

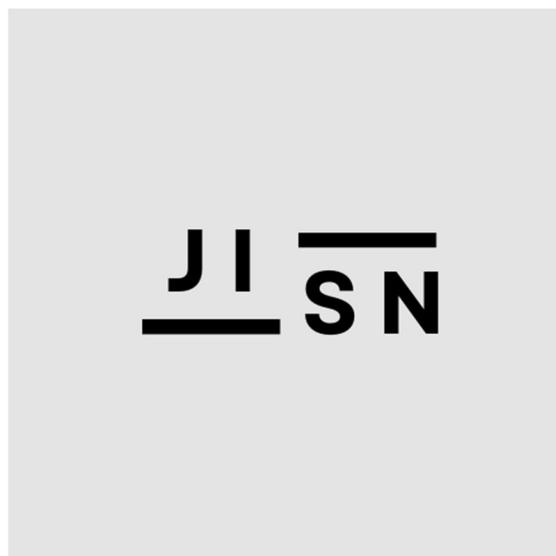
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IMPROVING THE EFFICIENCY OF RENEWABLE ENERGY SUPPLY SYSTEMS USING IOT TECHNOLOGIES

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ANNOTATION:

This paper presents a hybrid power supply system that combines renewable energy sources with conventional generation and storage devices to improve energy reliability and stability. However, such systems have complex stability problems due to their dynamic and decentralized nature. This paper presents a classification and key aspects of power system stability, the main causes and potential consequences of instability, and an analysis of these systems using IoT. Special attention is paid to the issues of voltage sag and energy loss, which are very important in hybrid systems. Smart Grid and IoT-based architecture are discussed in depth, defining their role in monitoring, control, and automation. The paper explains how Smart Grid Technologies can be effectively applied to improve voltage stability, reduce energy losses, and enhance the overall stability of hybrid power supply systems. Through a comprehensive synthesis of recent research, the review provides insights into the integration of Smart Grid and IoT systems solutions as a rational approach to stabilize modern power systems under conditions of variable electrical load and power generation.

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KEYWORDS: IoT, Hybrid power supply system, stability, smart grid, smart grid technologies, voltage drop, energy loss, inverter.

Introduction

The integration of renewable energy sources into the power grid is increasingly vital for ensuring energy sustainability and reducing the carbon footprint of traditional energy systems. Implementation of Hybrid Power Supply Systems (HPSS) are determine as one of the most effective solutions for this process. However, the reliability and stability of HPSS face significant challenges due to the variable nature of renewable energy generation, unpredictable demands, and the complexities involved in the integration of diverse energy sources. To address these challenges, Smart Grid (SG) technologies have been determined as a transformative solution capable of enhancing the stability, resilience, and efficiency of hybrid systems.

SGTs, characterized by their use of advanced communication networks, real-time data monitoring, and automated control systems, enable more efficient management of energy generation, distribution, and consumption. The application of SG in HPSS not only improves operational efficiency but also enhances grid stability by facilitating real-time demand-response mechanisms, predictive maintenance, fault detection, and optimized energy storage. Furthermore, the ability of SGs to integrate and manage diverse energy sources, including Distributed Generation (DG) systems, presents significant opportunities for improving grid resilience, reducing energy losses, and ensuring a

reliable power supply, even under fluctuating operational conditions.

HPSS combine diverse energy sources to leverage their complementary characteristics, ensuring continuous power supply and mitigating the stochastic nature of renewables. Common combinations include renewable energy sources, electrical grid and energy storage systems.

HPSS are categorized by their interaction with the main grid, influencing their design and operational complexity:

- grid-tied hybrid systems connect to the utility grid, allowing bidirectional power flow. Excess RDG energy (e.g., from PV or wind) is fed to the grid via net metering, while the grid supplies power during deficits. Grid-tied systems use smart hybrid inverters with volt-var control to maintain power quality and support demand response (DR) strategies.

- off-grid systems are designed for remote or isolated areas, off-grid HPSS operate independently, relying on RDG, BESS, and backup generators (e.g., diesel or fuel cells). These systems prioritize self-sufficiency, using advanced EMS to manage load and generation variability [24].

For instance, fuzzy logic controllers optimize battery charge/discharge cycles to extend lifespan in off-grid solar-wind-battery systems. Off-grid systems are critical for rural electrification, reducing fossil fuel dependency.

- microgrids are localized grids that can operate in grid-connected or islanded modes, integrating RDG,

BESS, and conventional sources [25, 26]. They enhance resilience by isolating from the main grid during outages, using distributed energy resources (DERs) and EMS for seamless transitions. Microgrid HPSS employ AI-based control to

optimize power flow and ensure stability under variable loads. They are ideal for communities, campuses, or industrial facilities, supporting peer-to-peer (P2P) energy trading via blockchain.

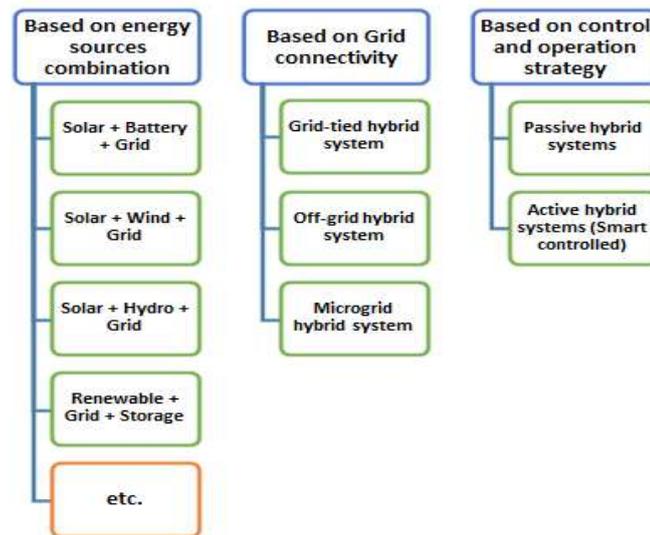


Fig. 1. Types of HPSS.

Operation strategies determine how HPSS manage energy flow, impacting efficiency and adaptability:

Passive Hybrid Systems use simple, rule-based controls without real-time optimization. Energy sources operate independently, with basic switches directing power to loads or storage. For example, in a passive solar-diesel-battery system, the diesel generator activates when battery state-of-charge (SOC) drops below a threshold. Passive systems are cost-effective for small-scale applications but lack efficiency due to minimal coordination, leading to higher losses. They are common in early-stage HPSS deployments with limited computational resources.

Active hybrid systems (Smart-controlled) employ advanced EMS with real-time monitoring and control, leveraging AI, fuzzy logic, or model predictive control (MPC) to optimize power dispatch. Smart-controlled HPSS dynamically adjust source output, storage cycles, and load schedules based on predictive analytics, weather forecasts, and demand.

For instance, machine learning optimizes RDG dispatch in solar-wind-battery systems, reducing curtailment and extending battery life. These systems integrate with smart grids, supporting DR, P2P trading, and fault-tolerant operation via self-healing algorithms. Active systems are more complex and costly but offer superior efficiency

and resilience, especially in microgrid and grid-tied HPSS. Operation strategies evolve with technological advancements,

transitioning from passive to smart-controlled systems to meet the demands of renewable-heavy, interconnected grid.

Table 1. Overview of published papers in the field of HPSS.

Reference	Remark	Indicator	Objective	Findings
Likonge Makai and Olawale Popoola	Despite the potential, Micro-Hybrid Energy Systems (MHES) remain underutilized in Sub-Saharan Africa.	-Electricity Access (Zambia) 2012: 3.1% -rural access 2021: 8.1%, 2024: 14.5% -national access: 47.8% (2024)	To assess the current state and identify key technical, financial, operational, and behavioral barriers hindering the implementation of MHES	Inadequate load planning and overreliance on single energy sources like solar or wind leads to system inefficiencies and risks, while hybrid solutions offer greater reliability and energy security.
Tolulope Falope et al	Integrated Energy Management Systems (IEMS) are essential in decentralized grids and renewable hybrid mini-grids.	Global energy demand is projected to rise by one-third by 2035, mainly in developing regions, where over 770 million people still lack electricity access.	Architectural configurations of distributed renewable systems including renewable smart hybrid mini-grids (RSHMG), mini-grids (MG), and renewable energy home systems (REHS).	Supply-side management with flexible power sources and smart grid technologies like AI-based forecasting and smart meters enhances stability and adaptability in off-grid and hybrid IEMS.
Ahmad et al., 2024	Review of Hybrid Renewable and Sustainable Power Supply Systems (HRSPSS).	Fossil fuels accounted for 82% of primary energy use in 2022.	Architectural configurations of renewable smart hybrid mini-grids (RSHMG), mini-grids (MG), and renewable energy home systems (REHS).	Smart Grid Technologies including smart meters, AMI, and AI-driven forecasting models play a crucial role in enhancing the responsiveness and adaptability of IEMS.
Mohamed I. Abdewala, et al.	The article provides an extensive review of hybrid AC/DC microgrids (MGs).	The key indicators discussed in the article: system efficiency, power quality, flexibility, cost-effectiveness, reliability,	To review hybrid AC/DC microgrids, discussing their structure, integration challenges, and benefits.	The combination of AC and DC systems in hybrid microgrids improves overall system stability and flexibility; ESSs improve system reliability by providing backup power during

		control optimization.		peak demand or grid outages.
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Power system stability factors
 Power system stability is governed by the balance between generation, transmission, and demand, and it is categorized into several key types, each addressing different physical and operational aspects (figure 3).

Voltage stability refers to the ability of a power system to maintain acceptable voltage levels at all buses under normal operating conditions and after being subjected to a disturbance, especially those related

to load increments or network topology changes. Unlike rotor angle or frequency stability, which are dominated by generator dynamics and system inertia, voltage stability is heavily influenced by the balance of reactive power supply and demand, the control of on-load tap changers, the dynamic behavior of loads, and the capability of voltage support devices such as synchronous condensers, STATCOMs, and capacitor banks (table2).

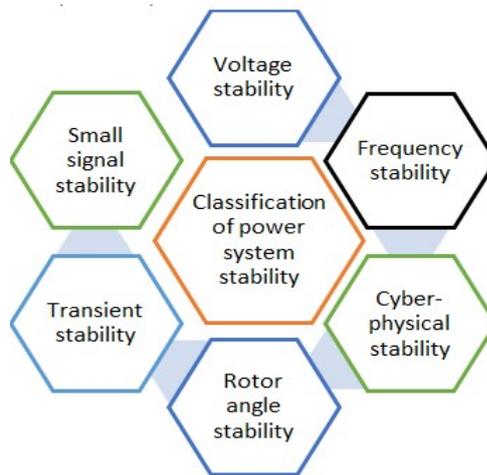


Fig.2. Classification of Smart Grid stability.

A system loses voltage stability when a disturbance, such as a line outage or a sudden increase in load demand, causes a progressive and uncontrollable voltage drop, ultimately leading to voltage collapse and system blackouts. This instability often manifests in heavily stressed transmission corridors or weakly connected distribution areas, where reactive power reserves are insufficient or poorly distributed. Moreover, in hybrid and

inverter-based power systems where conventional synchronous generators are replaced with power electronic converters, the voltage stability margin becomes more sensitive due to the lack of inherent voltage regulation and inertia. The phenomenon is further complicated by nonlinear load characteristics, delayed voltage recovery, and the slow response of traditional voltage controllers. Therefore, voltage stability assessment must

incorporate both steady-state (long-term) and transient (short-term) analyses, using tools like active power-voltage (PV) and reactive power-voltage (QV) curves, continuation power flow, and dynamic time-domain simulations. Ensuring voltage stability is not only critical for the continuous delivery of power to consumers but also for preventing wide-area blackouts, protecting equipment, and enabling the reliable integration of renewable and distributed energy resources within smart grid environments.

Frequency stability in power supply system's refers to the ability of an electrical grid to maintain a consistent frequency, typically 50 or 60 Hz, under varying operational conditions, ensuring reliable power delivery and system integrity. This stability is critical as deviations can lead to equipment malfunctions, cascading failures, or blackouts, particularly in modern grids with high penetration of renewable energy sources and distributed generation. Frequency stability is governed by the balance between power generation and load demand, where any mismatch causes frequency excursions. Primary

control, provided by governor response in synchronous generators, acts within seconds to mitigate these deviations, while secondary control, such as automatic generation control (AGC), restores frequency to nominal values over minutes. Inertia from rotating masses, traditionally provided by synchronous machines, plays a pivotal role in slowing frequency changes, but its reduction due to inverter-based renewable sources poses new challenges. Advanced control strategies, including virtual inertia emulation and demand-side management, are increasingly employed to enhance stability, particularly in microgrids and low-inertia systems. Moreover, frequency stability is intricately linked to voltage stability and transient stability, as disturbances like faults or sudden load changes can propagate across these domains, necessitating robust modeling and real-time monitoring (table 2). Standards such as IEEE 1547 outline requirements for frequency ride-through capabilities in distributed energy resources to ensure grid resilience.

Table 2. Overview of published papers in the field of voltage and frequency stability.

References	Aim of the study	Objects	Results
Youzhuo Zheng et al.	To improve the dynamic performance and stability of photovoltaic (PV) power generation systems by integrating an	Development of adaptive inertia control; Improvement of active power-frequency loop.	The adaptive inertia control method improves system stability, reduces oscillations, and provides robust voltage and frequency regulation. By dynamically adjusting the inertia, the proposed strategy ensures that the system can

	adaptive Virtual Synchronous Generator (VSG) control method.		effectively handle grid disturbances and PV intermittency, providing a promising solution for better integration of renewable energy into the power grid.
Ban H. Alajrash at al.	To provide a critical review on the impact of intermittent renewable energy generation on power system stability, security, reliability, and quality.	Evaluate impact on system Security and stability; Develop mitigation strategies.	Significant progress has been made in controlling harmonics, voltage sag, and flicker generated by inverter-based renewable energy systems. However, further development of harmonics compensation techniques, such as active filters and STATCOMs, is needed to address ongoing power quality concerns.
Sunny K atyara at al	The primary aim of this study is to analyze voltage stability in smart grid systems	Voltage stability analysis; Online monitoring; System evaluation under faulty conditions.	The proposed modified Thevenin model significantly improved the voltage stability margin in the grid, with better stability observed after integrating Distributed Generation (DG). The system's performance indices were higher, showing better voltage regulation and power flow management.
Gholam Ali Alizadeh, at al	To investigate the optimization of frequency regulation in microgrids, particularly in systems with low inertia, by utilizing the virtual inertia concept	Optimization of virtual inertia and communication delay; Improvement in frequency stability; Simulation and case study.	Optimizing virtual inertia size and communication delay using the NSGA-II algorithm can significantly improve frequency regulation in low-inertia microgrids. While increasing the virtual inertia reduces frequency oscillations, it also increases operational costs. Therefore, finding the right balance between performance and cost is essential for efficient microgrid operation.
Minas Patsalides, at al	To evaluate frequency stability in low inertia systems, particularly in grids with high penetration of Renewable Energy Sources (RES)	Evaluation of frequency stability; Hierarchical control approach; Application to real-world grid models.	The local control approach significantly reduces frequency deviations during disturbances. It minimizes the frequency reduction effectively, ensuring better frequency stability compared to systems without the control mechanism; The hierarchical control system significantly improves the overall stability of the grid, helping it avoid major shutdowns and ensuring better resilience in the face of disturbances.

Cyber-physical stability in power supply systems, a critical challenge in modern smart grids, refers to the ability of a cyber-physical power system (CPPS) to maintain reliable, secure, and stable operation under both physical disturbances (e.g., faults, load fluctuations) and cyber threats (e.g., false data injection attacks, communication delays) while ensuring seamless integration of computational, communication, and physical processes. The transition to smart grids, characterized by high penetration of inverter-based renewable energy sources (RES), distributed energy resources (DERs), and advanced information and communication technologies (ICTs), has amplified the interdependencies between cyber and physical layers, making stability analysis more complex[60]. Cyber-physical stability is compromised when cyber-attacks, such as those targeting supervisory control and data acquisition (SCADA) systems or wide-area monitoring, protection, and control (WAMPAC) systems, disrupt physical operations, potentially leading to frequency deviations, voltage instability, or cascading failures.

Comprehensive modeling, incorporating both cyber and physical dynamics, is essential to predict and prevent instability in modern interconnected grids. Rotor angle stability, also known as synchronous stability, is a critical aspect of power system dynamics that refers to the ability of synchronous machines within an

interconnected power grid to maintain synchronism under normal operating conditions and to regain a stable operating state following disturbances such as faults, load changes, or switching events. This stability is governed by the rotor angle, which represents the angular position of a synchronous generator's rotor relative to a synchronously rotating reference frame, typically the system's center of inertia. Rotor angle stability is classified into transient stability, which assesses the system's response to severe disturbances over a short time frame (e.g., 1–5 seconds), and small-signal stability, which evaluates the damping of low-frequency electromechanical oscillations (0.1–2 Hz) under small perturbations. Transient stability depends on the critical clearing time (CCT), the maximum duration a fault can persist before causing loss of synchronism, while small-signal stability is influenced by damping ratios and eigenvalue analysis of the system's state matrix. The increasing penetration of inverter-based resources (IBRs), such as wind and solar power, complicates rotor angle stability due to their low or zero inertia and differing fault response compared to traditional synchronous generators, necessitating advanced control strategies like power system stabilizers (PSS) and grid-forming converters to enhance damping and stability margins. Modern approaches, such as Lyapunov-based controllers and reinforcement learning-based PSS, have been

proposed to mitigate inter-area oscillations and improve transient response, particularly in systems with high renewable energy integration.

Additionally, rotor angle stability is interlinked with voltage and frequency stability, as rotor angle deviations can lead to voltage fluctuations and frequency excursions, potentially triggering

cascading failures if not addressed promptly. Accurate modeling, real-time monitoring using phasor measurement units (PMUs), and dynamic security assessment (DSA) are essential for predicting and maintaining rotor angle stability, ensuring reliable power delivery in increasingly complex and renewable-heavy grids (table 3).

Table 3. Overview of published papers in the field of transient and small-signal stability.

References	Aim of the study	Objects	Results
Huimin Wang, Zhaojun Li	To review and analyze methods for assessing transient stability in power systems.	Traditional AC grids and power-electronized systems with converters/FACTS. Smart grids with high renewable penetration and (WAMS).	The paper systematically compares transient stability assessment methods, emphasizing the need for hybrid approaches (e.g., AI + direct methods) to address limitations in traditional techniques.
Changjun He, Xiuqiang He, Hua Geng, Huadong Sun, Shiyun Xu	To investigate the transient stability of low-inertia power systems integrated with inverter-based generation (IBG).	Inverter-Based Generation (IBG); Synchronous Generators (SGs).	The paper identifies two novel LOS mechanisms in low-inertia systems, driven by IBG-SG power imbalances and inertia mismatches. The proposed energy-based criterion effectively assesses transient stability, validated by simulations.
Amel Brik, Nour El Yakine Kouba and Ahmed Amine Ladjici	To analyze the transient stability of a power system integrated with RESs.	The impact of RES on system stability; transient stability and prevent blackouts.	RES integration (wind/PV) improves transient stability but may worsen it during intermittent generation periods; Optimal placement of RES is critical for maximizing grid reliability.
Jafarpour Saber, et al.	To analyze the small-signal stability of electrical networks primarily composed of grid-following inverters in the context of future power systems.	Stability Analysis of Inverter-Dominated Networks: Application of Singular Perturbation Theory	by leveraging singular perturbation theory, the study develops a computationally efficient condition for assessing the small-signal stability of large inverter-dominated networks. The research emphasizes the

		Time-Scale Decomposition of Inverter Dynamics.	critical role of inverter dynamics, network topology, and control parameters in maintaining system stability.
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Causes and outcomes

The causes and consequences of power system instabilities are deeply interconnected, with disturbances in one domain often amplifying risks across others, potentially leading to severe disruptions in modern power grids.

Voltage instability arises from inadequate reactive power supply, excessive load demand, or transmission line outages, leading to progressive voltage declines and, in severe cases, voltage collapse, which can cause load shedding, equipment damage, or widespread blackouts. Frequency instability results from mismatches between active power generation and demand, often triggered by sudden generator outages, renewable energy intermittency, or large load changes, causing frequency excursions that may activate under-frequency load shedding, generator tripping, or system-wide collapse. Transient instability occurs due to severe disturbances, such as short-circuit faults or sudden line disconnections, which cause large rotor angle swings, leading to loss of synchronism, generator disconnection, or grid segmentation. Cyber-physical instability stems from cyber-attacks (e.g., data manipulation or denial-of-service) or physical damage to control and communication infrastructure, resulting in erroneous control actions, protection system failures, or cascading outages. Rotor angle

instability, encompassing both transient and small-signal instability, is driven by faults, weak grid interconnections, or insufficient damping, causing synchronous generators to lose synchronism, which can propagate voltage and frequency deviations across the system. Small-signal instability is caused by inadequate damping of low-frequency electromechanical oscillations (0.1–2 Hz), often due to poor controller tuning or high penetration of inverter-based resources (IBRs), leading to sustained oscillations that reduce power transfer capability, stress equipment, or trigger protective relays. The growing reliance on IBRs, such as wind and solar, exacerbates these instabilities by reducing system inertia and introducing complex control dynamics, increasing the risk of cascading failures across voltage, frequency, and rotor angle domains. For example, rotor angle instability can induce voltage drops, which may destabilize frequency, while cyber-physical attacks can disrupt critical control systems, amplifying physical instabilities. Consequences include localized outages, system-wide blackouts, economic losses, and compromised grid reliability, necessitating advanced monitoring with phasor measurement units (PMUs), robust modeling, and coordinated control strategies to mitigate these interconnected risks in renewable-dominated grids.

A smart grid is an advanced, technology-enabled electrical grid system incorporating information and communication technology. It allows for a two-way flow of power and has an enhanced metering infrastructure that is capable of self-healing and is resilient to attacks. Smart grids combine cutting-edge techniques to improve energy resource management, increase energy efficiency, reduce carbon emissions, and enhance operational performance.

Key components of smart grid technologies include advanced metering infrastructure (AMI), demand response technologies, energy storage systems, and wide-area monitoring systems (WAMS) [12]. AMI, which includes smart meters, enables real-time monitoring of energy consumption, while demand response technologies

allow consumers to adjust their energy usage based on price signals or grid conditions. Energy storage systems, such as batteries, can store excess energy and release it when needed, improving grid stability and reliability.

Smart grids offer several advantages over traditional power grids. They reduce operational costs, open new markets to utility providers, and allow for direct communication with customer premises through advanced metering infrastructure. Smart grids also enable self-healing in case of power outages and improve the integration of renewable energy sources. The adoption of smart grid applications enhances energy efficiency and reduces carbon emissions by combining various energy resources seamlessly.

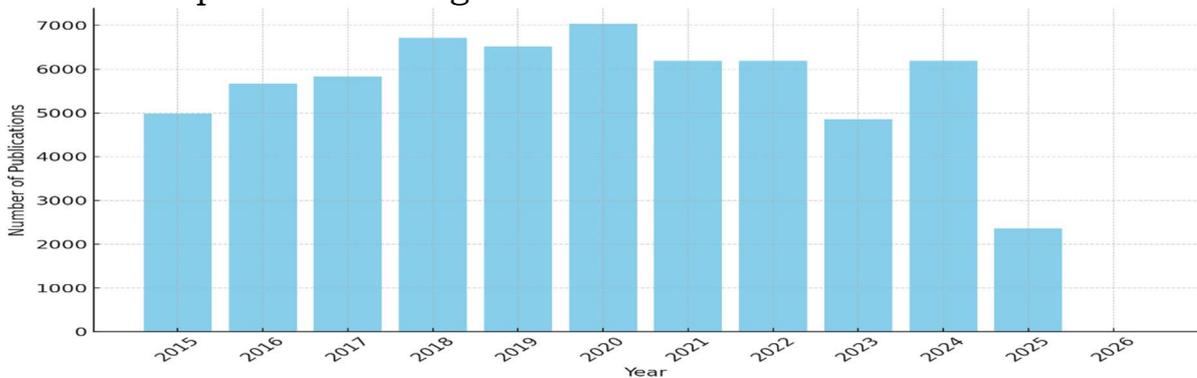


Fig.3. Publication trend at the WOS repository for Smart Grid.

Improving stabilities by Smart Grid

Smart grid technologies, characterized by advanced sensing, communication, control, and data analytics, offer significant potential to enhance the stability of power systems across all stability types—voltage stability, frequency stability, transient stability, cyber-physical

stability and small-signal stability—by enabling real-time monitoring, adaptive control, and resilient operation in increasingly complex, renewable-heavy grids (table 4). For voltage stability, smart grids leverage flexible AC transmission systems (FACTS) devices like STATCOMs and distributed energy resources (DERs) with volt-var

control to dynamically manage reactive power, mitigating voltage collapse risks during load variations or contingencies. Frequency stability is bolstered by demand response programs, energy storage systems (ESS), and grid-forming inverters, which provide fast frequency response and synthetic inertia to counteract frequency excursions in low-inertia systems dominated by inverter-based resources (IBRs). Transient stability benefits from wide-area monitoring systems using phasor measurement units (PMUs) and adaptive protection schemes that optimize fault clearing times, reducing the likelihood of synchronous generators losing synchronism during severe disturbances. Cyber-physical stability is critically enhanced through smart grid advancements like blockchain-based secure communication protocols, intrusion detection systems, and resilient distributed control architectures, which protect against cyber-attacks and ensure robust operation of control and communication nets. Rotor angle stability, encompassing transient and small-signal aspects, is improved by machine learning-based power system stabilizers

(PSS) and Lyapunov-based controllers that enhance damping and maintain synchronism, particularly in systems with high IBR penetration. Small-signal stability is similarly advanced through AI-driven PSS tuning and coordinated control of DERs, which damp low-frequency electromechanical oscillations by optimizing control parameters in real time. These stability types are interlinked, as undamped oscillations from small-signal instability can exacerbate voltage or frequency deviations, while cyber-physical vulnerabilities can trigger physical instabilities, potentially leading to cascading failures. Smart grid technologies address these interdependencies through integrated approaches, such as AI-driven dynamic security assessment (DSA), wide-area control systems, and real-time data analytics from PMUs, which enable predictive and corrective actions across all stability domains. The increasing integration of IBRs, with their low inertia and fast dynamics, underscores the necessity of smart grid solutions to maintain stability, ensuring reliable power delivery in modern, renewable-dominated systems.

Table 4. Stability improvement by Smart Grid.

Stability type	Improvable via Smart Grid?	Level of impact	Notes
Voltage Stability	Yes	high	Key target area of smart grid
Frequency Stability	Yes	moderate-high	Enabled via fast DERs and DR
Cyber-Physical Stability	yes (directly)	high	Requires secure ICT systems
Transient Stability	Partially	moderate	Enhanced by fast protection
Small-Signal Stability	Yes	high	Enabled by advanced control schemes

Voltage drops and energy losses in electrical nets, particularly in hybrid power supply systems (HPSS) that integrate renewable distributed generation (RDG) such as solar photovoltaic and wind turbines, form a vicious cycle that significantly undermines the stability of the system, primarily affecting voltage stability. Voltage drops occur when electrical energy is lost as heat due to the resistive and reactive components of nets impedance, as described by the power loss (equation 1) and Ohm's Law (equation 2), where increased current flow through transmission and distribution lines amplifies energy losses.

$$P = I^2R$$

(1)

$$V = IR$$

(2)

Conversely, a reduction in voltage prompts loads, particularly constant-power loads like motors, to draw higher currents to maintain their power demand, thereby increasing energy losses and further exacerbating voltage drops, which can lead to thermal overloading of equipment and reduced operational efficiency. In HPSS, the intermittent nature of renewable sources and their reliance on inverter-based resources (IBRs) with low inertia intensify these issues, as fluctuating power injections contribute to unstable voltage profiles and higher losses in radial or weakly interconnected nets. These voltage drops directly threaten voltage stability by pushing bus voltages below acceptable thresholds,

potentially triggering voltage collapse, which manifests as cascading load disconnections or widespread outages. Increased energy losses further strain the system by reducing the effective power available, necessitating higher generation or curtailment of loads, which can exacerbate voltage deviations in HPSS with high RDG penetration. The impact is particularly severe in distribution nets, where long feeders and high resistance amplify losses and voltage drops, compromising system reliability. Advanced mitigation strategies, such as optimal RDG placement using algorithms like the modified forensic-based investigation and the strategic deployment of capacitor banks or FACTS devices like STATCOMs, are critical for minimizing losses and stabilizing voltage profiles, ensuring robust operation of HPSS. Unaddressed, these phenomena lead to equipment degradation, reduced power quality, and potential system-wide instability, highlighting the need for real-time monitoring and adaptive control to maintain voltage stability in renewable-integrated grids.

Voltage stability improvement by SGT

Smart grid technologies can improve voltage stability through several mechanisms. These include real-time monitoring, advanced control systems, demand-side management, energy storage integration, and grid automation, which allow for effective responses to voltage fluctuations (figure 6).

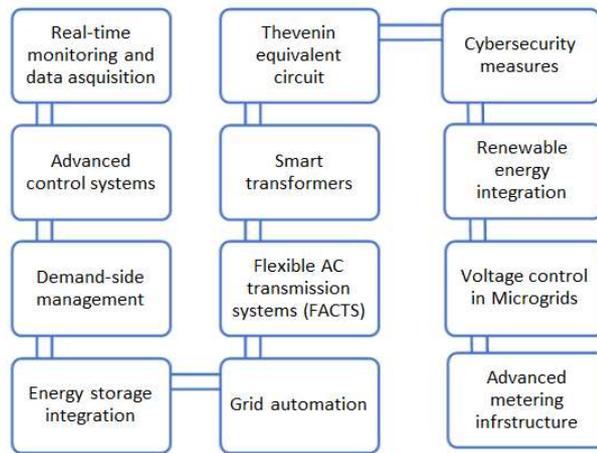


Fig. 4. Smart grid mechanisms to improve voltage stability.

Smart grids use advanced sensors and communication systems to monitor grid conditions in real time. Phasor Measurement Units (PMUs) are particularly valuable for assessing voltage stability margins in real-time systems. Smart meters provide data on voltage, active power, and reactive power, which can be used to estimate the state of the distribution system. This enhanced monitoring enables quicker detection of potential voltage instability issues.

Smart grids employ sophisticated control systems to regulate voltage levels. These systems can automatically adjust transformer taps and switch capacitor banks to maintain voltage within acceptable limits. Model predictive control is also used in smart grid connected multilevel inverters to enhance grid stability. Fuzzy logic-based control systems can improve energy storage control, further promoting grid stability.

Demand response programs can shift or reduce electricity demand during peak periods, which helps to alleviate stress on the grid and improve voltage stability. By

managing load variations, smart grids can prevent voltage drops that may lead to instability. Integrating battery energy storage systems (BESS) into the grid can enhance power system stability. BESS can quickly inject or absorb reactive power to support voltage levels during disturbances. Fuzzy logic control can also be used to manage energy storage systems for grid stability. Smart grid technologies facilitate grid automation, allowing for rapid responses to changing conditions. Automated nets reconfiguration can optimize grid performance and improve voltage stability. Self-healing technologies can detect and isolate faults, minimizing disruptions and maintaining stable voltage levels.

FACTS devices, such as STATCOMs (Static Synchronous Compensators), play a significant role in improving voltage stability. STATCOMs can provide fast reactive power compensation to stabilize voltage levels. They are particularly useful in mitigating voltage variations caused by disturbances and integrating renewable energy sources like wind power. Integrating

PV solar farm inverters as STATCOM devices can also enhance system performance. Studies have shown that optimized STATCOM controllers can effectively improve voltage stability in grid-connected hybrid network systems. A combination of TCSC (Thyristor Controlled Series Compensator) and STATCOM can also be used to improve voltage stability in wind power grid-connected systems.

Smart transformers determine the voltage of low voltage nets. They can improve voltage quality by addressing disturbances such as sags, swells, and harmonics. Adaptive voltage control in smart transformer-fed grids is crucial for maintaining stability. Estimating grid stability using the Thevenin equivalent circuit concept is a popular technique. It allows for the determination of maximum available power and grid area stability without knowing the grid model. Real-time voltage stability prediction can be achieved using

smart meter data and improved Thevenin estimates. Protecting smart grids from cyberattacks is essential for maintaining voltage stability. Cyberattacks on voltage support devices like SVC and STATCOM can negatively impact transient voltage stability. Smart grids facilitate the integration of renewable energy sources like solar and wind power. However, the integration of inverter-based generators (IBGs) requires advanced control strategies to ensure voltage stability. Smart grid technologies are used for voltage control in microgrids, which often incorporate renewable energy sources. Techniques such as using capacitor banks and tap-changing transformers can help ensure adequate voltage quality in microgrids.

AMI is used for low voltage distribution systems in smart grids for monitoring applications. It enhances reliability and efficiency in energy distribution.

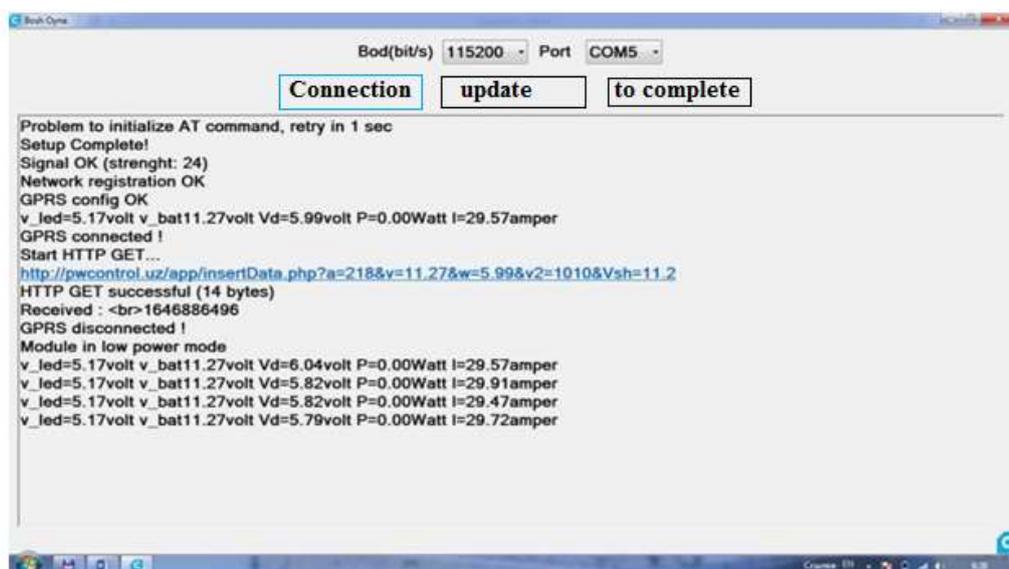


Fig.5. General view of the main working area of the software package for monitoring energy supply sources by source..

Figure 7 from illustrates the voltage deviation over a 24-hour period with and without PV systems and PVSTATCOM. The graph shows that the addition of PV systems can increase voltage deviation, but the use of PVSTATCOM helps to significantly reduce and stabilize voltage levels.

The ongoing development of renewable energy and microgrid technologies has transformed conventional energy infrastructure. Smart grid technologies are essential for addressing the voltage stability challenges associated with these changes. By enabling real-time monitoring, advanced control, and flexible grid management, smart grids can effectively improve voltage stability and ensure a reliable power supply.

SG technology can improve voltage

In modern smart grid architectures, especially smart inverters and smart meters are considered essential smart grid applications within Home Area Networks (HANs), providing real-time monitoring, two-way communication, and voltage control functionalities. When deployed in residential photovoltaic systems, smart inverters can interact with the HAN and extend their control capabilities to the Local Grid (LG), offering ancillary services such as voltage regulation and reactive power support.

By strategically installing these devices at voltage-depressed nodes in the LG, it becomes possible to inject surplus energy from HAN-connected PV systems back into the

local grid at nominal voltage. This approach not only supports voltage recovery at weak nodes but also enhances overall voltage stability within the LG. Several studies have validated this mechanism, emphasizing the role of smart inverters and meters in bridging HAN and LG for decentralized voltage support and improved grid resilience.

Conclusion

Submitted results of scientific research let to do conclusion, that the stabilities of hybrid power supply systems are multifaceted challenge influence of factors such as voltage fluctuations, energy losses, and the variable nature of renewable sources. By classifying types of power system stability and examining the root causes of instabilities, it becomes clear that traditional control methods are insufficient in ensuring consistent system performance. The integration of SGTs emerges as a transformative solution, offering advanced monitoring, automation, and real-time data analytics. These capabilities not only mitigate voltage drop and energy losses but also provide a robust framework for enhancing voltage stability and overall system reliability. Ultimately, the implementation of Smart Grid-based strategies represents a key advancement toward creating more stable, resilient, and efficient hybrid power systems suitable for the energy demands of the future.

Reference

1. I. Kh. Siddikov, A. B. Abubakirov, A. U. Djalilov, T. U. Kurbaniyazov, A. A. Abdumalikov;

Statistical descriptions of multiphase current sensors of reactive power control systems in renewable power supply power systems. *AIP Conf. Proc.* 23 June 2023; 2789 (1): 060002. <https://doi.org/10.1063/5.0145430>

2. I. Kh. Siddikov, Kh.A. Sattarov, A.A. Abdumalikov; The static characteristics of primary current transducers of current of specific electrical loads of renewable power sources. *AIP Conf. Proc.* 15 March 2023; 2612 (1): 050002. <https://doi.org/10.1063/5.0115211>

3. Siddikov, Ilkhomjon and A. A. Abdumalikov. "Modeling and research signals conversion proceses of multhipase power measure and control devices." *2020 International Conference on Information Science and Communications Technologies (ICISCT)* (2020): 1-4.

4. I. K. Siddikov, A. A. Abdumalikov and M. T. Makhsudov, "Modeling and Research Multiphases Signal Transducers of Power Control Systems," *2020 International Conference on Information Science and Communications Technologies (ICISCT)*, Tashkent, Uzbekistan, 2020, pp. 1-4, doi: 10.1109/ICISCT50599.2020.9351482.

5. I. Siddikov, M. Sobirov, A. Abdumalikov and K. Sattarov, "Equipment and Software for Energy Supply Monitoring and Control Process," *2021 International Conference on Information Science and Communications Technologies*

(*ICISCT*), Tashkent, Uzbekistan, 2021, pp. 1-6, doi: 10.1109/ICISCT52966.2021.9670126.

6. I. K. Siddikov, M. A. Anarbaev, A. A. Abdumalikov, M. A. Sobirov, M. T. Maxsudov and I. M. Xonturaev, "Technological aspects of modelling and research of smart grid," *2019 International Conference on Information Science and Communications Technologies (ICISCT)*, Tashkent, Uzbekistan, 2019, pp. 1-5, doi: 10.1109/ICISCT47635.2019.9011936.

7. I.K. Siddikov, M.A. Anarbaev, A.A. Abdumalikov, A. B. Abubakirov, M.T. Maxsudov and I.M. Xonturaev, "Modelling of transducers of nonsymmetrical signals of electrical nets," *2019 International Conference on Information Science and Communications Technologies (ICISCT)*, Tashkent, Uzbekistan, 2019, pp. 1-6, doi: 10.1109/ICISCT47635.2019.9011981.

8. A.Q. Ergashev, O.K. Turakulov, A.A. Abdumalikov and O.A. Kayumov, "Algorithms for highlighting the contours of images based on the theory of fuzzy sets," *2022 International Conference on Information Science and Communications Technologies (ICISCT)*, Tashkent, Uzbekistan, 2022, pp. 1-4, doi: 10.1109/ICISCT55600.2022.10146799.

9. Siddikov, Ilkhomjon & Abdumalikov, Akmaljon & Turakulov, Olim & Tojiev, Alisher. (2024). Algorithms and hardware

and software for improving energy efficiency in telecommunications facilities. 060020.

10.1063/5.0242040.

10. Gheorghe, S., et al. *Smart Grid, Integration of Renewable Sources and Improvement of Power Quality*. in *21st International Conference on Control Systems and Computer Science (CSCS)*. 2017. Univ Politehnica Bucharest, Bucharest, ROMANIA.<https://doi.org/10.1109/cscs.2017.98>.

11. Khalid, W., et al., *Dynamic Simulation and Optimization of Off-Grid Hybrid Power Systems for Sustainable Rural Development*. *Electronics*, 2024. **13**.ARTN2487
<https://doi.org/10.3390/electronics13132487>.

12. Sayeed, M.A. and K. Manikandan, *Smart Integration of Renewable Energy into Transportation: Challenges, Innovations, and Future Research Directions*. *Journal of Renewable Energies*, 2024.
<https://doi.org/10.54966/jreen.v27i2.1300>

13. Ali, M.B., et al., *Voltage Profile Improvement by Integrating Renewable Resources with Utility Grid*. *Energies*, 2022.
<https://doi.org/10.3390/en15228561>.

14. Anthony, K. and V. Arunachalam, *Voltage stability monitoring and improvement in a renewable energy dominated deregulated power system: A review*. *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, 2025.

<https://doi.org/10.1016/j.prime.2024.100893>.

15. Roy, D., et al., *Hybrid renewable energy systems for sustainable power supply in remote location: Techno-economic and environmental assessment*. *Energy Conversion and Management: X*, 2024.

<https://doi.org/10.1016/j.ecmx.2024.100793>.

16. Marevac, E., et al. *Application of Deep Learning and Neural Networks for Smart Grid Stability Predictions*. in *12th International Conference on Smart Energy Grid Engineering*. 2024. Ontario Tech University, Oshawa, CANADA.<https://doi.org/10.1109/sege62220.2024.10739561>.

17. Ohanu, C.P., S.A. Rufai, and U.C. Oluchi, *A comprehensive review of recent developments in smart grid through renewable energy resources integration*. *Heliyon*, 2024. **10**: p. e25705.<https://doi.org/10.1016/j.heliyon.2024.e25705>.

18. Qays, M.O., et al., *Key communication technologies, applications, protocols and future guides for IoT-assisted smart grid systems: A review*. *Energy Reports*, 2023. **9**: p. 2440-2452.<https://doi.org/10.1016/j.egy.2023.01.085>.

19. Giannelos, S., et al., *Option value, investment costs and deployment levels of smart grid technologies*. *Sustainable Energy Research*, 2024.
<https://doi.org/10.1186/s40807-024-00143-x>.

20. Kim, S.-K. and J.-H. Huh, *A Study on the Improvement of Smart*

- Grid Security Performance and Blockchain Smart Grid Perspective*. Energies, 2018. <https://doi.org/10.3390/en11081973>.
21. Kumar, M.P., Bhupesh, *Smart Grid Technologies: A Comprehensive Review*. Turkish Journal of Computer and Mathematics Education (TURCOMAT), 2020. **11**: p. 2895–2899. <https://doi.org/10.61841/turcomat.v11i3.14656>.
22. Gaudi, M.K., et al., *Predicting the stability of smart grid for improving the sustainability using distributed generation technology*. e-Prime - Advances in Electrical Engineering, Electronics and Energy, 2023. <https://doi.org/10.1016/j.prime.2023.100185>.
23. Hasan, M.K., et al., *Smart Grid Communication Networks for Electric Vehicles Empowering Distributed Energy Generation: Constraints, Challenges, and Recommendations*. Energies, 2023. <https://doi.org/10.3390/en16031140>.
24. Ammari, C., et al., *Sizing, optimization, control and energy management of hybrid renewable energy system—A review*. Energy and Built Environment, 2022. **3**: p. 399-411. <https://doi.org/10.1016/j.enbenv.2021.04.002>.
25. Laurențiu-Alex, M. and H. Elena, *Research Trends in Hybrid Power Supply Systems for Standalone Houses*. Annals of the University of Craiova Electrical Engineering Series, 2025. **48**: p. 93-98. <https://doi.org/10.52846/aucee.2024.14>.
26. Ahmad, S., et al., *A Review of Hybrid Renewable and Sustainable Power Supply System: Unit Sizing, Optimization, Control, and Management*. Energies, 2024. <https://doi.org/10.3390/en17236027>.
27. Mohammad Reza Maghami and A.G.O. Mutambara, *Challenges associated with Hybrid Energy Systems: An artificial intelligence solution*. Energy Reports, December 2023. **9**: p. 924-940. <https://doi.org/10.1016/j.egyr.2022.11.195>.
28. Nikolaos, P.C., F. Marios, and K. Dimitris, *A Review of Pumped Hydro Storage Systems*. Energies, 2023. <https://doi.org/10.3390/en16114516>.
29. Simão, M. and H. Ramos, *Hybrid Pumped Hydro Storage Energy Solutions towards Wind and PV Integration: Improvement on Flexibility, Reliability and Energy Costs*. Water, 2020. <https://doi.org/10.3390/w12092457>.
30. Ergun, S., et al., *Large-Scale Renewable Energy Integration: Tackling Technical Obstacles and Exploring Energy Storage Innovations*. Sustainability, 2025. <https://doi.org/10.3390/su17031311>.
31. Awad, H. and E.H.E. Bayoumi, *Next-Generation Smart Inverters: Bridging AI, Cybersecurity, and Policy Gaps for Sustainable Energy Transition*. Technologies, 2025. <https://doi.org/10.3390/technologies13040136>.

32. Rahif, H.S., *The Design of an MPPT Solar Energy System Based on Fuzzy Logic Systems*. Mathematical Modelling of Engineering Problems, 2024. **11**: p. 2405-2417. <https://doi.org/10.18280/mnep.110913>.
33. Rekioua, D., et al., *Optimization and intelligent power management control for an autonomous hybrid wind turbine photovoltaic diesel generator with batteries*. Sci Rep, 2023. **13**: p. 21830. <https://doi.org/10.1038/s41598-023-49067-4>.
34. Khallouf, K.N., et al., *Adaptive fuzzy logic control for microgrid-connected hybrid photovoltaic/wind generation systems*. Energy Reports, 2024. **12**: p. 4741-4756. <https://doi.org/10.1016/j.egy.2024.10.042>.
35. Gharahbagh, A.A., et al., *Enhancing Efficiency in Hybrid Solar-Wind-Battery Systems Using an Adaptive MPPT Controller Based on Shadow Motion Prediction*. Applied Sciences, 2024. <https://doi.org/10.3390/app142411710>.
36. Son, Y.-B., et al., *Privacy-Preserving Peer-to-Peer Energy Trading in Blockchain-Enabled Smart Grids Using Functional Encryption*. Energies, 2020. <https://doi.org/10.3390/en13061321>.
37. Atawi, I.E., et al., *Recent Advances in Hybrid Energy Storage System Integrated Renewable Power Generation: Configuration, Control, Applications, and Future Directions*. Batteries, 2022. <https://doi.org/10.3390/batteries9010029>.
38. Kamolov, Dostonbek. (2023). GLOBALIZATION PHENOMENON AND GLOBALISM. 1. 4-9. 10.5281/zenodo.10433143.
39. Meiirkhan, Spanov & Kamolov, Dostonbek. (2023). MODERN PROBLEMS AND SOLUTIONS OF DEMOCRACY AND MORALITY IN UZBEKISTAN СОВРЕМЕННЫЕ ПРОБЛЕМЫ И ПУТИ ИХ РЕШЕНИЯ В ОБЛАСТИ ДЕМОКРАТИИ И ПРАВСТВЕННОСТИ В УЗБЕКИСТАНЕ. 1. 168-172. 10.5281/zenodo.10113202.
40. Kamolov, Dostonbek. (2023). ДУХОВНО-ПРАВСТВЕННАЯ СРЕДА ОБЩЕСТВА. 1. 128-133. 10.5281/zenodo.10003781.
41. Kamolov, Dostonbek. (2023). ON THE WAY TO THE DIGITAL EDUCATION SYSTEM OF UZBEKISTAN.
42. Kamolov D. JIZZAX VILOYATIDA TURIZM KLASTERI RIVOJLANISHINING HUDUDNING IJTIMOY-IQTISODIY SALOHIYATIGA TA'SIRINI BAHOLASH: STRATEGIK YONDASHUV VA RIVOJLANISH ISTIQBOLLARI //Scientific practical conference. – 2025. – Т. 1. – №. 1. – С. 48-52.
43. Kamolov D. VIRTUAL TURIZM (VR) XIZMATLARINING RIVOJLANISH ISTIQBOLLARI //Scientific practical conference. – 2025. – Т. 1. – №. 1. – С. 372-374.
44. Khudoyarov R., Kamolov D., Azamatov B. Economic growth, business circulation and economic development //Science technology&Digital finance. – 2024. – Т. 2. – №. 2. – С. 21-24.