1/012029.

23. Baier CR, Melin PE, Torres MA, Ramirez RO, Muñoz C, Quinteros A. Developing and evaluating the operating region of a grid-connected current source inverter from its mathematical model. *Mathematics*. 2024;12(12):1775. doi:10.3390/math12121775.
24. Cavus M. Advancing power systems with renewable energy and intelligent technologies: a comprehensive review on grid transformation and integration. *Electronics*. 2025;14(6):1159. doi:10.3390/electronics14061159.
25. Che EE, Abeng KR, Iweh CD, Tsekouras GJ, Fopah-Lele A. The impact of integrating variable renewable energy sources into grid-connected power systems: challenges, mitigation strategies, and prospects. *Energies*. 2025;18(3):689. doi:10.3390/en18030689.
26. Nzoundja Fapi CB, Touré ML, Camara MB, Dakyo B. Control strategy for DC micro-grids in heat pump applications with renewable integration. *Electronics*. 2025;14(1):150. doi:10.3390/electronics14010150.
27. Elazim SMA, Elkholy MH, Elgarhy A, Senjyu T, Gamil MM, Song D, et al. Enhancing stability and power quality in electric vehicle charging stations powered by hybrid energy sources through harmonic mitigation and load management. *Sci Rep*. 2025;15(1):28077. doi:10.1038/s41598-025-14143-4.
28. Farajollahi A, Jalalvand M, Rostami M. Double objective decentralized transactive energy market framework for multi-energy microgrid. *Energy Inform*. 2025;8(1):134. doi:10.1186/s42162-025-00579-5.
29. Farooq U, Mushtaq MF, Ullah Z, Ejaz MT, Akram U, Aslam S. Time series analysis of solar power generation based on machine learning for efficient monitoring. *Eng Rep*. 2025;7(2):e70023. doi:10.1002/eng2.70023.
30. Mansouri N, Lashab A, Ali M, Bouchoucha C, Guerrero J, Vasquez J. Reserve technique in integrating large sustainable energy sources: a case study of the Tunisian grid. *Sustainability*. 2024;16(23):10791. doi:10.3390/su162310791.
31. Abdelkader M, Ahmed EM, Mohamed EA, Aly M, Alshahir A, Alrahili YS, et al. Frequency stabilization based on a TFOID-accelerated fractional controller for intelligent electrical vehicles integration in low-inertia microgrid systems. *World Electr Veh J*. 2024;15(8):346. doi:10.3390/wevj15080346.
32. Ou K, Gao S, Wang Y, Zhai B, Zhang W. Assessment of the renewable energy consumption capacity of power systems considering the uncertainty of renewables and symmetry of active power. *Symmetry*. 2024;16(9):1184. doi:10.3390/sym16091184.
33. Pilalum P, Taksana R, Chitgreayan N, Sa-nga-ngam W, Marsong S, Buayai K, et al. Mitigation of voltage magnitude profiles under high-penetration-level fast-charging stations using optimal capacitor placement integrated with renewable energy resources in unbalanced distribution networks. *Smart Cities*. 2025;8(4):102. doi:10.3390/smartcities8040102.