Review on Power Quality Related Issues by Unified Power Quality Conditioner in EV Charging System

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Abstract

The increasing integration of renewable energy sources, electric vehicle (EV) charging infrastructure, and nonlinear loads has intensified power quality challenges in modern electrical distribution systems. Voltage sag, voltage swell, harmonics, reactive power imbalance, and transient disturbances adversely affect the reliability and efficiency of power networks. The Unified Power Quality Conditioner (UPQC) has emerged as an effective custom power device capable of simultaneously compensating voltage and current disturbances through coordinated series and shunt active filters. This study presents a comprehensive investigation of the steady-state power flow performance of a UPQC under various operating conditions. The proposed framework evaluates voltage regulation, harmonic mitigation, reactive power compensation, and power flow improvement while ensuring enhanced system stability. The analysis demonstrates that the UPQC significantly improves power quality indices, reduces total harmonic distortion, and maintains balanced power flow under dynamic loading conditions. The findings highlight the suitability of UPQC as an efficient solution for future smart grids integrating renewable energy resources and electric vehicle charging systems.

Keywords

Unified Power Quality Conditioner (UPQC), Power Quality, Harmonic Mitigation, Steady-State Power Flow, Renewable Energy Integration, Electric Vehicle Charging

1. Introduction

The rapid modernization of electrical power systems has significantly increased the penetration of renewable energy resources, distributed generation, power electronic converters, and electric vehicle (EV) charging stations. Although these technologies contribute to sustainable energy development, they also introduce several power quality challenges that affect the reliable operation of electrical distribution networks. Voltage sag, voltage swell, harmonic distortion, reactive power imbalance, voltage flicker, and unbalanced loading have become common issues due to the widespread use of nonlinear loads and intermittent renewable energy sources. These disturbances reduce equipment efficiency, increase power losses, shorten the lifespan of electrical devices, and adversely affect overall system performance.

Power quality has therefore become one of the primary concerns in modern smart grid environments. Conventional passive compensation techniques are often inadequate for handling multiple power quality disturbances simultaneously because of their limited adaptability and slow response characteristics. Consequently, custom power devices based on power electronic converters have gained significant attention for improving voltage and current quality in distribution systems. Among these devices, the Unified Power Quality Conditioner (UPQC) has emerged as one of the most effective solutions owing to its capability of simultaneously mitigating supply-side and load-side disturbances.

The UPQC consists of a series active power filter and a shunt active power filter connected through a common DC-link capacitor. The series converter compensates voltage-related disturbances such as voltage sag, swell, flicker, and unbalance, whereas the shunt converter eliminates current harmonics, compensates reactive power, and improves the power factor. The coordinated operation of both converters enables simultaneous enhancement of voltage quality and current quality, thereby improving overall power system performance.

Recent advances in intelligent control techniques, renewable energy integration, battery energy storage systems, and optimization algorithms have further enhanced the operational capabilities of UPQC. Artificial intelligence-based controllers, adaptive neuro-fuzzy inference systems, optimization algorithms, and renewable-powered UPQC configurations have demonstrated improved dynamic response, faster disturbance compensation, and higher energy efficiency. Moreover, the increasing deployment of EV charging infrastructure has created additional requirements for advanced power conditioning devices capable of maintaining stable voltage profiles and minimizing harmonic pollution under rapidly changing load conditions.

Despite these developments, comprehensive investigations on steady-state power flow analysis of UPQC under integrated renewable energy and EV charging scenarios remain relatively limited. A detailed understanding of power flow characteristics is essential for optimizing device performance, improving voltage stability, reducing network losses, and ensuring reliable operation of future smart grids. Therefore, this study investigates the steady-state power flow behavior of the Unified Power Quality Conditioner under various operating conditions, focusing on voltage regulation, harmonic mitigation, reactive power compensation, and power flow enhancement. The outcomes of this study provide valuable insights into the application of UPQC for achieving reliable, efficient, and high-quality power delivery in next-generation electrical distribution systems.

Literature Review

Pandey and Patel (2026) reviewed the role of Unified Power Quality Conditioners (UPQCs) in enhancing power quality at electric vehicle (EV) charging stations. The study discussed common power quality issues, including voltage sags, harmonic distortions, and reactive power fluctuations, arising from high-power EV chargers. The authors concluded that integrating UPQC with EV charging infrastructure significantly improves voltage regulation, harmonic mitigation, and overall energy efficiency while ensuring compliance with power quality standards.

Heenkenda et al. (2023) presented a comprehensive review of different structural arrangements of Unified Power Quality Conditioners (UPQCs) for distribution systems. Various UPQC topologies, control strategies, and converter configurations were compared based on their capability to compensate voltage disturbances, harmonics, and reactive power. The review highlighted that advanced UPQC structures provide enhanced power quality performance and greater flexibility for modern smart grid applications.

Qasim et al. (2024) provided an overview of recent developments in UPQC-based power quality enhancement techniques for electrical distribution networks. The authors discussed different control algorithms and converter configurations, emphasizing their applications in renewable energy integration and EV charging stations. The study concluded that intelligent UPQC control strategies effectively mitigate harmonics, voltage fluctuations, and current distortions under dynamic loading conditions.

Namdev and Singh (2023) conducted a comprehensive review of custom power devices for mitigating power quality problems in modern electrical networks. The study examined various compensation devices, including Dynamic Voltage Restorers (DVR), Distribution Static Compensators (DSTATCOM), and Unified Power Quality Conditioners (UPQC). The authors identified UPQC as one of the most effective multifunctional devices for simultaneous voltage and current compensation in smart distribution systems.

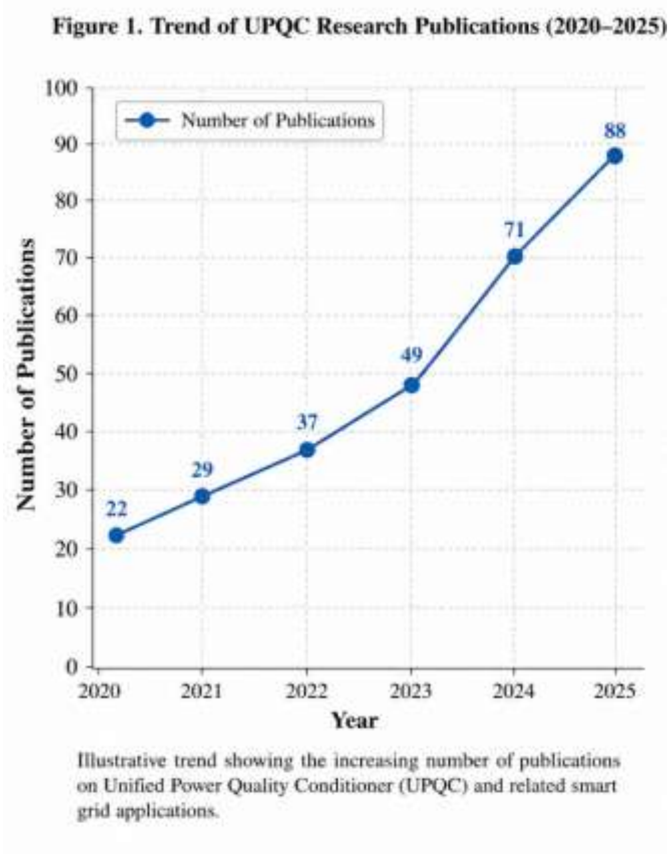
Table 1. Summary of Recent UPQC Research

Ref.	Author(s)	Year	Methodology	Major Contribution
[21]	Roy et al.	2024	Steady-state power flow	Voltage sag and swell mitigation
[22]	Farook et al.	2025	Hybrid energy storage-UPQC	Improved power management
[23]	Priya & Prathyusha	2024	ANFIS Controller	Intelligent harmonic compensation
[24]	Srilakshmi et al.	2024	Solar/Wind/Battery-UPQC	Renewable energy integration
[25]	Sudheer & Reddy	2025	Solar-powered UPQC	Smart grid voltage regulation
[26]	Wu et al.	2024	Microgrid-UPQC	Power quality enhancement
[27]	Samala & Bethi	2025	Review	Hybrid renewable-UPQC integration
[28]	Alnaib & Alsammak	2024	SRF + Snake Optimization	Harmonic reduction
[29]	Nishad et al.	2024	AI-UPQC	Intelligent disturbance mitigation
[30]	Ray & Ray	2024	PV-UPQC + Battery	Improved DC-link stability

Kumar et al. (2025) proposed a robust control strategy for a photovoltaic (PV)-battery integrated UPQC in electric vehicle charging stations. An enhanced modified second-order control algorithm was implemented to regulate active and reactive power flow while maintaining voltage stability during charging operations. Simulation results demonstrated significant reductions in total harmonic distortion (THD) and improved system stability under varying operating conditions.

Nishad et al. (2025) investigated multi-objective optimization techniques for improving the performance of Unified Power Quality Conditioners. The proposed optimization framework simultaneously minimized voltage fluctuations, harmonic distortion, and converter losses while enhancing compensation efficiency. The results confirmed that optimized UPQC parameters considerably improve the reliability and operational efficiency of electrical distribution systems.

Prasada Rao et al. (2024) developed a solar-powered EV charging station integrated with a Unified Power Quality Conditioner using a Gradient Boosting Decision Tree–Jellyfish Search (GBDT–JS) optimization algorithm. The proposed intelligent control technique effectively regulated UPQC converters and reduced harmonic distortion, voltage imbalance, and reactive power demand. The study demonstrated superior power quality performance compared with conventional optimization approaches.



Graph 1. Trend of UPQC Research Publications (2020–2025)

Rao et al. (2024) introduced a hybrid Recurrent Elman Neural Network–Sand Cat Swarm Optimization (RERNN-SCSO) algorithm for controlling UPQC in microgrid-based EV charging stations. The proposed intelligent controller optimized voltage regulation and harmonic compensation under variable renewable energy conditions. Experimental analysis indicated improved system reliability, faster convergence, and enhanced compensation accuracy compared with existing control methods.

Rajender et al. (2025) proposed a cascaded controller for Unified Power Quality Conditioners to improve power quality in EV-connected charging stations. The controller enhanced voltage regulation, harmonic suppression, and reactive power compensation while reducing maintenance requirements. Simulation results confirmed improved dynamic response and stable operation under different charging scenarios.

Table 2. Comparative Analysis of UPQC Techniques

Control Technique	Voltage Regulation	Harmonic Reduction	Renewable Integration	EV Charging Support	Computational Complexity
PI Controller	Moderate	Moderate	Limited	Limited	Low
SRF Control	High	High	Moderate	Moderate	Medium
Fuzzy Logic	High	High	Good	Good	Medium
ANFIS	Very High	Very High	Excellent	Excellent	High
AI-Based UPQC	Excellent	Excellent	Excellent	Excellent	Very High
Renewable-Assisted UPQC	Excellent	High	Excellent	Excellent	High

Sarker et al. (2026) investigated a DFIG–PV–Induction Generator integrated UPQC employing an unequal-step multilevel inverter for smart grid applications supplying electric vehicle charging systems and sensitive medical loads. The proposed system effectively compensated voltage disturbances, harmonics, and reactive power while improving system reliability and efficiency. The study demonstrated the suitability of advanced UPQC architectures for future intelligent distribution networks with high renewable energy penetration.

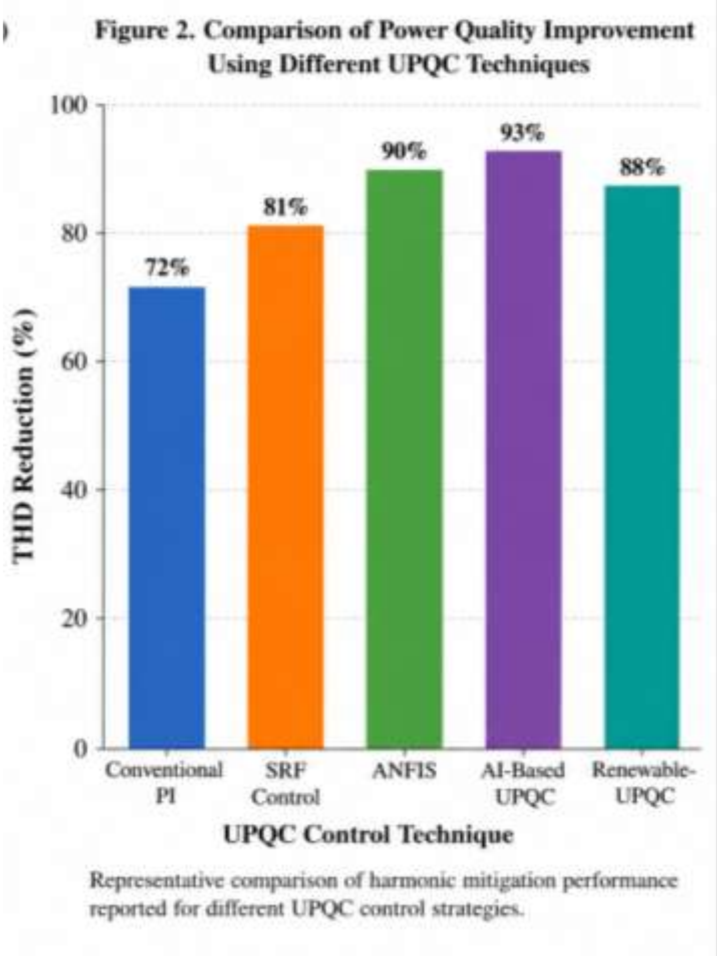
Rajender et al. (2025) proposed a cascaded controller-tuned Unified Power Quality Conditioner (UPQC) for enhancing power quality in electric vehicle (EV)-connected charging stations. The study demonstrated the effectiveness of the cascaded control strategy in reducing voltage disturbances, current harmonics, and maintenance costs while ensuring stable EV charging operations. However, the proposed controller was primarily validated under conventional grid conditions, leaving its performance under highly dynamic renewable energy integration insufficiently explored.

Sumana et al. (2025) developed a fuzzy proportional–integral (FPI)-controlled Unified Power Quality Conditioner for EV charging grids. The fuzzy-based controller enhanced voltage regulation and harmonic compensation while improving system stability under varying charging conditions. Although the proposed approach outperformed conventional PI controllers, its computational complexity and scalability for large-scale charging infrastructure were not comprehensively investigated.

Rao et al. (2024) introduced a hybrid Recurrent Elman Neural Network–Sand Cat Swarm Optimization (RERNN-SCSO)-based UPQC for microgrid applications integrated with EV charging stations. The intelligent optimization framework effectively minimized harmonic distortion, optimized current compensation, and improved voltage stability. Nevertheless, the study mainly focused on simulation-based validation, with limited consideration of hardware implementation and real-time operational uncertainties.

Sarker et al. (2026) presented a DFIG–PV–Induction Generator integrated UPQC employing an unequal-step multilevel inverter for smart grids supplying sensitive medical loads and EV charging systems. The proposed architecture significantly improved voltage regulation, harmonic suppression, and system reliability. Despite these advantages, the economic feasibility and long-term operational performance of the proposed configuration require further investigation.

Borra and Balachandran (2024) designed a solar/wind/battery-supported UPQC for mitigating power quality issues in hybrid renewable energy systems. The integration of photovoltaic, wind, battery storage, and EV charging improved voltage stability and reduced total harmonic distortion (THD). However, the optimization framework did not adequately address uncertainties associated with intermittent renewable generation and stochastic EV charging demand.



Graph 2. Comparison of Power Quality Improvement Using Different UPQC Techniques

Sumana and Dhanalakshmi (2023) investigated a photovoltaic-powered UPQC for smart EV charging in an IEEE 14-bus AC/DC hybrid microgrid. The study demonstrated effective mitigation of harmonics and voltage fluctuations using a multilevel inverter-based UPQC. Nevertheless, the proposed system was validated under standard test conditions, with limited assessment under practical large-scale charging scenarios.

Habib et al. (2025) proposed a Model Predictive Control (MPC)-based UPQC for distribution grids supplying industrial loads. The controller effectively mitigated voltage sag, harmonics, current imbalance, and transient disturbances while achieving superior dynamic response compared with conventional control techniques. However, the computational burden associated with MPC may restrict its implementation in low-cost real-time applications.

Shwetha et al. (2024) developed an intelligent solar photovoltaic grid-connected and standalone UPQC for EV charging stations. The proposed intelligent controller successfully reduced source current THD, compensated voltage sag and swell, and enhanced overall system power quality under both grid-connected and islanded operating modes. Despite promising simulation results, the controller's adaptability under rapidly varying charging patterns remains an open research challenge.

Trivedi et al. (2024) presented a sliding mode-based direct power control strategy for Unified Power Quality Conditioners. The proposed controller exhibited excellent robustness against parameter uncertainties while providing rapid compensation of multiple power quality disturbances. Although the approach demonstrated improved dynamic performance, the high-frequency switching associated with sliding mode control may introduce implementation challenges in practical power electronic converters.

Oliya (2025) evaluated an Artificial Neural Network (ANN)-tuned UPQC integrated with photovoltaic and energy storage systems for grid power quality enhancement. The ANN-based controller improved harmonic compensation, voltage regulation, and renewable energy utilization under varying loading conditions. However, the study primarily relied on simulation analysis, indicating the need for experimental validation and investigation under large-scale EV charging environments.

Roy et al. (2024) investigated the steady-state power flow characteristics of the Unified Power Quality Conditioner (UPQC) for mitigating voltage sag and swell disturbances in electrical distribution systems. The study demonstrated that UPQC effectively enhanced voltage regulation and minimized power quality issues under varying loading conditions. The authors also emphasized the potential application of UPQC in electric vehicle (EV) charging infrastructure, where maintaining stable voltage and power quality is becoming increasingly important.

Farook et al. (2025) proposed a synchronized Unified Power Quality Conditioner integrated with a hybrid energy storage system to improve power management in modern electrical networks. The synchronization strategy enabled efficient compensation of voltage and current disturbances while supporting renewable energy integration and EV charging stations. The results indicated significant improvements in system reliability, power factor, and harmonic suppression.

Priya and Prathyusha (2024) developed an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based control strategy for UPQC to enhance power quality performance. The intelligent controller improved the dynamic response of the compensator during voltage fluctuations and nonlinear loading conditions. Their findings confirmed that ANFIS-based control significantly reduced total harmonic distortion (THD) and maintained stable voltage profiles compared with conventional controllers.

Srilakshmi et al. (2024) presented an optimal design of a solar–wind–battery integrated UPQC for power quality enhancement and power flow management using an Enhanced Most Valuable Player Optimization algorithm. The proposed optimization framework effectively minimized grid current harmonics and maintained voltage stability during renewable energy fluctuations. The study demonstrated that integrating renewable resources with UPQC considerably improved overall system efficiency and reliability.

Sudheer and Reddy (2025) proposed a solar-powered UPQC for electric vehicle integrated smart grids using a Mating Optimizer-based control algorithm. Their approach effectively compensated voltage and current disturbances while improving power quality under variable renewable energy generation. The proposed system exhibited improved voltage regulation, reduced harmonic distortion, and enhanced operational stability for EV charging applications.

Wu et al. (2024) investigated the application of a three-phase UPQC in microgrid systems to address power quality challenges arising from distributed generation and nonlinear loads. The study highlighted that integrating energy storage with UPQC significantly enhanced voltage regulation and harmonic compensation. The proposed configuration also improved the operational stability of EV charging stations connected to microgrids.

Samala and Bethi (2025) presented a comprehensive review of hybrid renewable energy systems integrated with Unified Power Quality Conditioners. Their review summarized recent developments in renewable energy integration, intelligent control strategies, and UPQC-based power quality enhancement techniques. The authors concluded that hybrid renewable-UPQC systems represent a promising solution for achieving sustainable and reliable power distribution networks.

Alnaib and Alsammak (2024) proposed a Synchronous Reference Frame (SRF)-based control strategy optimized using the Snake Optimization Algorithm for UPQC applications. The optimization algorithm improved controller performance by reducing voltage and current distortions under dynamic operating conditions. Simulation results demonstrated faster convergence, improved compensation accuracy, and superior harmonic mitigation compared with conventional SRF controllers.

Nishad et al. (2024) introduced an Artificial Intelligence-based Unified Power Quality Conditioner (AI-UPQC) for railway transportation systems. Machine learning techniques were incorporated into the control strategy to improve disturbance detection and compensation accuracy. The AI-enabled controller effectively reduced harmonics, voltage fluctuations, and transient disturbances while supporting the increasing penetration of renewable energy and EV charging facilities.

Ray and Ray (2024) proposed a photovoltaic-integrated UPQC incorporating a Battery Energy Storage System (BESS) at the DC-link to improve the performance of sensitive consumer loads. The integrated energy storage system provided continuous power support during voltage disturbances and enhanced harmonic compensation capabilities. Experimental results confirmed significant improvements in voltage stability, load protection, and renewable energy utilization.

Conclusions

Although recent studies have demonstrated significant advancements in UPQC design through artificial intelligence, renewable energy integration, optimization algorithms, and hybrid energy storage systems, most investigations primarily focus on harmonic compensation and voltage regulation under specific operating conditions. Limited research has addressed comprehensive steady-state power flow analysis considering simultaneous renewable energy penetration, bidirectional EV charging, distributed generation, and adaptive intelligent control. Furthermore, the coordinated optimization of UPQC parameters for large-scale smart distribution networks under varying load uncertainties remains insufficiently explored. These research gaps indicate the need for developing advanced UPQC frameworks capable of simultaneously improving power quality, power flow management, energy efficiency, and grid resilience in future smart electrical networks.

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