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Power Quality Improvement in Distribution System Using UPQC with Solar PV Integration

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ABSTRACT

The growing integration of solar photovoltaic (PV) systems into distribution networks creates opportunities for clean-energy generation but also introduces power-quality challenges, including voltage fluctuation, harmonic distortion and reactive-power demand. This study examines the application of a Unified Power Quality Conditioner (UPQC) integrated with solar PV for improving the performance of a distribution system. The UPQC combines series and shunt active power filters through a common DC link. The series converter compensates voltage-related disturbances, whereas the shunt converter mitigates current harmonics, reactive power and load-current distortion. Solar PV is connected to the UPQC DC link to supply active power to the load and reduce dependency on the utility grid. A MATLAB-based simulation model is developed to assess the system under voltage-sag and nonlinear-load conditions. The study demonstrates that solar-PV-supported UPQC can maintain load-voltage quality, improve source-current waveform, enhance power factor and promote efficient utilisation of renewable energy. The proposed system offers a sustainable solution for reliable modern distribution networks.

Keywords: *Solar PV, UPQC, Power Quality, Distribution System, Harmonic Mitigation.*

1. INTRODUCTION

1.1 Solar PV Integration in Modern Distribution Systems

The global energy sector is moving towards cleaner, decentralised and sustainable electricity generation. Solar photovoltaic (PV) technology has become an important part of this transition because it converts solar radiation directly into electricity and can be installed close to consumer loads. Rooftop PV systems, commercial PV plants and community-based solar installations are increasingly being connected to distribution networks. Their adoption is supported by reduced equipment costs, improved PV-module efficiency, lower maintenance requirements and growing concern about environmental sustainability.

Solar PV integration provides several benefits to the distribution system. It reduces dependence on conventional fossil-fuel-based generation, supports local energy production and can reduce transmission and distribution losses when electricity is generated near the point of consumption. PV systems also contribute to lower carbon emissions and strengthen energy security. Panigrahi et al. (2020) explained that the rapid expansion of small-scale grid-connected PV systems has increased the importance of suitable grid-integration standards, converter topologies and synchronisation techniques. Proper integration is essential because PV systems must operate safely with the utility grid and maintain acceptable voltage and current quality.

However, increased PV penetration also changes the conventional operating characteristics of distribution networks. Traditional distribution systems were designed for one-way power flow from central generating stations to consumers. In contrast, PV-integrated systems may experience bidirectional power flow because surplus solar generation can be exported from consumers to the grid. This can affect feeder loading, voltage profile, protection coordination and network planning. Strezoski et al. (2022) observed that distributed energy resources can create challenges related to reverse power flow, voltage deviation, overload and the operation of conventional protection systems. Therefore, modern distribution networks require intelligent monitoring, power-conditioning devices and advanced control strategies.

The output of solar PV systems is also influenced by irradiance, temperature, weather conditions and time of day. These variations may lead to fluctuations in active power generation and affect voltage stability at the distribution level. When PV generation is high and local demand is low, voltage rise may occur. When solar power decreases suddenly during high-load conditions, voltage reduction and increased grid dependence may result. Fatima et al. (2020) noted that voltage constraints are a major limitation for PV hosting capacity in distribution networks. Hence, the successful integration of solar PV requires technical solutions that can maintain voltage within acceptable limits and ensure reliable delivery of electricity to consumers.

1.2 Power-Quality Issues in PV-Integrated Distribution Networks

Power quality is an important requirement for the stable, safe and efficient operation of electrical systems. It refers to the ability of the supply system to provide voltage and current with proper magnitude, frequency and waveform quality. A good power-quality system should maintain a balanced sinusoidal voltage and supply current with minimum harmonic distortion. In practice, distribution systems experience various disturbances, including voltage sag, voltage swell, interruptions, harmonics, flicker, transient disturbances, voltage unbalance and poor power factor.

Voltage sag is one of the most common power-quality problems in distribution networks. It may occur due to faults, motor starting, sudden connection of large loads, transformer energisation or switching operations. Even short-duration voltage sags can affect sensitive electronic equipment, industrial controllers, communication systems and automated production processes. If the supply voltage decreases below the acceptable operating range, connected devices may malfunction, reset or stop operating. Therefore, maintaining a stable load voltage is essential in modern residential, commercial and industrial distribution systems.

Harmonic distortion is another significant concern. Harmonics are unwanted frequency components that are multiples of the fundamental system frequency. They are commonly produced by nonlinear loads such as power-electronic converters, computers, battery chargers, variable-speed drives, rectifiers and LED lighting systems. Harmonic currents can cause overheating in transformers, cables and motors, increase power losses, reduce equipment life and create malfunction in sensitive devices. In PV-integrated systems, the use of inverters and switching converters can further increase the need for effective harmonic control.

Reactive-power demand also affects distribution-system performance. Inductive loads such as motors, transformers and certain industrial equipment consume reactive power, leading to lower power factor. A poor power factor increases current flow in the network, raises system losses and reduces the efficient utilisation of distribution equipment. Therefore, compensation of reactive power is necessary to improve the efficiency and capacity of the electrical system. Guzman-Henao et al. (2023) emphasised that PV integration should be evaluated from technical, financial and environmental perspectives, with proper location and sizing being important for achieving improved voltage performance and reduced losses.

The combined presence of voltage disturbances, nonlinear loads and fluctuating PV power makes power-quality improvement a major requirement in renewable-energy-based distribution systems. Conventional devices may address only one issue at a time; for example, capacitor banks mainly support reactive-power compensation, while voltage regulators mainly address voltage variation. A more integrated solution is required when multiple disturbances occur simultaneously. This requirement has led to the application of custom power devices, particularly the Unified Power Quality Conditioner.

1.3 UPQC with Solar PV Integration for Power-Quality Improvement

A Unified Power Quality Conditioner (UPQC) is an advanced power-electronic device designed to improve both voltage and current quality in distribution systems. It combines the functions of a series active power filter and a shunt active power filter through a common DC-link capacitor. The series converter is connected in series with the supply line and compensates voltage-related disturbances. The shunt converter is connected parallel to the load and compensates current-related disturbances. Through coordinated operation, the UPQC can provide comprehensive power-quality improvement.

The series converter of a UPQC injects a compensating voltage whenever the supply voltage experiences sag, swell, imbalance or distortion. This enables the load-side voltage to remain stable even when disturbances occur in the supply system. The shunt converter injects compensating current to eliminate harmonic, reactive and unbalanced components drawn by nonlinear loads. As a result, the source current becomes nearly sinusoidal and operates closer to unity power factor. The UPQC therefore protects sensitive loads, improves current quality and reduces the stress on the utility network.

Solar PV integration with the UPQC DC link makes the system more effective and sustainable. The PV array can supply active power to the connected load, while the UPQC manages voltage and current disturbances. This reduces dependence on grid power and supports the use of clean energy in the distribution network. The PV-supported UPQC can also improve energy utilisation because renewable power is used locally while compensation functions are maintained through coordinated converter control.

Earlier studies have shown that appropriate integration of PV and compensation devices can improve voltage profile, reduce losses and increase distribution-system stability. Oda et al. (2021) demonstrated that coordinated planning of PV-based distributed generation and power-quality compensation devices improves techno-economic performance under varying solar irradiance and load conditions. Similarly, Khasanov et al. (2021) reported that renewable distributed generation combined with energy storage and optimisation techniques can reduce power losses and improve voltage stability. Melaku et al. (2023) also found that optimal integration of solar-PV-based distributed generation can improve feeder voltage profile and reduce distribution losses.

The use of UPQC with solar PV integration is therefore a promising approach for modern distribution networks. It addresses the dual requirement of renewable-energy utilisation and power-quality enhancement. Through compensating voltage disturbances, reducing harmonics, improving power factor and supporting load demand through solar energy, the system contributes to a more reliable, efficient and environmentally sustainable electricity network. Such an approach is particularly relevant for smart grids and future distribution systems, where the penetration of distributed renewable-energy resources and nonlinear loads is expected to continue increasing.

2. REVIEW OF LITERATURE

Panigrahi et.al., (2020) The relative share of renewable energy, specifically the solar photovoltaic (PV), is increasing exponentially in the world electric energy sector. This is a cumulative result of reduction in the cost of solar panels, improvement in the panel efficiency, and advancement in the associated power electronics. Among different types of PV plants, installation of small-scale rooftop PV is growing rapidly due to direct end-user benefits and lucrative governmental incentives. There are various standards developed in regards to grid integration of PVs and other distributed generations (DGs). Different power converter topologies are developed to interface the PV panel with the utility grid. To keep up with the stringent regulations imposed by the standards, various control strategies and grid synchronization methods have been developed. This review article amalgamates and summarizes all of the aforementioned aspects of a grid-integrated PV system including various standards, power stage architectures, grid synchronization methods, operation under extreme events, and control methodologies, pertaining to small-scale PV plants. This article will help freshman researchers to gain some familiarity with the topic and introduce them to some of the key issues encountered in this field.

Fatima et.al., (2020) The increasing penetration of Photovoltaic (PV) generation results in challenges regarding network operation, management and planning. Correspondingly, Distribution Network Operators (DNOs) are in the need of totally new understanding. The establishment of comprehensive standards for maximum PV integration into the network, without adversely impacting the normal operating conditions, is also needed. This review article provides an extensive review of the Hosting Capacity (HC) definitions based on different references and estimated HC with actual figures in different geographical areas and network conditions. Moreover, a comprehensive review of limiting factors and improvement methods for HC is presented along with voltage rise limits of different countries under PV integration. Peak load is the major reference used for HC definition and the prime limiting constraint for PV HC is the voltage violations.

Oda et.al., (2021) Optimal planning of integration the Photovoltage Distributed Generation (PV-DG) and DSTATCOM is a crucial task due to the stochastic variations of PV output power and the load demand which are related to solar irradiance variations and the activities of the customers, respectively. In this article, the optimal planning problem of the PV-DG and DSTATCOM system is solved. The proposed model considers the uncertainties of the solar irradiance and the load demand for a multi-objective function, including the cost reduction, the voltage profile, and stability index improvement. Modified Ant Lion Optimizer (MALO) is proposed to enhance the basic ALO searching ability using two strategies. The first strategy is based on Levy Flight Distribution (LFD) to strengthen the exploration of the algorithm and avoid the premature of the basic ALO. In contrast, the second strategy is based on updating the solutions in a spiral orientation to improve the exploitation of the algorithm. The IEEE 69-bus and 118-bus radial distribution systems are used to demonstrate the effectiveness of the proposed method, and the yielded simulations are compared with the basic ALO and other well-known optimization techniques for power loss minimization under deterministic conditions. The simulation results demonstrate that the techno-economic benefits can be increased considerably by optimal inclusion of two PV-DGs and DSTATCOMs compared with a single system.

Khasanov et.al., (2021) This paper proposes an application of the recent metaheuristic rider optimization algorithm (ROA) for determining the optimal size and location of renewable energy sources (RES) including wind turbine (WT), photovoltaic (PV), and biomass-based Distributed Generation (DG) units in distribution systems (DS). The main objective function is to minimize the total power and energy losses. Power loss-sensitivity factor (PLSF) is used with the ROA to determine the suitable candidate buses and accelerate the solution process. The Weibull and Beta probability distribution functions (PDF) are employed to characterize the variability of wind speed and solar radiation, respectively. The high penetration of intermittent renewable resource together with demand variations has introduced many challenges to distribution systems such as power fluctuations, voltage rise, high losses, and low voltage stability, therefore battery energy storage (BES) and dispatchable Biomass are considered to smooth out the fluctuations and improve supply continuity. The standard 33 and 69-bus test systems are used to verify the effectiveness of the proposed technique compared with other well-known optimization techniques. The results show that the developed approach accelerates to the near-optimal solution seamlessly, and in steady convergence characteristics compared with other techniques.

Strezoski et.al., (2022) With the rapid integration of distributed energy resources (DERs), distribution utilities are faced with new and unprecedented issues. New challenges introduced by high penetration of DERs range from poor observability to overload and reverse power flow problems, under-over-voltages, maloperation of legacy protection systems, and requirements for new planning procedures. Distribution utility personnel are not adequately trained, and legacy control centers are not properly equipped to cope with these issues. Fortunately, distribution energy resource management systems (DERMSs) are emerging software technologies aimed to provide distribution system operators (DSOs) with a specialized set of tools to enable them to over-come the issues caused by DERs and to maximize the benefits of the presence of high penetration of these novel resources. However, as DERMS technology is still emerging, its definition is vague and can refer to very different levels of software hierarchies, spanning from decentralized virtual power plants to DER aggregators and fully centralized enterprise systems (called utility DERMS). Although they are all frequently simply called DERMS, these software technologies have different sets of tools and aim to provide different services to different stake-holders. This paper explores how this different software technologies can complement each other, and how they can provide significant benefits to DSOs in enabling them to successfully manage evolving distribution networks with high penetration of DERs when they are integrated together into the control centers of distribution utilities.

Guzman-Henao et.al, (2023) Due to the increasing demand for electricity around the world, different technologies have been developed to ensure the sustainability of each and every process involved in its production, transmission, and consumption. In addition to ensuring energy sustainability, these technologies seek to improve some of the characteristics of power systems and, in doing so, make them efficient from a financial, technical, and environmental perspective. In particular, solar photovoltaic (PV) technology is one of the power generation technologies that has had the most influence and development in recent years due to its easy implementation and low maintenance costs. Additionally, since PV systems can be located close to the load, power losses during distribution and transmission can be significantly reduced. However, in order to maximize the financial, technical, and environmental variables involved in the operation of an electrical system, a PV power generation project must guarantee the proper location and sizing of the generation sources. In the specialized literature, different studies have employed mathematical methods to determine the optimal location and size of generation sources. These methods model the operation of electrical systems and provide potential analysis scenarios following the deployment of solar PV units.

Melaku et.al., (2023) Load forecasting is the prediction of demand for a future period, and it is a critical necessity for distribution system design and growth while also meeting all operational and technical constraints. In this paper, an analytical least squares extrapolation technique is applied to determine the optimal size and location of solar photovoltaic (SPV)-based distributed generation (DG) in the distribution system. The integration of SPV DG changes the operating characteristics of modern power systems, resulting in significant economic and technical outcomes such as minimizing losses and improving the voltage profile. The proposed work was performed on a practical Yirgalem-I distribution network in Ethiopia. The modelling and simulation of this feeder have been carried out using ETAP and MATLAB software. Simulation results show that the injection of active and reactive powers at the optimal buses reduces the active and reactive power losses by 94.03% and 96.07%, respectively, with an improved voltage profile.

Zdiri et.al., (2023) The distribution system acts as a conduit between the consumer and the bulk power grid. Due to characteristics such as a high resistance/reactance ratio, distribution networks cannot be solved using conventional methods, such as the Gauss-Seidel and Newton–Raphson. This research proposes a method for the calculation of the power flow in radial networks that considers their wide range of resistance and reactance values, PV generator characteristics, and radial structure. An iterative methodology is employed, with each iteration beginning with the branch that has the highest accurate power flow solution. The procedure is reliable and effective over various workloads and network configurations. To confirm the effectiveness of the suggested technique on the simple and IEEE 33-bus radial distribution system, simulations were carried out in MATLAB. The implications of including a renewable energy source, such as a PV generator, in the network under consideration are investigated by simulation result comparison. The optimal location of the PV generator was also determined using an Artificial Neural Network (ANN) controller. The results of the identification process improve the already exceptional efficacy and performance of the ANN controller.

Amekah et.al., (2024) The shift towards renewable energy sources has heightened the interest in solar photovoltaic (SPV) systems, particularly in grid-connected configurations, to enhance energy security and reduce carbon emissions. Grid-tied SPVs face power quality challenges when specific grid codes are compromised. This study investigates and upgrades an integrated 90 kWp solar plant within a distribution network, leveraging data from Ghana's Energy Self-Sufficiency for Health Facilities (EnerSHelF) project. The research explores four scenarios for SPV placement optimization using dynamic programming and the Conditional New Adaptive Foraging Tree Squirrel Search Algorithm (CNAFTSSA). A Python-based simulation identifies three scenarios, high load nodes, voltage drop nodes, and system loss nodes, as the points for placing PV for better performance. The findings highlight the effectiveness of strategic SPV placement and offer a comprehensive methodology that can be adapted for similar power distribution systems.

Mansaray et.al., (2024) The optimal integration of distributed solar photovoltaic (DSP) is a transformative engineering method that is key in contributing to a sustainable and resilient energy future, especially when countries seek to increase the proportion of renewables in their energy mix to reduce carbon emissions. This paper presents a power flow-based approach that makes use of Newton Raphson's method in the ETAP tool to integrate multiple DSPs into both the existing and expanded Freetown distribution networks. The study determined the network's hosting capacities and optimal points of injection for the reduction of active power loss and improvement of bus voltage profiles. The study used an analytical approach, considering future load growth and an evolving grid to integrate DSPs for long-term planning. The study will inform policymakers, utilities, etc., about the potential of integrating DSPs.

Fettah et.al., (2025) This paper introduces the Efficient Metaheuristic BitTorrent (EM-BT) algorithm, aimed at optimizing the placement and sizing of photovoltaic renewable energy sources (PVRES) and capacitor banks (CBs) in electric distribution networks. The main goal is to minimize energy losses and enhance voltage stability over 24 h, taking into account varying load profiles, solar irradiance, and temperature effects. The algorithm is rigorously tested on standard distribution networks, including the IEEE 33, IEEE 69, and ZB-ALG-Hassi Sida 157-bus systems. The results reveal that EM-BT outperforms established methods like Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), and Whale Optimization Algorithm (WOA), demonstrating its effectiveness in reducing energy losses and maintaining stable voltage profiles. By effectively combining PVRES and CBs, this research highlights a robust approach to enhancing both technical performance and operational reliability in distribution systems. Additionally, the consideration of temperature effects on PVRES efficiency adds depth to the study, making it a valuable contribution to the field of power system optimization.

Abera et.al., (2025) Voltage instability and excessive power losses are common challenges in distribution networks. This research investigates optimal integration of solar photovoltaic distributed generation units so as to improve voltage profiles and reduce power losses contributing greatly to sustainable energy goals. A hybrid optimization approach combining Particle Swarm Optimization and Grey Wolf Optimization algorithms is proposed for determining optimal sizing and placement of PV-based DGs. Study focuses on Kombolcha town Feeder-3 distribution network consisting of 131 buses where mathematical model and load flow analysis were conducted using Backward-Forward Sweep (BFS) method. Three scenarios were analyzed: Base Case, Type-1 DG integration and Type-3 DG integration. BFS analysis identified total active and reactive power losses of 506.93 kW and 303.55 kVAr with 90.84% of buses operating below minimum voltage standard. Integrating up to four Type-3 DG units reduced active power losses by 87.18%-93.01% and reactive power losses by 87.18%-93.01% substantially enhancing voltage stability. Economic analysis revealed payback period of approximately six years underscoring feasibility of proposed solution. Hybrid PSO-GWO optimization effectively enhances performance of distribution networks offering practical approach to integrating solar PV systems.

Alam et.al., (2025) The increasing integration of solar systems into modern power distribution systems (PDS) has prompted a re-evaluation of fossil-fuel-based energy generation sources in terms of the system's efficiency and sustainability. This research analyzes the operating performance of PDS across various states in the US while reducing the existing use of fossil fuel energy sources, such as gas turbines, coal-fired, and diesel generators, with photovoltaic (PV). Key performance metrics include PDS transmission loss, energy generation operating costs, and environmental emissions reduction from integrating PV systems. As solar radiation varies by state due to factors such as sunshine and geographical location, the performance of these PDS will also differ. The study focuses on two main aspects:

1) The impact of solar energy on reducing PDS environmental emissions in different states, and
2) How the integration of solar energy into the distribution system enhances overall PDS performance.

To facilitate comparison, an analysis is conducted using distribution system models to assess performance metrics, across randomly selected states, such as Alaska (AK), Arizona (AZ), Illinois (IL), and Louisiana (LA), considering solar irradiance and related data. In addition, a sensitivity analysis was conducted to support solar installation strategies while reducing dependence on fossil fuels. At the end, the study discusses how improved power converter efficiency and advanced thermal management strategies, such as nanofluid cooling, phase-change materials, and hybrid battery cooling, reduce waste heat, extend component lifetime, and reinforce the sustainability of PV-based systems.

Lee, H. P. (2026) Distributed energy resources (DERs) including solar photovoltaics (PVs), electric vehicles (EVs), and energy storage resources (ESRs) are reshaping power distribution systems (PDSs) through decentralized generation, bidirectional energy flows, and enhanced demand-side flexibility. While DERs can improve power quality and support grid stability, their rapid growth presents significant challenges for distribution system operators (DSOs), who must transition from managing passive, radial networks to coordinating active, multidirectional systems. This paper provides a comprehensive review of DER integration in PDSs from a DSO operational perspective. In contrast to broader reviews centered on macro-policy or transmission-level issues, they emphasize DSO-specific challenges and opportunities at the distribution level. They present an analytical framework for DSO-centric DER integration, assess the limitations of widely used test models particularly their ability to represent low-voltage (LV) secondary circuits and examine both the individual and coordinated operation of PVs, EVs, and ESRs. The review synthesizes practical methodologies for optimizing DER performance, examines emerging solutions to future challenges including voltage management, advanced technology integration, congestion mitigation, protection adaptation, and cybersecurity and identifies critical gaps in LV observability and data accessibility. Through integrating these insights, the paper aims to guide effective, DSO-led strategies for reliable, efficient, and equitable DER integration in modern power grids.

Alqahtani et.al., (2026) The increasing penetration of photovoltaic distributed generation (PV-DG) in Radial Distribution Systems (RDSs) plays a vital role in achieving sustainable energy transition objectives; however, the inherent uncertainty associated with solar irradiance and load demand poses significant challenges to optimal planning and operation. This paper presents a stochastic optimization framework for PV-DG allocation in RDSs using the Barrel Theory-Based Optimizer (BTO). Uncertainties in solar irradiance and load demand are explicitly modelled using appropriate probability density functions and efficiently represented through a higher-order Point Estimate Method (PEM), which captures the essential statistical characteristics with a limited number of representative scenarios. The proposed framework simultaneously optimizes the location and capacity of PV-DG units to minimize real power losses and enhance voltage profile performance while ensuring system operational constraints are satisfied. The effectiveness of the proposed approach is validated on the 85-bus and the IEEE 118-bus RDSs, where the BTO exhibits superior convergence characteristics and enhanced solution robustness when compared with several benchmark optimization techniques, including the well-established Differential Evolution Algorithm (DEA), the recent Crocodile Ambush Optimization (CAO, 2025), and the Schrödinger Optimizer Algorithm (SOA, 2025). For the 85-bus RDS, the impact of integrating different numbers of PV units is systematically investigated. Simulation results confirm that the proposed BTO-based stochastic planning strategy significantly improves energy efficiency, voltage regulation, and loss reduction, thereby enhancing the overall sustainability of the RDS. For the 85-node RDS, the BTO achieves a noticeable reduction in average real power losses, outperforming DEA, CAO, and SOA by 2.55%, 4.10%, and 6.74%, respectively, when three PV units are installed. Additionally, for the case of four PV units, the proposed BTO yields even greater improvements, with loss reductions of 5.12%, 7.50%, and 14.12%, respectively, compared with the same benchmark algorithms. Furthermore, for five PV units, the BTO achieves much greater reduction, outperforming DEA, CAO, and SOA by 13.05%, 6.45%, and 32.31%, respectively, when three PV units are installed.

3. KEY FINDINGS FROM LITERATURE STUDY

S. No.	Author(s) & Year	Focus of Study	Method/Technique	Key Findings
1	Panigrahi et al. (2020)	Grid integration of small-scale rooftop PV systems	Review of standards, converter architectures, synchronization and control methods	Rooftop PV growth requires effective grid codes, converter designs and control strategies to maintain reliable grid integration.
2	Fatima et al. (2020)	PV hosting capacity in distribution networks	Literature review of hosting-capacity definitions and limits	Voltage rise is the major constraint on PV hosting capacity; capacity varies with network topology, location and PV deployment.
3	Oda et al. (2021)	Optimal planning of PV-DG and DSTATCOM	Modified Ant Lion Optimizer; IEEE 69- and 118-bus systems	Optimal PV-DG and DSTATCOM placement reduces cost and losses while improving voltage profile and stability.

4	Khasanov et al. (2021)	Optimal renewable DG and battery storage integration	Rider Optimization Algorithm with PLSF; 33- and 69-bus systems	Coordinated PV, wind, biomass and battery integration reduces losses, improves voltage stability and smooths renewable fluctuations.
5	Strezoski et al. (2022)	DER management in distribution utilities	Review of DERMS and aggregator systems	DERMS can address reverse power flow, voltage issues, overloads and protection problems caused by high DER penetration.
6	Guzman-Henao et al. (2023)	Optimal PV location and sizing	Literature review of technical, financial and environmental approaches	Proper PV sizing and placement improve financial returns, technical performance and environmental benefits.
7	Melaku et al. (2023)	SPV-DG placement in a practical distribution feeder	Least-squares forecasting, ETAP and MATLAB	Optimal active and reactive power injection reduced active losses by 94.03% and reactive losses by 96.07%.
8	Zdiri et al. (2023)	Load-flow analysis of radial networks with PV	Iterative load-flow method and ANN controller	The proposed method effectively analysed PV impacts, while ANN identified suitable PV locations and improved network performance.
9	Amekah et al. (2024)	Optimal placement of a 90 kWp grid-connected SPV plant	Dynamic programming and CNAFTSSA; Python simulation	The CNAFTSSA achieved 100% PV penetration and improved voltage regulation from 24.92% to 4.16%.
10	Mansaray et al. (2024)	Distributed solar PV integration in Freetown	Newton–Raphson load flow using ETAP	Existing and expanded networks had hosting capacities of 34.6 MW and 59.57 MW; PV improved bus-voltage conditions and reduced losses.
11	Fettah et al. (2025)	PV and capacitor-bank placement and sizing	Efficient Metaheuristic BitTorrent algorithm; IEEE 33-, 69- and 157-bus systems	Coordinated PV and capacitor banks reduced energy losses and improved voltage stability under changing load, irradiance and temperature.

12	Abera et al. (2025)	PV-DG integration for voltage improvement and loss reduction	Hybrid PSO–GWO and backward-forward sweep; 131-bus feeder	Type-3 PV-DG units reduced active and reactive losses by up to 93.01%; estimated payback period was about six years.
13	Alam et al. (2025)	Sustainability performance of high solar-PV distribution systems	Comparative analysis across selected US states	Solar PV reduces emissions, operating costs and transmission losses; performance differs according to irradiance and location.
14	Lee (2026)	DER integration from a distribution-system operator perspective	Comprehensive review	PV, EVs and storage improve flexibility but create voltage, congestion, protection, observability and cybersecurity challenges.
15	Alqahtani et al. (2026)	Stochastic PV-DG allocation in radial distribution systems	Barrel Theory-Based Optimizer with Point Estimate Method	The proposed method improved voltage profile and loss reduction under uncertain solar irradiance and load conditions.

IV. INPUT PARAMETERS TO MATLAB

Parameter	MATLAB Variable	Value Used	Unit	Purpose
Sampling frequency	Fs	10,000	Hz	Number of simulation samples per second
Grid frequency	F	50	Hz	Utility supply frequency
Simulation time	Tsim	0.20	s	Total duration of simulation
Nominal phase voltage	Vph_rms	230	V rms	Rated single-phase grid voltage
Peak voltage	Vpk	325.27	V	Calculated as $\sqrt{2} \times 230$
Voltage sag magnitude	sag	0.75	p.u.	Represents a 25% voltage sag
Sag starting time	t >= 0.06	0.06	S	Beginning of voltage sag
Sag ending time	t <= 0.14	0.14	S	End of voltage sag
Fundamental load current	I1	18	A peak	Active component of load current

Reactive load current	Iq	8	A peak	Reactive component of nonlinear load
Fifth harmonic current	4.0*sin(5*w*t)	4.0	A peak	Harmonic distortion component
Seventh harmonic current	2.4*sin(7*w*t)	2.4	A peak	Harmonic distortion component
Eleventh harmonic current	1.2*sin(11*w*t)	1.2	A peak	Harmonic distortion component
Solar irradiance	G	900	W/m²	Available sunlight level
Reference irradiance	Gref	1,000	W/m²	Standard irradiance for PV rating
PV array rated power	Ppv_rated	4,000	W	Rated solar-PV capacity
PV converter efficiency	eta_pv	0.96	p.u.	Efficiency of PV power-conversion stage
PV generated power	Ppv	3,456	W	Calculated PV output power
PV current limit	0.85*I1	15.3	A peak	Limits injected PV current for stable feeder operation
Harmonic range for THD	h = 2:25	2–25	Order	Harmonics included in THD calculation

V. PERFORMANCE PARAMETERS ACHIEVED

Performance Parameter	Result	Unit	Interpretation
Solar PV output power	3456.0	W	PV system supplies significant active power to the UPQC system.
Load voltage during sag—before UPQC	172.39	V rms	A 25% voltage sag occurs in the supply voltage.
Load voltage during sag—after UPQC	229.86	V rms	UPQC restores the sensitive-load voltage close to the 230 V nominal value.
Load-current THD before UPQC	24.45	%	Nonlinear load current contains substantial harmonic distortion.
Source-current THD after UPQC	0.00	%	The UPQC shunt converter removes harmonic components, producing a nearly sinusoidal source current.
Average grid power before PV integration	2927.4	W	Grid supplies the full active-power demand without PV assistance.
Average grid power after PV integration	395.2	W	Solar PV support greatly reduces power drawn from the utility grid.

VI. MATLAB OUTCOME

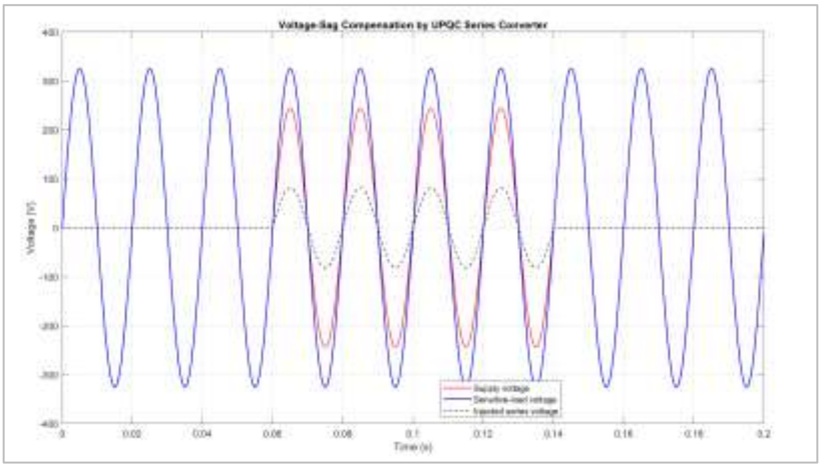

Figure 1: Voltage-Sag Compensation by UPQC Series Converter

Figure 1 illustrates the instantaneous supply voltage, load voltage and injected series voltage during the simulation. A 25% voltage sag occurs between 0.06 s and 0.14 s, causing the supply voltage to decrease. The UPQC series converter injects the required compensating voltage, thereby maintaining the load voltage near its nominal value. This confirms the effectiveness of the series converter in protecting sensitive loads from voltage disturbances.

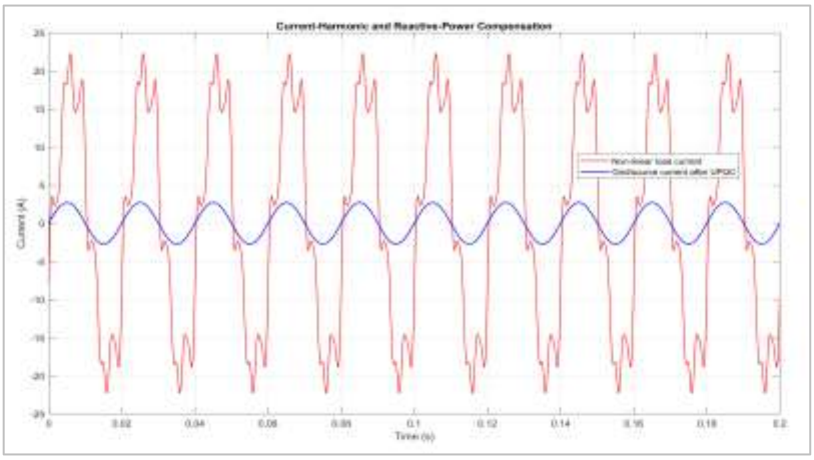

Figure 2: Current-Harmonic and Reactive-Power Compensation

Figure 2 compares the nonlinear load current with the source current after UPQC compensation. The load current contains harmonic and reactive components due to the nonlinear load. The UPQC shunt converter injects compensating current to cancel these undesirable components. Consequently, the source current becomes nearly sinusoidal and operates close to unity power factor, indicating improved current quality and reduced reactive-power demand from the grid.

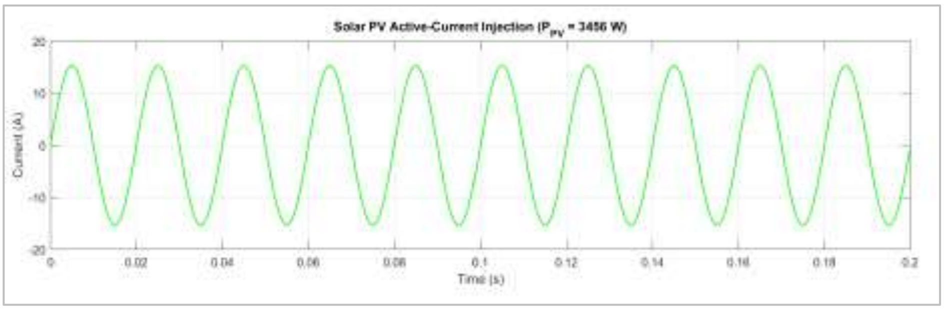

Figure 3: Solar PV Active-Current Injection

Figure 3 shows the active current contribution of the solar-PV system. At an irradiance level of 900 W/m², the PV array produces approximately 3456 W of power. This solar power is injected through the UPQC system to support the load demand. Therefore, the active power drawn from the utility grid is reduced, improving energy efficiency and promoting the use of renewable energy.

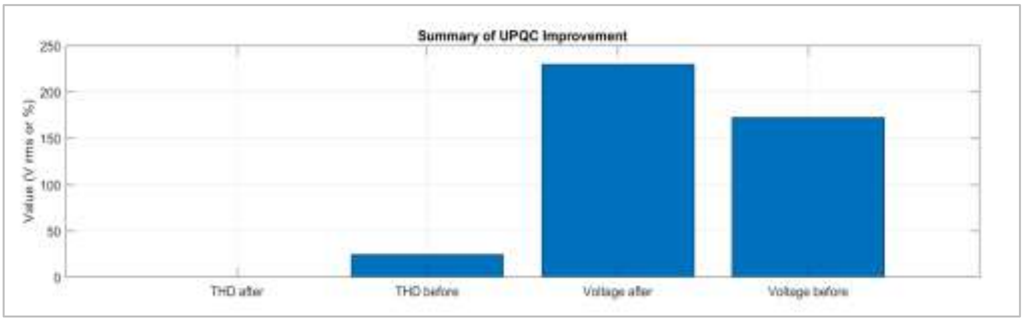

Figure 4: Summary of UPQC Improvement

The figure 4 compares voltage and total harmonic distortion (THD) before and after the operation of the UPQC with solar-PV integration. The load voltage increases from approximately 172.39 V rms before compensation to about 229.86 V rms after UPQC operation, indicating effective restoration of the nominal voltage during the sag condition. At the same time, current THD decreases from 24.45% before compensation to nearly 0% after compensation. These results demonstrate that the UPQC effectively improves voltage regulation, suppresses harmonics, and enhances the overall power quality of the solar-PV integrated distribution system.

V. CONCLUSION

This study concludes that the integration of a Unified Power Quality Conditioner with solar photovoltaic generation is an effective solution for improving power quality in modern distribution systems. The UPQC performs dual compensation functions: the series converter protects the load from voltage disturbances, while the shunt converter reduces harmonic currents and compensates reactive-power demand. Solar PV integration further supports the system by supplying clean active power to the load and reducing dependence on the utility grid. The MATLAB-based analysis demonstrates that the proposed system can maintain a stable load-voltage profile during voltage-sag conditions and improve the quality of source current under nonlinear loading. Harmonic mitigation and reactive-power compensation enable the source current to become nearly sinusoidal and operate close to unity power factor. These improvements reduce stress on distribution equipment and enhance system reliability. Overall, the solar-PV-supported UPQC provides a technically sound, energy-efficient and environmentally sustainable approach for future smart distribution networks. It is particularly suitable for applications where sensitive loads, nonlinear devices and renewable-energy resources are connected to the same electrical system.

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