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Review on AI-Based Power Quality Enhancement in Grid-Connected Solar PV Systems

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ABSTRACT
The use of artificial intelligence (AI) is increasing in various sectors of photovoltaic (PV) systems, due to the increasing computational power, tools and data generation. The currently employed methods for various functions of the solar PV industry related to design, forecasting, control, and maintenance have been found to deliver relatively inaccurate results. Further, the use of AI to perform these tasks achieved a higher degree of accuracy and precision and is now a highly interesting topic. In this context, this paper aims to investigate how AI techniques impact the PV value chain. The investigation consists of mapping the currently available AI technologies, identifying possible future uses of AI, and also quantifying their advantages and disadvantages in regard to the conventional mechanisms.
Keywords: artificial intelligence; photovoltaic systems; optimal sizing; irradiance forecasting; condition monitoring; transition control; reliability

I. INTRODUCTION

The incorporation of non-conventional power resources such as photovoltaic (PV), battery storage, and wind generation into the grid has gained significant attention due to their environmental benefits and potential to reduce dependency on conventional fossil fuels. However, the variability and intermittency of these renewable sources pose challenges to grid stability and power quality. Power fluctuations, voltage sags, harmonics, and power factor variations are among the issues that can impact the reliability and performance of grid-connected systems. A study on power quality enrichment in a gridlinked PV, wind & battery system using UPQC with atom search optimisation was conducted by [1]. The main findings of the study include improved power quality, reduced harmonics, and enhanced voltage regulation in the system. It does not consider the impact of varying weather conditions on the performance of the PV/wind/battery system, which could affect the overall power quality enhancement.[2] investigated the performance of a grid-linked distributed production structure incorporating a hybrid wind & Solar farm using UPQC. The study focused on analysing the system's stability, efficiency, and power quality improvement. It does not address the economic feasibility of implementing a hybrid wind-PV farm with UPQC, which could be a crucial factor for real-world applications.

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A performance analysis of a UPQC for microgrid structures with integrated solar PV array and storage was conducted by [3]. The study aimed to optimize the system's power quality, efficiency, and reliability. It does not consider the impact of varying load conditions on the performance of the PV and battery combined UPQC, which could affect the overall system performance.[4] investigated power quality improvement in a solar photovoltaic/wind energy integrated system using UPQC. The study focused on reducing harmonics, improving voltage regulation, and enhancing power quality in the system.[5] analysed the performance of a fuzzy-based controller for wind and battery-fed UPQC in microgrid systems. The study focused on improving power quality, stability, and efficiency in the system. It does not consider the impact of communication delays or signal processing limitations on the performance of the fuzzy-based controller for wind and battery-fed UPQC, which could affect the overall system performance.

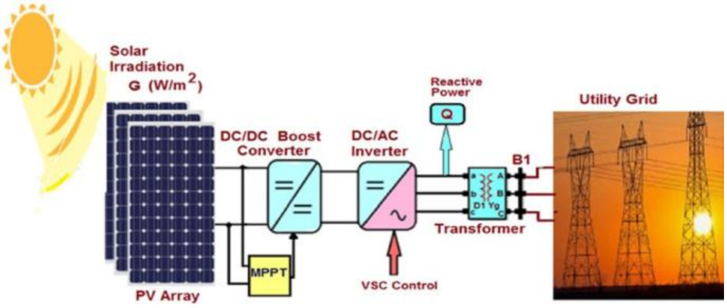

Fig.1. Solar Grid.

II. AI-BASED POWER QUALITY ENHANCEMENT

AI-based power quality enhancement involves the application of intelligent algorithms to monitor, detect, classify, and mitigate disturbances in electrical power systems. In modern grids, the increasing penetration of renewable energy sources, electric vehicle charging loads, and power electronic converters introduces nonlinearities and uncertainties that degrade power quality. Conventional methods based on fixed control strategies often fail to respond effectively under dynamic conditions. Artificial intelligence techniques provide a data-driven and adaptive approach, enabling real-time analysis and intelligent decision-making for maintaining acceptable voltage, current, and frequency profiles.

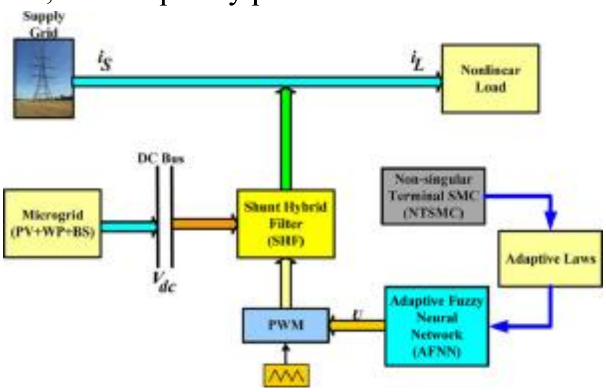

Fig.2. AI-based power quality.

In an AI-driven framework, power system signals such as voltage and current are continuously acquired through sensors, smart meters, or phasor measurement units. These signals are processed using advanced signal processing techniques like Fast Fourier Transform or wavelet transforms to extract meaningful features such as total harmonic distortion, RMS values, and transient characteristics. These extracted features are then fed into AI models, which are trained to identify and classify different types of power quality disturbances including voltage sag, swell, harmonics, flicker, and transients. Artificial neural networks are widely used due to their ability to model nonlinear relationships, while fuzzy logic systems handle uncertainty through rule-based reasoning. More advanced approaches such as deep learning and reinforcement learning further enhance prediction accuracy and enable adaptive control in highly dynamic environments.

Once disturbances are identified, AI techniques are employed to generate optimal control actions for mitigation. These actions are implemented through power electronic compensation devices such as shunt active power filters, unified power quality conditioners, and dynamic voltage restorers. AI-based controllers can dynamically adjust switching patterns and reference signals of these devices to minimize harmonics, compensate reactive power, and stabilize voltage profiles. For instance, neural network-based controllers can generate precise reference currents for active filters, while reinforcement learning algorithms can continuously improve control policies based on system feedback. This results in faster response times and improved overall system performance compared to traditional controllers.

The integration of AI with flexible AC transmission system devices significantly enhances their effectiveness in power quality improvement. AI enables these devices to operate optimally under varying load and generation conditions, ensuring better compensation and reduced losses. Moreover, AI-based systems can predict potential disturbances before they occur, allowing preventive actions rather than reactive corrections. This predictive capability is particularly useful in smart grids where distributed energy resources and variable loads create complex operating scenarios.

Despite its advantages, AI-based power quality enhancement faces challenges such as the need for large and high-quality datasets for training, computational complexity, and integration with existing infrastructure. However, ongoing advancements in machine learning, edge computing, and IoT technologies are addressing these limitations. Overall, AI-based approaches provide a robust, flexible, and intelligent solution for improving power quality in modern electrical systems, making them essential for the reliable operation of future smart grids.

III. GRID-CONNECTED SOLAR PHOTOVOLTAIC (PV) SYSTEM

A grid-connected solar photovoltaic (PV) system is an electricity generation system in which solar panels convert sunlight into electrical energy and supply it directly to the utility grid without the need for standalone storage as a primary component. These systems are widely adopted due to their high efficiency, scalability, and ability to reduce dependency on conventional fossil-fuel-based generation. The core principle involves the conversion of solar

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irradiance into direct current (DC) using PV modules, followed by conversion into alternating current (AC) through power electronic interfaces so that it can be synchronized with grid parameters such as voltage, frequency, and phase.

The fundamental components of a grid-connected PV system include PV modules, a DC-DC converter, a DC-AC inverter, filters, protection devices, and grid interfacing equipment. PV modules, typically composed of semiconductor materials such as silicon, generate DC power based on the photovoltaic effect. Since the output of PV panels varies with solar irradiance and temperature, a maximum power point tracking (MPPT) algorithm is implemented through a DC-DC converter to ensure that the system operates at its optimal power point under varying environmental conditions. The inverter plays a critical role by converting DC power into synchronized AC power that matches grid specifications. Advanced inverters also incorporate control strategies for voltage regulation, reactive power support, and harmonic minimization.

In grid-connected operation, synchronization with the utility grid is essential. This is achieved using phase-locked loop (PLL) techniques that align the inverter output with the grid voltage waveform. Once synchronized, the system injects active power into the grid, and in some cases, it can also provide reactive power compensation depending on control strategies and grid requirements. During periods of high solar generation, excess power is exported to the grid, while during low generation periods, power is drawn from the grid, ensuring a continuous supply to the load. Net metering policies in many regions enable consumers to receive credit for the surplus energy fed back into the grid.

Control strategies in grid-connected PV systems are designed to ensure stability, efficiency, and power quality. Current control techniques such as hysteresis control, proportional-integral control, and model predictive control are commonly used to regulate inverter output. With increasing system complexity, artificial intelligence-based controllers, including neural networks and fuzzy logic, are being explored to enhance dynamic performance and adapt to varying grid conditions. These controllers improve tracking accuracy, reduce harmonic distortion, and enhance fault ride-through capability.

Power quality is a critical consideration in grid-connected PV systems. The switching action of inverters and the variability of solar input can introduce harmonics, voltage fluctuations, and flicker into the grid. To mitigate these issues, filters such as LC or LCL filters are employed at the inverter output. Additionally, advanced control techniques are used to ensure compliance with grid codes regarding total harmonic distortion, voltage limits, and frequency stability. Integration with flexible AC transmission system devices and active power filters further enhances system performance.

Protection and safety mechanisms are integral to grid-connected PV systems. Anti-islanding protection ensures that the PV system disconnects from the grid during outages to prevent safety hazards for utility workers. Other protections include overvoltage, overcurrent, short-circuit, and ground fault protection. Modern systems also incorporate monitoring and communication technologies for real-time performance analysis and fault detection.

The advantages of grid-connected PV systems include reduced electricity bills, lower carbon emissions, high system efficiency, and minimal maintenance requirements. However, challenges such as intermittency of solar power, grid stability issues at high penetration levels, and the need for advanced control and energy management systems must be addressed. Emerging solutions such as hybrid systems with energy storage, smart inverters, and AI-based energy management strategies are helping overcome these limitations.

In conclusion, grid-connected solar PV systems represent a key technology in the transition toward sustainable and decentralized energy systems. Their ability to integrate renewable energy into existing grid infrastructure while maintaining efficiency and reliability makes them an essential component of modern power systems. Ongoing research focuses on improving control strategies, enhancing grid interaction, and integrating intelligent algorithms to ensure optimal performance under diverse operating conditions.

IV. LITERATURE REVIEW

Rayed AlGhamdi et al. [1] As the global transition toward sustainable energy holds, grid-connected solar photovoltaic (PV) systems have come to be of great use in strengthening the resilience and reliability of the power system. However, integrating those renewable energy sources into the grid creates enormous problems in reactive power compensation, crucial for voltage stabilization and power quality enhancement. The outline of this paper presents the Meta-Reinforced Graph-Based Multi-Task Learning (Meta-RG-MTL) framework, which is capable of resolving the issue of optimal reactive power compensation in grid-connected solar PV systems. The solution put forward integrates Graph Neural Networks (GNNs) for the purpose of simulating spatial–temporal relationships, Reinforcement Learning (RL) for the making of real-time adaptive control decisions and also for the provision of automatic feedback, and LSTM networks for the precise prediction of the conditions of the sun and the grid.

Edward Dodzi Amekah et al. [2] Although rooftop grid-connected solar PV systems (RGCSPVS) play a crucial role in the global energy transition to mitigate climate change, reactive power imbalance remains a significant power quality challenge, intensifying as the system approaches its optimal penetration limit. This study examines the amount of reactive power an optimally sized GCSPVS can accommodate without exceeding voltage limits. A Python-based dynamic programming approach placed optimally, shunt capacitor (SC) targeting high loads, voltage drops, and losses nodes.

Nikhil Agrawal et al. [3] Integrating renewable energy sources (RES) into hybrid energy systems (HES) creates significant power quality (PQ) challenges, including harmonics and voltage fluctuations. This paper presents a dual-mode solar PV integrated reduced switch multilevel inverter (RSFLMLI) that also functions as a shunt active power filter (SAPF) to enhance PQ and enable cost-effective RES integration. The proposed topology minimizes power switches, making the system more economically viable. An advanced Trianguzoidal pulse width modulation (PWM) technique, combined with the instantaneous reactive power

(P-Q) theory, ensures precise harmonic mitigation and achieves a near-unity power factor. The RSFLMLI operates in two modes: during the day, it supplies active power to the load while compensating for PQ issues; at night, it operates solely as a compensator to maintain grid stability. Validated under varying loads, its performance was compared against conventional PWM techniques. Simulation results confirm a significant reduction in Total Harmonic Distortion (THD), ensuring compliance with IEEE-519 standards. The proposed system enhances technical performance and contributes to sustainable energy development by improving power quality, increasing RES integration, and reducing costs in HES.

Mihir Mehta et al. [4] This research article introduces advanced control strategies for grid-connected hybrid renewable energy systems, focusing on a doubly fed induction machine (DFIM) based wind power plant and a photovoltaic based solar power plant. The proposed approach integrates Direct Torque Control (DTC) with modified filters and a fractional Proportional-Integral (PI) controller for the DFIM wind power plant. The modified DTC utilizes estimated torque and flux, employing a modified filter to minimize deviations, and a fractional PI controller for improved vector selection.

Alok Jain et al. [5] The growing prevalence of electric vehicles (EVs) and the incorporation of renewable energy sources require sophisticated control algorithms for effective energy management in grid-connected EV charging systems. This study assesses two adaptive control algorithms—the Least Mean Square (LMS) and the Logarithmic Normalized-Least Mean Square (LN-LMS)—to improve the performance of solar photovoltaic (PV)-based electric vehicle (EV) charging stations integrated with a battery energy storage system (BESS). These algorithms regulate power delivery while improving system stability and power quality. The LMS algorithm, widely used in adaptive filtering, is assessed for its effectiveness in reducing distortions and ensuring stable power transfer. However, its conventional structure exhibits limitations in handling rapid system variations. In contrast, the LN-LMS algorithm employs a logarithmic normalization factor, offering improved convergence speed, robustness, and adaptability to dynamic load and irradiation conditions. Both algorithms are used in a grid-tied solar photovoltaic-integrated electric vehicle charging system to assess their efficacy.

Sujatha Radhakrishnan et al. [6] The evolution of photovoltaic (PV) systems has been instrumental in the transition towards sustainable and renewable energy. However, in the real world, in PV monitoring, there are issues that are yet to be resolved. There is a dearth of failure-labelled data, and the present models do not generalise well across many different PV systems and edge deployment settings. This paper suggests a robust deep learning model to detect and classify photovoltaic system (GPVS) faults on solar panels by exploiting frontier technologies, such as the utilisation of Generative Adversarial Networks (GAN) for data augmentation and carbon-efficient deep learning for classification.

R.K. Padmashini et al. [7] This study presents the design and analysis of a symmetrical 7-level modular multilevel inverter (MMI) integrating photovoltaic (PV) solar modules using multicarrier pulse width modulation (MCPWM). The proposed MMI reduces the number of switches, DC sources, and power diodes compared to conventional topologies. To improve the fundamental voltage and total harmonic distortion (THD), the frequency and amplitude of the carriers were varied. The MMI configuration includes three solar PV panels, seven switches, and three diodes, implementing various PWM schemes such as Phase Disposition (PD), Alternative Phase Opposition Disposition (APOD), Phase Opposition Disposition (POD), Variable Amplitude (VA), and Variable Frequency (VF). MATLAB/Simulink simulations yielded 94.7 % efficiency, 17.28 % THD, 2.34 % capacitor voltage ripple, and 66.7 V voltage stress across switches. The proposed MCPWM methods were validated through hardware implementation using an FPGA XC3S500-320 F chip, confirming the simulation results.

Pranay Prasoon et al. [8] The study conducts performance evaluation of a 5 MWp grid-connected solar photovoltaic (PV) power plant commissioned by NTPC Limited in Dadri, India. The plant is among the earliest large-scale solar power installations in India, established in 2013, under Phase I of the Jawaharlal Nehru National Solar Mission. The plant site receives an annual average solar irradiation of 4.59 kWh/m2/day and experiences an annual mean temperature of approximately 25.13 °C. This study thoroughly assesses the operational performance of the plant, considering both controllable and non-controllable factors influencing the plant operation, using data monitored during the financial year 2022–23.

Panneerselvam Priya et al. [9] Ongoing improvements in MPPT methods are essential for boosting the energy production and cost-effectiveness of solar photovoltaic (PV) systems. This review explores foundational PV modelling approaches, including single-diode, double-diode, and three-diode models that accurately reflect the solar cells' nonlinear properties in different environmental settings. Photovoltaic characteristics are analyzed through P–V and I–V curves across different scenarios, including standard irradiance, partial shading, and dusty environments.

A. Ananda Kumar et al. [10] This paper presents a unique high-dimensional data-driven approach for enhancing the detection of cyber-physical attacks in photovoltaic (PV)-connected distribution power grids using Deep Q-Networks (Deep-QNN). The increasing integration of renewable energy sources like PV systems to power grids poses significant cybersecurity argues, particularly from false data injection (FDI) attacks that can disrupt grid stability and operations. To address these challenges, a comprehensive dataset was generated through detailed simulations of PV-connected distribution grid systems using SIMULINK under various conditions, including normal operations, grid faults, PV inverter faults, and FDI into the reactive power reference values.

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Table 1 Literature Review

S. No.	Author(s) & Year	Objective	Methodology/Technique	Key Contribution/Findings
1	AlGhamdi et al. (2026)	Enhance power quality via reactive power compensation	Meta-Reinforced Graph-Based Multi-Task Learning (Meta-RG-MTL)	Achieved optimized reactive power control with improved voltage stability and reduced losses
2	Amekah et al. (2025)	Analyze impact of reactive power injection	Optimal PV sizing + reactive power control analysis	Improved power factor and reduced system losses significantly
3	Agrawal et al. (2026)	Improve PQ in hybrid PV systems	Dual-mode PV-integrated Shunt Active Power Filter (SAPF)	Reduced switch count and enhanced harmonic mitigation and grid support
4	Mehta & Mehta (2024)	Develop advanced control for hybrid renewable systems	Modified DTC for DFIG + ANFIS-based MPPT	Enhanced dynamic performance and efficient solar energy extraction
5	Jain et al. (2025)	Improve control in PV-based EV charging systems	LMS and LN-LMS adaptive algorithms	Improved convergence speed and system stability in grid-tied operation
6	Radhakrishnan et al. (2026)	Fault detection in PV systems	Deep Learning + GAN-based data augmentation	High accuracy in fault diagnosis with improved dataset robustness
7	Padmashini et al. (2025)	Enhance PQ using PWM techniques	Sensor-based Variable Frequency Multicarrier PWM	Reduced harmonic distortion and improved waveform quality
8	Prasoon et al. (2026)	Evaluate long-term PV plant performance	Case study of 5 MWp PV plant (NTPC Dadri)	Provided real-time performance insights and degradation analysis
9	Priya & Stonier (2025)	Review MPPT advancements	Comparative analysis of MPPT techniques	Identified efficient MPPT methods for dynamic environmental conditions
10	Kumar & Rao (2026)	Enhance cyber-security in PV grids	Deep Q-Network (DQN)-based detection	Improved detection of cyber-physical attacks in smart grids

V. CONCLUSION

In conclusion, grid-connected solar PV systems have emerged as a reliable and efficient solution for sustainable power generation, enabling seamless integration of renewable energy into existing electrical grids. The review highlights that advancements in power electronic converters, control strategies, and maximum power point tracking techniques have significantly improved system performance and energy extraction efficiency. Furthermore, the incorporation of intelligent control methods and smart inverters has enhanced grid stability, power quality, and dynamic response under varying operating conditions. However, challenges such as intermittency, harmonic distortion, voltage fluctuations, and grid synchronization issues remain critical, especially at higher penetration levels. The study indicates that the adoption of advanced control techniques, energy storage integration, and AI-based energy management systems can effectively address these limitations. Overall, grid-connected PV systems play a vital role in modern smart grids, and continued research in optimization, control, and intelligent integration is essential to ensure reliable, stable, and high-quality power delivery.

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