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Investigation of improved control strategies of photovoltaic inverter systems for the integration of distributed generations

Olusayo Adekunle Ajeigbe * and Oreoluwa Omolade Adeyemi

Department of Electrical and Electronics Engineering, Faculty of Engineering, Ajayi Crowther University, Oyo, Nigeria.

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Abstract

The incorporation of photovoltaic (PV) systems into power networks poses issues owing to the variability and intermittency of solar energy. This paper examines sophisticated control algorithms for photovoltaic inverters to promote grid stability, maximize energy conversion, improve power quality, and facilitate the smooth integration of dispersed renewable energy sources. This study conducts a thorough examination of current control methods and their shortcomings, identifying and assessing novel algorithms designed to address these issues. Significant contributions encompass the execution of Maximum Power Point Tracking (MPPT) techniques, voltage management at the Point of Common Coupling (PCC), synchronization methods for grid frequency and phase alignment, as well as measures for mitigating harmonic distortion and voltage fluctuations. Both simulation and experimental validations substantiate the efficacy of these control mechanisms across various climatic and grid conditions. The suggested solutions markedly improve photovoltaic system performance and reliability, promoting steady integration of dispersed generation and facilitating the advancement of sustainable power systems.

Keywords: Control Strategies; Photovoltaic Inverter Systems; Distributed Renewable Energy Generations; Power Systems; Distribution System

1. Introduction

With the increasing prevalence of sustainable energy, photovoltaic (PV) systems have become integral components of distributed generation (DG) systems, facilitating the transition to reduced emissions and energy autonomy [1, 2]. Integrating photovoltaic systems into the electricity grid presents technological challenges due to the intermittent nature of solar energy, resulting in difficulties such as grid stability concerns, voltage variations, and harmonic distortion. PV inverters, serving as the vital connection between PV systems and the grid, are crucial in addressing these challenges, rendering their control imperative for stable distributed generation integration [2, 3]. This study examines sophisticated control mechanisms for photovoltaic inverters to tackle these issues, with the objective of improving grid stability, energy efficiency, and system resilience and enhances the reliable integration of distributed renewable energy by optimizing photovoltaic inverter control, hence promoting a more sustainable and resilient energy infrastructure.

1.1. Context of the study

The shift to renewable energy sources, including solar power, is propelled by environmental, economic, and regulatory considerations. The fluctuating characteristics of photovoltaic power necessitate sophisticated control systems to guarantee stable and efficient grid integration. Conventional inverter control methods frequently fail to manage the complications arising from elevated levels of PV integration, hence requiring the development of novel control strategies [3,4,5]. The examination of enhanced control algorithms for photovoltaic (PV) inverter systems to integrate distributed renewable energy sources is a vital research domain focused on improving the efficiency, dependability, and

* Corresponding author: Olusayo Adekunle Ajeigbe.

stability of power grids. As solar PV systems become more prevalent, appropriate control mechanisms are crucial for optimizing energy conversion, maintaining grid stability, and ensuring smooth integration with existing power infrastructure [5, 6]. These control strategies determine the performance, efficiency, and stability of photovoltaic systems, therefore affecting their overall influence on the power grid.

The inquiry will entail a thorough examination of current control techniques and their shortcomings, succeeded by the experimental assessment of specific control algorithms designed to enhance the performance of photovoltaic inverter systems. The effectiveness of the control techniques was assessed through simulated studies and experimental validation across diverse operating circumstances and grid situations.

This study aims to enhance solar inverter technology and promote the smooth integration of distributed renewable energy sources into the power grid as well expedite the transition to a more sustainable and resilient energy infrastructure by addressing the technical constraints related to photovoltaic system controls.

Maximum Power Point Tracking (MPPT) methodologies are crucial in photovoltaic (PV) systems for optimizing power extraction under fluctuating environmental circumstances. A variety of MPPT strategies have been created, each possessing unique attributes, benefits, and drawbacks. This paper assesses many notable MPPT methodologies as per the current literature [4, 7, 8].

Perturb and Observe (P&O) is among the most uncomplicated and prevalent MPPT techniques, owing to its easy implementation and minimal computational demands. It intermittently alters the operating voltage and monitors the variation in power to identify the maximum power point (MPP). P&O may have persistent oscillations around the Maximum Power Point (MPP) and may not efficiently track the MPP during rapidly fluctuating irradiance circumstances [9, 10]. The P&O method functions by periodically adjusting the output terminal voltage of the photovoltaic system, comparing the power generated in the current cycle with that of the preceding cycle. If the voltage fluctuates and the power escalates, the control system adjusts the operating point accordingly; otherwise, it modifies the operating point in the contrary direction. Upon determining the direction for the alteration of current, the current is adjusted at a uniform pace. This rate is a parameter that must be calibrated to achieve a balance between rapid response and minimal variation in steady state [11, 12].

Fuzzy Logic Control (FLC) use fuzzy logic to manage the non-linear attributes of photovoltaic (PV) systems. It can deliver seamless and precise MPP tracking under diverse settings without necessitating an exact mathematical model. The design and optimization of FLC systems can be intricate, necessitating specialized knowledge to establish suitable membership functions and regulations. The fuzzy logic controller offers a broad spectrum of applications in renewable energy systems. The utilization of fuzzy logic controllers has surged over the past decade due to their simplicity, ability to manage imprecise inputs, lack of requirement for an exact mathematical model, and capacity to address nonlinearity. FLC can function as a controller to maximize the power output of PV modules under varying weather conditions [12, 13]. The FLC procedure consists of three stages: fuzzification, rule assessment, and defuzzification. The fuzzification process is converting a precise input, like the variation in voltage readings, and integrating it with established membership functions to generate fuzzy inputs. To convert crisp inputs into fuzzy inputs, a membership function must first be assigned to each input. Upon the assignment of membership functions, fuzzification processes real-time inputs and juxtaposes them with the stored membership function data to generate fuzzy input values. The second phase of fuzzy logic processing is rule evaluation, when the fuzzy processor employs linguistic rules to ascertain the appropriate control action based on a specified set of input values. The outcome of rule assessment yields a nebulous output for each category of resultant action. The final phase in fuzzy logic processing, when the anticipated value of an output variable is obtained by extracting a precise value from the universe of discourse of the output fuzzy sets. In this approach, all fuzzy output values effectively alter their corresponding output membership functions. A prevalent defuzzification approach is known as the Center of Gravity (COG) or centroid method. The fuzzy logic controller is employed for optimizing the highest power output of photovoltaic systems due to its robustness, relative simplicity in design, and lack of necessity for precise model information [8, 14].

Assessing voltage control tactics of photovoltaic (PV) inverters necessitates comprehension of how these systems administer and regulate voltage levels inside a power grid. Effective voltage regulation is crucial for sustaining grid stability, boosting power quality, and improving the integration of renewable energy sources. This paper provides an overview of essential voltage control mechanisms for photovoltaic inverters and associated assessment criteria. Principal Voltage Regulation Strategies [9, 15].

Assessing various contemporary controllers for photovoltaic inverters is essential for mitigating concerns related to harmonic distortion, power quality, and grid stability. Efficient current regulation is crucial for enabling PV inverters to deliver clean and stable energy to the grid. An overview of main contemporary control mechanisms and associated assessment criteria are provided [16]: Proportional-Integral (PI) Control mechanism employs proportional and integral gains to modulate the current, achieving a balance between velocity and stability. PI controllers are prevalent because to their straightforwardness and ease of deployment. They offer commendable steady-state performance and are proficient at regulating the mean output current. PI controllers may exhibit difficulties in dynamic performance and may inadequately manage abrupt alterations in grid conditions or non-linear loads. They possess restricted capacity to mitigate harmonic aberrations. It may experience difficulties with tracking precision and dynamic responsiveness under fluctuating grid circumstances. A limitation of the PI controller is its inability to accurately track a sinusoidal reference without incurring steady-state error, attributable to the dynamics of the integral term. The inability to monitor a sinusoidal reference necessitates the utilization of grid voltage as a feed-forward term to achieve an improved dynamic response, assisting the controller in attaining steady state more rapidly [11, 17].

This study examines different photovoltaic inverter management systems for maximum power point tracking, grid synchronization, voltage regulation, power quality enhancement, and grid support functionalities to tackle the issues related to photovoltaic integration. Conventional control approaches frequently demonstrate inadequacies in managing the dynamic characteristics of photovoltaic systems, resulting in inefficiency and grid instability problems. This work also seeks to examine and propose enhanced control algorithms for solar inverter systems, concentrating on the problems related to the integration of dispersed renewable energy sources. The paper aims to improve the reliability, efficiency, and grid compatibility of photovoltaic systems by utilizing breakthroughs in control theory, power electronics, and renewable energy technology.

2. Methodology

2.1. Methodology for evaluating MPPT algorithms in photovoltaic applications.

The average model of the DC-DC boost converter was employed to simulate load variation controlled using Matlab/Simulink, incorporating a fluctuation in the average model to depict the impact of inductor ripple current. All tests were conducted under consistent temperature and irradiation conditions, incorporating both positive and negative increments.

2.2. Methodology for evaluating voltage control strategies of solar inverters

Configuration of Simulation: The research employed OpenDSS software to model a distribution network and simulate multiple scenarios. Three sophisticated inverter control systems were assessed: Volt-Watt, Fixed Power Factor, and Volt-Var control. The efficacy of these solutions was evaluated against a baseline scenario without voltage regulation.

2.3. Methodology for evaluating synchronization techniques for photovoltaic inverters.

The investigation of synchronization techniques for power systems encompasses various new methodologies, including Phase-Locked Loop (PLL), Frequency-Locked Loop (FLL), and Enhanced Phase-Locked Loop (EPLL). Reference [12] (Karimi-Ghartemani and Iravani (2004)) illustrated the PLL's proficiency in precisely measuring frequency and its rate of change, underscoring its dependability in power system applications. Reference [13] Zhu and Zhao (2007) presented the FLL method, which utilizes a second-order generalized integrator (SOGI) for frequency estimation, demonstrating significant benefits over conventional techniques, especially in its adaptability to grid fluctuations. Reference [14] Agrawal, Sharma, and Birla conducted more research on the Enhanced PLL (EPLL) for synchronizing grid-interactive hybrid systems that include photovoltaic (PV) and solid oxide fuel cell (SOFC) sources. Their research concentrated on strengthening synchronization precision and control using the Hysteresis Band Current Controller (HBCC), demonstrating the efficacy of EPLL in regulating intricate grid conditions and improving power quality.

2.4. Methodology for evaluating several current controllers in mitigating difficulties associated with PV inverters.

The empirical outcomes from a grid-connected inverter indicate a greater steady-state error with the PI current controller in comparison to the PR current controller, aligning with the simulations. The PI controller generated a peak current of around 8.72A for a 50Hz sinusoidal reference current of 8A, yielding a 9% inaccuracy. This discrepancy arises from the non-ideal characteristics of the practical inverter. Conversely, the PR controller attained a current peak of precisely 8A, exhibiting a 0% inaccuracy. The anticipated minor inaccuracy did not manifest, since the resonant term gain was adequate to track the reference without complications. Both controllers surpassed the harmonic thresholds established by IEEE and IEC standards for the 3rd and 5th harmonics, attributable to inverter non-linearities and grid supply complications. Although the PR controller has superior performance in tracking a sinusoidal reference, both controllers require supplementary harmonic compensation to comply with regulatory standards.

The study conducted by E.S.L. Narayana and R.M. Brisilla on Model Predictive Control (MPC) of single-phase grid-connected inverters for photovoltaic systems examines contemporary reference schemes to improve control efficacy. Here is a comprehensive elucidation of their discoveries.

3. Results and Discussion

3.1. Evaluation results of MPPT algorithms for photovoltaic applications

Figure 1 indicates that the tracking factor reveals the P&O and IC modified, Ripple Correlation, and Beta methods have strong performance, with the Beta approach attaining the maximum energy extraction at roughly 98.8%. Figure 2a illustrates the steady-state ripple, emphasizing that the Ripple Correlation and Beta techniques exhibit the minimal ripple. MPPT methods must be assessed for their dynamic response, particularly for their performance when the power panel's output fluctuates rapidly from 10W to 200W, as seen in Figure 2b. The results demonstrate that the Beta and modified IC approaches perform exceptionally well, with the modified IC method achieving steady state in the briefest duration (about 0.2 seconds). The IC and P&O approaches exhibit comparable performance indices because they both operate on the premise of identifying the Maximum Power Point Tracking (MPPT), characterized by dP/dV equating to zero at the Maximum Power Point (MPP).

The experimental results assessed the approaches based on their initialization performance, analyzing their responses while commencing from a zero state and subjected to both positive and negative power steps. All techniques shown commendable performance, modifying PV output power within 20ms in response to power fluctuations (100W-200W and vice versa).

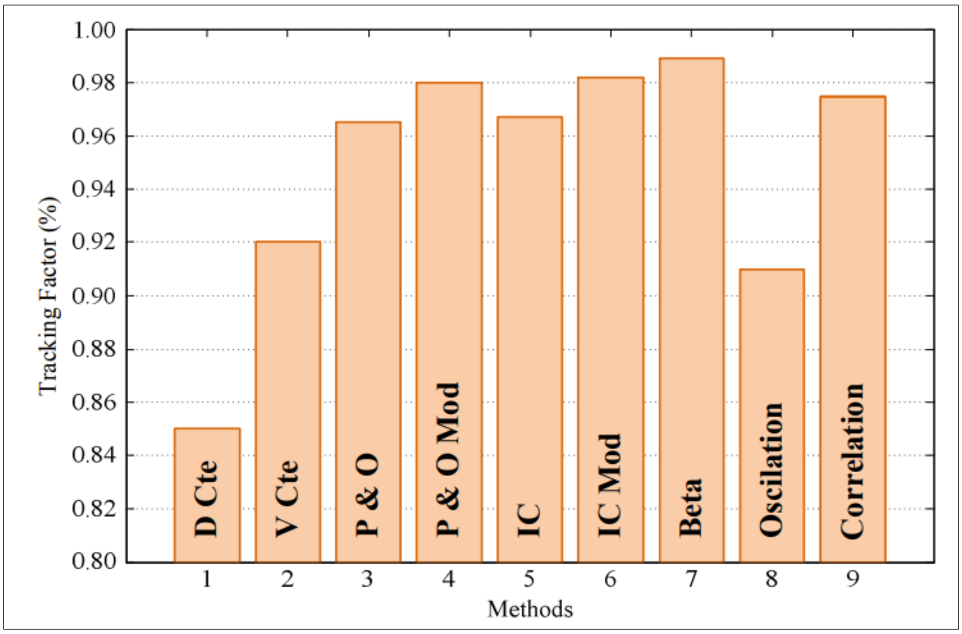

Figure 1 Percent of Energy Extracted from PV Panel

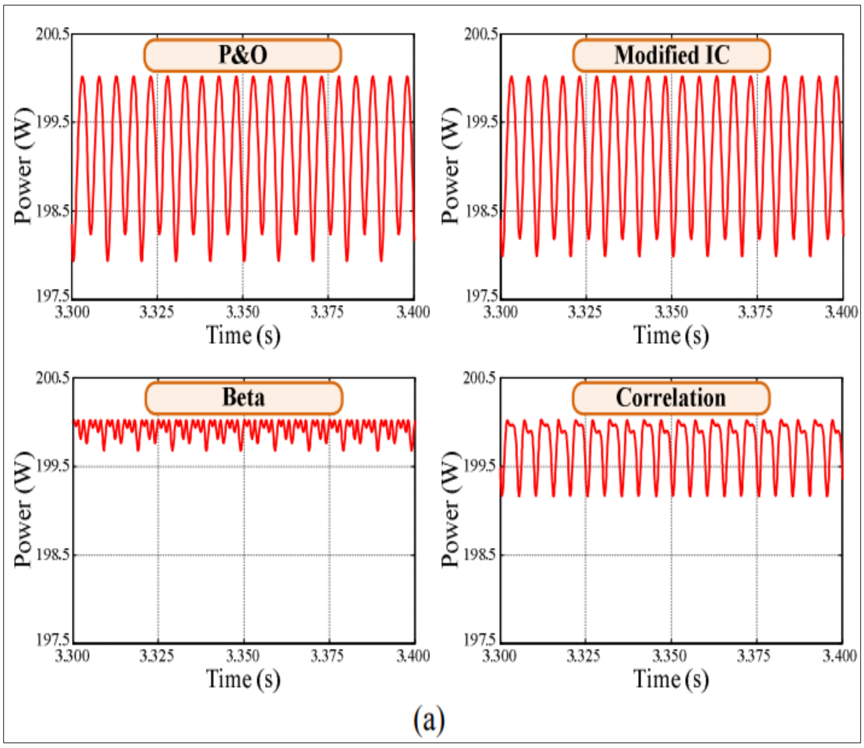

Figure 2a Power Ripple in Steady State

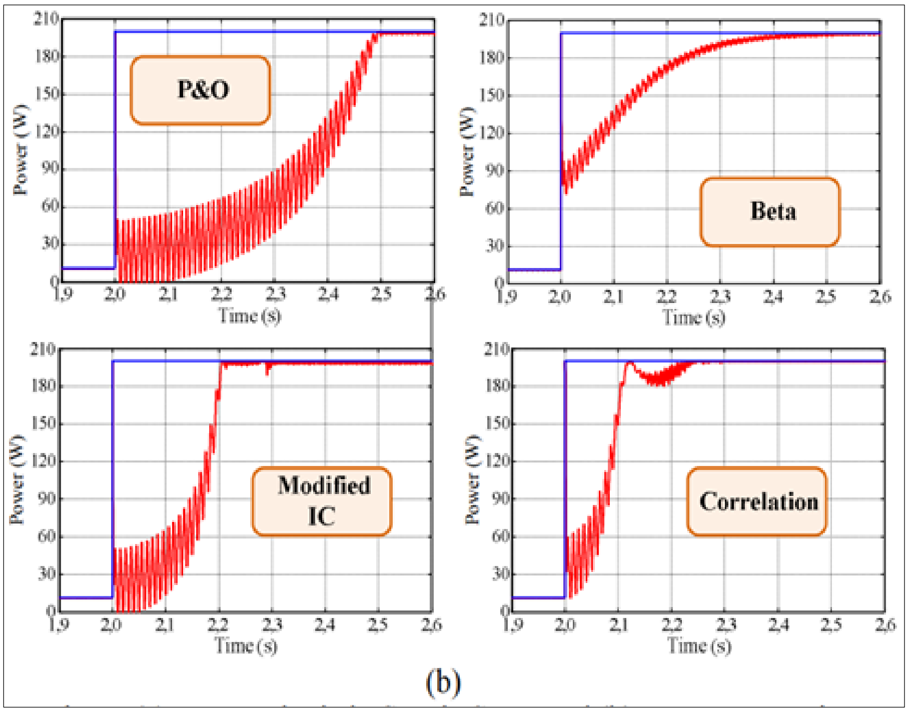

Figure 2b MPPT Dynamic Behaviour

The Vcte technique exhibited suboptimal initialization, requiring 1.6 seconds to attain maximum power from an off state. The Beta technique exhibited an initialization duration of approximately 500 milliseconds. The IC and P&O approaches exhibited superior initialization performance; however, continuous perturbations led to power loss in steady state due to the persistent fluctuations in PV output voltage.

A C++ Builder acquisition management system was employed to calculate the Tracking Factor (TF). This technology facilitated remote programming of the Array Emulator with diverse irradiation and temperature profiles to simulate power characteristics, modified either randomly or according to particular environmental conditions. The data interchange between the computer and the array emulator was conducted via GPIB-USB. The energy derived from the Photovoltaic Emulator (E4350B) utilizing MPPT algorithms, with PMAX (red chart) denoting the maximum available power and PMPPT (green chart) indicating the converted energy. The methods were optimized for identical irradiation and temperature parameters, with the Beta method extracting 98% of energy, the P&O method 96%, and the Vcte method 92%. The experimental results closely aligned with the simulated outcomes, illustrating the efficacy of the analytical method. The commercial specs for the photovoltaic module utilized in the Array Simulator are detailed in Table 1.

Table 1 Commercial specifications for the photovoltaic module used in the Array Simulator

S/No	PV ELECTRICAL PARAMETERS	Value
1	Maximum Power	P_{max} = 200 Wp
2	Voltage at MPP	V_{MPP} = 26.3 V
3	Current at MPP	I_{MPP} = 7.61 A
4	Open Circuit Voltage	V_{OC} = 32.9 V
5	Short Circuit Current	I_{SC} = 8.21 A
6	Temperature Coefficient of I_{SC}	$\alpha = 3.18 \times 10^{-3}$ A/°C

3.2. Outcomes of the Assessment of Voltage Regulation Strategies for Photovoltaic Inverters

The assessment of voltage control systems for photovoltaic (PV) inverters revealed significant effects on voltage regulation, power generation, and network performance. In the baseline scenario devoid of regulation, numerous nodes encountered overvoltage complications. The Volt-Watt management technique efficiently alleviated overvoltage by diminishing active power output when voltage surpassed a predetermined threshold, however this resulted in a decrease in total active power generation. Fixed Power Factor control addressed voltage difficulties by maintaining constant power factor modifications, necessitating more reactive power absorption. The Volt-Var control modulated reactive power in reaction to voltage fluctuations, effectively mitigating overvoltage while minimizing active power reduction and requiring less reactive power than Fixed Power Factor control. Concerning network losses, both Volt-Watt and Volt-Var controls diminished losses, with Volt-Var attaining optimal efficiency through the equilibrium of active and reactive power losses. Examination of daily nodal voltage fluctuations revealed that all techniques-maintained voltages within permissible limits, with Volt-Var control yielding the most consistent voltage profile over the course of the day.

3.3. Outcomes from the Assessment of Synchronization Techniques for Photovoltaic Inverters

The assessment of synchronization techniques for PV inverters underscored the specific benefits of Phase Locked Loop (PLL), Frequency Locked Loop (FLL), and Enhanced Phase Locked Loop (EPLL) regarding precision, resilience, and power quality. The PLL, featuring a nonlinear adaptive filter, demonstrated great accuracy and swift reaction in real-time frequency estimation, sustaining performance in noisy and disrupted situations, hence confirming its suitability for renewable integration. The FLL, utilizing a second-order generalized integrator (SOGI), exhibited superior precision and rapid response to frequency fluctuations, offering improved stability compared to PLL under non-ideal grid settings. The EPLL, utilized in a hybrid PV-SOFC system, demonstrated superior synchronization during grid disruptions owing to its improved filtering capabilities that mitigated noise and harmonics. The integration of a Hysteresis Band Current Controller (HBCC) with the EPLL enhanced power quality by diminishing Total Harmonic Distortion (THD) and promptly adapting to load fluctuations, thus augmenting system stability and facilitating hybrid grid-interactive applications.

3.4. Evaluation results of several current controllers in mitigating difficulties associated with PV inverters

The evaluation of the grid-connected inverter's performance indicated that the PI current controller demonstrated a greater steady-state error than the PR controller, consistent with simulation forecasts. Upon testing with a 50Hz sinusoidal reference current of 8 A peak, the PI controller achieved an 8.72 A peak, reflecting a 9% inaccuracy due to inverter non-idealities. Conversely, the PR controller attained an exact 8 A peak with 0% error, due to adequate resonant gain. Notwithstanding the PR controller's precision, both controllers surpassed IEEE and IEC harmonic standards for the 3rd and 5th harmonics, signifying a requirement for further harmonic compensation. The assessment of the Model Predictive Control (MPC) method revealed notable enhancements in power quality, as it efficiently reduced total harmonic distortion (THD) in the inverter's output. MPC exhibited a swift dynamic reaction to changes in grid and photovoltaic output, demonstrating resistance to solar variability and improving grid stability. Moreover, MPC's exact current regulation enabled accurate set-point monitoring via predictive modifications, surpassing conventional controllers by forecasting forthcoming alterations in operating conditions.

4. Conclusion

This research offers significant insights into enhanced control strategies for photovoltaic (PV) inverter systems, intended to increase the integration of distributed renewable energy sources into the power grid. The research highlights the efficacy of advanced algorithms in maximizing power point tracking (MPPT), regulating voltage at the Point of Common Coupling (PCC), and synchronizing photovoltaic inverter output with grid frequency and phase, by concentrating on critical aspects such as grid stability, energy conversion efficiency, power quality, and support for vital grid services. Extensive simulations and experimental validations demonstrate that control strategies, including Low Voltage Ride-Through (LVRT), Voltage Ride-Through (VRT), Frequency Ride-Through (FRT), and model predictive control, substantially enhance the dynamic response and stability of PV inverters amid environmental fluctuations and grid disturbances. Moreover, the incorporation of energy storage devices is demonstrated to significantly improve energy management and grid resilience. These findings highlight the necessity of using sophisticated PV inverter control systems to facilitate the sustainable, stable, and efficient integration of dispersed generation in contemporary power networks.

Recommendations

This study's findings on enhanced control strategies for photovoltaic (PV) inverter systems yield various recommendations to facilitate the effective integration of distributed generation (DG) into power grids. Utilities and grid operators ought to implement advanced control methodologies, including Model Predictive Control (MPC), adaptive control, and droop control, which have demonstrated efficacy in augmenting voltage regulation, frequency stability, and power quality, thereby enhancing grid stability under fluctuating conditions. It is advisable to integrate energy storage systems (ESS) with photovoltaic (PV) inverters to reduce PV power fluctuation and improve grid resilience via enhanced energy management, encompassing load balancing and frequency control, particularly in regions with significant renewable energy integration. Furthermore, photovoltaic inverters must employ optimized Maximum Power Point Tracking (MPPT) algorithms to enhance energy output and possess Voltage and Frequency Ride-Through capabilities (LVRT, VRT, and FRT) to ensure stable operation during grid disturbances, thereby averting unnecessary disconnections and augmenting reliability. Subsequent research should concentrate on standardized testing methodologies for sophisticated control strategies to assess performance in real-world settings and guarantee uniform integration standards. Policymakers are urged to facilitate this transition by providing explicit rules and incentives for sophisticated photovoltaic inverter management and energy storage system integration, thereby fostering robust, grid-compatible photovoltaic systems. Investing in training and capacity building for utility engineers on the application and maintenance of modern technologies is essential for facilitating smoother adoption and ongoing management. Executing these recommendations can enhance PV inverter performance, bolster grid stability, and facilitate sustainable energy infrastructure, establishing a solid framework for the integration of renewable energy sources into contemporary power networks.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they do not have any conflict of interest.

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