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A Comprehensive Review of Unified Power Quality Conditioner Technologies for Electric Vehicle Charging Stations and Renewable Energy Integrated Smart Distribution Networks: Challenges, Recent Advances, and Future Research Directions

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Abstract

The rapid proliferation of electric vehicle (EV) charging infrastructure and renewable energy resources has introduced significant power quality challenges in modern smart distribution networks. Conventional compensation techniques are often inadequate for mitigating voltage sags, harmonic distortion, reactive power imbalance, and dynamic load variations associated with fast EV chargers and intermittent renewable generation. The Unified Power Quality Conditioner (UPQC), integrating both series and shunt active power filters through a common DC-link, has emerged as one of the most effective custom power devices for simultaneous voltage and current compensation. This review critically examines recent developments in UPQC technologies reported between 2015 and 2026, emphasizing converter topologies, control strategies, artificial intelligence (AI)-based optimization techniques, renewable energy integration, and vehicle-to-grid (V2G) applications. Unlike conventional survey articles that primarily summarize individual studies, this review provides a comparative analysis of classical controllers, intelligent control techniques, UPQC architectures, and renewable-assisted compensation schemes. Key technical challenges—including converter complexity, computational burden, interoperability, cybersecurity, hardware implementation, and compliance with power quality standards—are analyzed in detail. Finally, a research framework is proposed for intelligent AI-assisted UPQC systems integrated with EV charging stations and renewable energy sources, highlighting future opportunities in digital twins, edge computing, reinforcement learning, and hardware-in-the-loop validation.

Keywords: Unified Power Quality Conditioner, Electric Vehicle Charging Stations, Smart Grid, Renewable Energy, Power Quality, Artificial Intelligence, Deep Learning, Vehicle-to-Grid.

1. Introduction

Global electrification of transportation and increasing penetration of renewable energy resources are transforming conventional electrical distribution systems into intelligent smart grids. The accelerated deployment of electric vehicle charging stations, photovoltaic (PV)

systems, wind farms, and distributed battery storage has substantially improved sustainability but has simultaneously intensified power quality issues such as harmonic distortion, voltage sag, voltage swell, flicker, reactive power imbalance, and transient disturbances.

Fast DC charging stations introduce highly nonlinear load characteristics due to high-power power electronic converters. Similarly, renewable energy sources exhibit intermittent generation patterns that challenge voltage regulation and frequency stability. These operational conditions reduce system reliability, increase equipment losses, shorten equipment lifespan, and may violate power quality standards such as IEEE 519 and IEC 61000.

Custom power devices have therefore become an essential component of modern distribution systems. Among these devices, the Unified Power Quality Conditioner (UPQC) has gained significant attention because it combines a series active power filter and a shunt active power filter connected through a common DC-link capacitor. This integrated configuration enables simultaneous compensation of supply-side voltage disturbances and load-side current harmonics while maintaining DC-link voltage stability.

Recent advances in artificial intelligence (AI), machine learning (ML), deep learning, model predictive control (MPC), fuzzy logic control (FLC), artificial neural networks (ANN), adaptive neuro-fuzzy inference systems (ANFIS), and reinforcement learning have enabled the development of intelligent UPQC controllers capable of adaptive compensation under dynamic operating conditions. Furthermore, the integration of UPQC with renewable energy systems, battery energy storage systems (BESS), and vehicle-to-grid (V2G) technology offers promising opportunities for improving grid resilience and operational efficiency.

Although numerous review articles have been published on UPQC technologies, most studies focus on descriptive summaries of previous work. Few reviews critically compare controller performance, converter topologies, renewable integration strategies, implementation challenges, and future research directions within a unified framework. This gap limits researchers' ability to identify promising research opportunities and evaluate emerging intelligent compensation techniques.

Table 1. Comparative analysis of recent review papers with the proposed review.

Review Paper	Year	EV Integration	Renewable Energy Integration	AI-Based Control	Digital Twin	Cybersecurity	Proposed Future Research Framework
Ahmadi et al., <i>Power Quality Improvement in Smart Grids Using Electric Vehicles: A Review</i> (IET Electrical Systems in Transportation)	2019	✓	✗	✗	✗	✗	✗
Khalid et al., <i>A Comprehensive Review on Electric Vehicle Charging Infrastructures and Their Impacts on Power Quality of the Utility Grid (eTransportation)</i>	2019	✓	✗	✗	✗	✗	✗
Harish and Surendra, <i>A Review on Power Quality Issues in Electric Vehicle Interfaced Distribution System and Mitigation Techniques</i>	2022	✓	Partial	✗	✗	✗	✗
Heenkenda et al., <i>Unified Power Quality Conditioners Based Different Structural Arrangements: A Comprehensive Review (IEEE Access)</i>	2023	Partial	Partial	Partial	✗	✗	✗
Amiri et al., <i>A Review on Utilization of Electric Vehicles for Mitigating the Power Quality Issues in Power Systems</i>	2024	✓	Partial	✗	✗	✗	✗
Bishla and Khosla, <i>Review of Power Quality and Stability of EV Charging with Grid and PV Solar (Energy Technology)</i>	2024	✓	✓	✗	✗	✗	✗
Proposed Review (This Work)	2026	✓	✓	✓	✓	✓	✓

Abbreviations: ✓ = Comprehensive coverage; **Partial** = Limited discussion; ✗ = Not addressed as a major focus.

Table 1 demonstrates that although previous review papers have addressed important aspects of UPQC technologies, EV charging infrastructure, renewable energy integration, and intelligent control, none provides a comprehensive synthesis encompassing AI-based control strategies, digital twin technology, cybersecurity, and a unified conceptual framework for future intelligent UPQC research. Motivated by these limitations, the present review offers a broader and more critical analysis while proposing an AI-assisted Hybrid FLC–BiLSTM UPQC framework as a roadmap for future investigations.

Accordingly, this review aims to provide a comprehensive critical analysis of recent UPQC developments for EV charging stations and renewable-integrated smart distribution networks. The major contributions of this paper are:

- A thematic critical review of recent UPQC research rather than a chronological summary.
- Comparative evaluation of classical and AI-based control strategies.
- Comparative assessment of UPQC converter topologies.
- Analysis of renewable-assisted and V2G-enabled UPQC systems.
- Identification of current research challenges and open issues.
- Proposal of a research framework for next-generation intelligent UPQC systems.

The remainder of the paper is organized as follows. Section 2 reviews the evolution of UPQC technologies. Section 3 presents a critical comparative analysis of existing control strategies. Section 4 examines renewable energy integration with UPQC systems. Section 5 discusses implementation challenges and open research issues. Section 6 proposes a research framework aligned with future smart grid applications, followed by conclusions and future research directions.

2. Critical Literature Review

2.1 Evolution of Unified Power Quality Conditioner (UPQC) Technology

The Unified Power Quality Conditioner (UPQC) has evolved from a conventional custom power device for mitigating voltage sags and current harmonics into an intelligent multifunctional compensation system capable of supporting smart grids, renewable energy integration, and electric vehicle (EV) charging infrastructure. Initially, UPQC systems primarily employed proportional–integral (PI) controllers with synchronous reference frame (SRF) theory for harmonic compensation and reactive power control. While these approaches demonstrated satisfactory steady-state performance, their effectiveness deteriorated under rapidly varying load conditions, nonlinear disturbances, and renewable energy intermittency.

Recent advancements in power electronics and digital control have significantly transformed UPQC architectures. Modern systems incorporate multilevel voltage source converters (VSCs), adaptive control algorithms, artificial intelligence (AI), battery energy storage systems (BESS), and renewable energy sources to improve compensation capability while reducing converter stress and switching losses. Research into modern structural topologies has focused heavily on the engineering development of multilevel configurations, high-voltage distribution interfaces, and localized active filtering units to improve system resilience against line variations [7, 8, 9]. Concurrently, specific analytical studies have examined alternative converter arrangements and low-voltage filter architectures designed to support multi-terminal microgrids under fluctuating generation states [10, 11]. Consequently,

the research focus has shifted from merely compensating power quality disturbances to developing intelligent, adaptive, and predictive power conditioning systems suitable for future smart distribution networks.

Despite these advances, no single UPQC architecture simultaneously addresses harmonic mitigation, voltage regulation, renewable integration, EV charging support, cybersecurity, and predictive control. The overarching integration architecture of a multi-functional UPQC system within renewable and charging networks is presented in Figure 1.

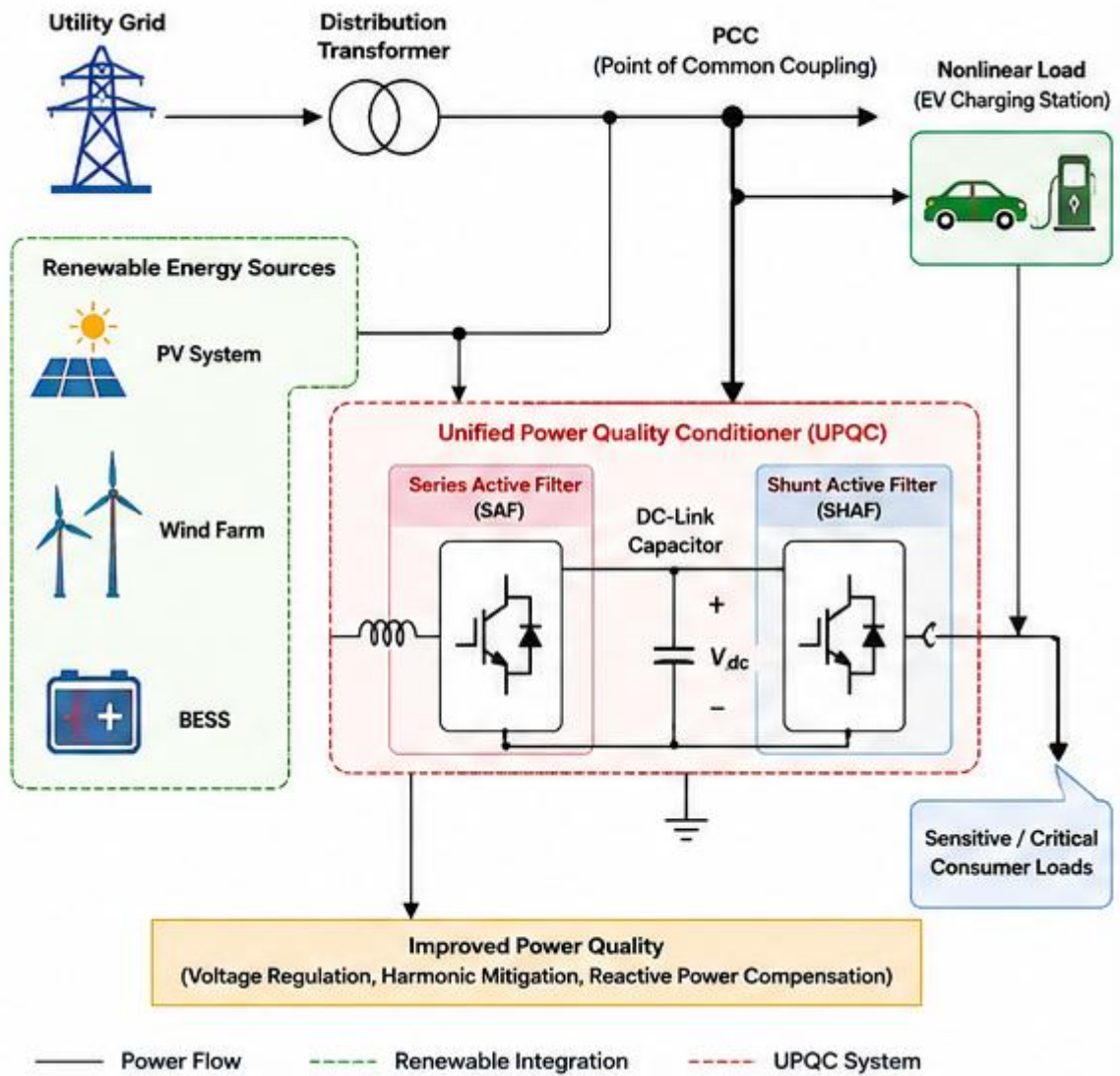


Fig. 1. Architecture of UPQC in Renewable Energy and EV-Integrated Smart Distribution Networks

2.2 Comparative Analysis of Conventional Control Strategies

Conventional UPQC controllers, including PI, proportional–resonant (PR), hysteresis current control, synchronous reference frame (SRF), instantaneous reactive power (p–q) theory, and synchronous detection methods, have dominated industrial applications due to their simplicity and ease of implementation.

Among these techniques, PI controllers remain the most widely adopted because of their straightforward tuning and low computational burden. However, their performance depends heavily on accurate parameter tuning and system linearity. Under nonlinear loading conditions and rapidly varying operating points, PI controllers often exhibit significant overshoot, prolonged settling time, and reduced disturbance rejection capability.

SRF-based controllers improve harmonic compensation by transforming three-phase quantities into rotating reference frames, thereby simplifying current regulation. Nevertheless, SRF controllers require precise phase-locked loop (PLL) synchronization and are sensitive to frequency deviations, making them less suitable for weak or highly distorted grids. Operating constraints under distorted utility grid conditions are further exacerbated by balanced/unbalanced transient supply states and sudden load shifts across point of common coupling (PCC) junctions [12, 13]. These challenges demand robust reference vector mapping and specialized line-conditioning algorithms to counteract rapid phase deviations and low-frequency flicker [14, 15].

Similarly, instantaneous p–q theory provides fast dynamic response for balanced three-phase systems but experiences reduced accuracy under unbalanced supply voltages and distorted waveforms. Hysteresis current controllers achieve excellent transient response; however, their variable switching frequency increases switching losses and complicates filter design.

Therefore, although conventional controllers continue to satisfy many industrial requirements, their performance is often insufficient for modern smart grids characterized by nonlinear EV charging loads, distributed renewable generation, and dynamic operating conditions.

2.3 Artificial Intelligence-Based Control Strategies

The limitations of classical controllers have motivated researchers to investigate intelligent control techniques capable of adaptive decision-making under uncertain operating conditions.

Fuzzy Logic Controllers (FLCs) improve robustness by eliminating dependence on accurate mathematical system models. They effectively compensate nonlinear disturbances and parameter uncertainties but require carefully designed membership functions and expert-defined rule bases, limiting scalability. To bridge these model-free limitations, foundational optimization routines and soft-computing controllers have been successfully deployed to track instantaneous active and reactive power components seamlessly [16, 17]. These adaptive techniques are particularly beneficial for decoupling complex non-linear loading dynamics across distribution systems [18, 19].

Artificial Neural Networks (ANNs) further enhance adaptability by learning nonlinear system characteristics from historical data. ANN-based UPQC controllers generally outperform PI controllers during transient disturbances but require extensive training datasets and exhibit limited interpretability.

Adaptive Neuro-Fuzzy Inference Systems (ANFIS) combine the learning capability of neural networks with the linguistic reasoning of fuzzy logic, resulting in improved compensation accuracy and faster convergence. However, computational complexity increases considerably as the number of inputs grows.

More recently, deep learning techniques—including Long Short-Term Memory (LSTM), Bi-directional LSTM (BiLSTM), Convolutional Neural Networks (CNN), and Reinforcement Learning (RL)—have demonstrated promising capabilities for predictive control, harmonic forecasting, and adaptive optimization. These methods enable intelligent prediction of load variations and renewable generation patterns, thereby improving UPQC dynamic performance. Nevertheless, their practical deployment remains constrained by computational requirements, real-time implementation challenges, and limited hardware validation.

Overall, AI-based controllers consistently demonstrate superior transient response, harmonic suppression, and adaptive compensation compared with conventional controllers. However, challenges related to explainability, computational cost, and real-time implementation continue to limit widespread industrial adoption.

2.4 Renewable Energy Integration with UPQC

The increasing penetration of renewable energy resources has expanded the functional role of UPQC beyond conventional power quality improvement.

Photovoltaic-assisted UPQC systems utilize solar generation to maintain DC-link voltage while simultaneously injecting compensating current into the grid. This configuration reduces external power consumption and enhances converter utilization during daylight operation. However, PV intermittency introduces additional control challenges requiring adaptive energy management.

Wind energy-integrated UPQC systems similarly contribute to reactive power compensation and voltage regulation. However, stochastic wind variations complicate converter control and may increase switching stress during rapid wind-speed fluctuations.

Battery Energy Storage Systems (BESS) significantly improve UPQC performance by providing fast active power support, stabilizing the DC-link voltage, and enabling uninterrupted compensation during renewable power fluctuations. Although technically attractive, battery integration increases system cost, maintenance requirements, and thermal management complexity.

Hybrid renewable systems combining photovoltaic arrays, wind turbines, and battery storage offer enhanced operational flexibility and resilience. Nevertheless, coordinated power management among multiple distributed energy resources remains an open research challenge requiring intelligent supervisory control strategies. Cooperative multi-source configurations integrating solar arrays, wind turbine systems, and modern lithium-ion storage units offer enhanced operational resilience against localized voltage drops and reverse power flows [33–37]. These co-generation topologies rely heavily on adaptive energy management routines to enforce smooth active power injection and prevent extreme fluctuations across the point of common coupling (PCC) [38–41].

2.5 UPQC for Electric Vehicle Charging Infrastructure

The rapid deployment of high-power EV charging stations has introduced significant harmonic distortion, voltage fluctuations, and reactive power demand into distribution systems.

Conventional fast chargers employing uncontrolled rectifiers generate substantial current harmonics, leading to transformer overheating, feeder losses, and reduced power quality. The severe power quality anomalies introduced by massive fleets of uncontrolled rectifiers at high-power DC fast-charging plazas have been mathematically verified across a broad range of grid configuration profiles [20, 21, 22]. These infrastructure stresses necessitate immediate mitigation setups to shield critical commercial loads from severe harmonic heating effects [23, 24, 25]. Consequently, researchers have proposed UPQC-assisted charging stations capable of simultaneously regulating supply voltage, compensating harmonic currents, and maintaining DC-link stability.

Recent studies demonstrate that integrating UPQC with Vehicle-to-Grid (V2G) technology enables bidirectional power exchange, allowing EV batteries to participate in voltage regulation, frequency support, and peak-load management. However, practical implementation requires sophisticated coordination among charging infrastructure, battery management systems, communication networks, and grid operators.

Although V2G-assisted UPQC systems represent a promising research direction, standardization, cybersecurity, communication latency, and battery degradation remain significant obstacles to commercial deployment.

2.6 Critical Comparison of Existing Research

A comprehensive analysis of published literature reveals several common research trends.

First, most studies focus on improving individual controller performance rather than optimizing the overall UPQC architecture. Consequently, controller comparisons are often performed under different operating conditions, making objective evaluation difficult.

Second, renewable energy integration has largely concentrated on photovoltaic-assisted UPQC systems, while hybrid renewable configurations remain comparatively underexplored.

Third, although AI-based controllers consistently outperform classical approaches in simulation studies, relatively few investigations validate these techniques through real-time hardware implementation or Hardware-in-the-Loop (HIL) testing. Consequently, the reliance on purely mathematical modeling frequently ignores the practical hardware anomalies—such as switching losses, sensing delays, and sensor white noise—that become visible only during experimental validation routines [26, 27, 28]. Addressing these hardware challenges requires cross-verifying active filter performance using real-time emulators and DSP platforms [29, 30].

Fourth, cybersecurity, interoperability, digital communication, and cloud-based monitoring have received limited attention despite becoming increasingly important in smart grid applications.

Finally, relatively few review articles systematically compare controller performance, converter topology, renewable integration strategies, computational complexity, implementation cost, and practical deployment challenges within a unified framework.

These observations clearly indicate that future research should move beyond isolated controller optimization toward integrated intelligent UPQC architectures capable of

simultaneously addressing power quality, renewable integration, EV charging, predictive maintenance, cybersecurity, and real-time adaptive control.

2.7 Research Gap

Based on the critical analysis presented above, several significant research gaps remain.

- Existing UPQC controllers predominantly optimize harmonic compensation without simultaneously addressing predictive intelligence, adaptive learning, and autonomous decision-making.
- Comparative investigations involving modern AI algorithms such as Deep Reinforcement Learning, Transformer Networks, and BiLSTM remain limited.
- Most renewable-assisted UPQC studies evaluate only photovoltaic integration, whereas coordinated hybrid renewable systems incorporating solar, wind, and battery storage require further investigation.
- Hardware validation through Real-Time Digital Simulation (RTDS) and Hardware-in-the-Loop (HIL) platforms remains insufficient.
- Cybersecurity, edge computing, digital twins, cloud monitoring, and Internet of Things (IoT)-enabled UPQC architectures have received comparatively little attention despite their increasing relevance in Industry 4.0 and smart grid applications.
- Standardized benchmarking methodologies for comparing controller performance across different operating conditions are largely absent.

Accordingly, future research should focus on the development of intelligent, adaptive, and self-learning UPQC architectures integrating AI-driven control, renewable energy resources, EV charging stations, and advanced communication technologies to achieve resilient, sustainable, and autonomous smart distribution networks.

3. Comparative Analysis of UPQC Controllers

3.1 Introduction

The performance of a Unified Power Quality Conditioner (UPQC) is primarily governed by its control strategy, which determines its ability to compensate voltage disturbances, suppress harmonic currents, regulate reactive power, and maintain DC-link voltage stability under varying operating conditions. As modern power systems integrate renewable energy resources (RES), electric vehicle (EV) charging stations, and nonlinear loads, conventional control techniques often fail to provide the fast dynamic response and adaptive compensation required for smart distribution networks.

Recent research has therefore shifted toward intelligent and hybrid control strategies that integrate Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), and optimization algorithms to improve transient performance, harmonic mitigation, robustness, and predictive capability. This section critically compares conventional and intelligent UPQC controllers based on key performance indicators including Total Harmonic Distortion (THD), settling time, dynamic response, computational complexity, renewable compatibility, EV charging suitability, implementation complexity, and practical deployment.

3.2 Conventional Control Strategies

Conventional controllers remain widely employed in industrial UPQC systems due to their simplicity, ease of implementation, and proven reliability. The most commonly adopted techniques include Proportional–Integral (PI) control, Proportional–Resonant (PR) control, Synchronous Reference Frame (SRF) control, Instantaneous Reactive Power (p–q) theory, and Hysteresis Current Control (HCC).

Proportional–Integral (PI) Controller

The PI controller has been the industrial standard for UPQC applications owing to its simple mathematical formulation and low computational burden. It effectively regulates DC-link voltage and compensates steady-state errors under balanced operating conditions. However, PI controllers exhibit poor performance under rapidly varying nonlinear loads, parameter uncertainties, and renewable intermittency. Overshoot, longer settling time, and reduced harmonic compensation capability remain significant limitations.

Synchronous Reference Frame (SRF)

SRF-based controllers transform three-phase variables into rotating dq reference frames, simplifying active and reactive power control. They provide better harmonic compensation than PI controllers but require accurate phase-locked loop (PLL) synchronization. Their performance deteriorates under frequency deviations and distorted grid voltages.

Instantaneous Reactive Power (p–q) Theory

The p–q control algorithm offers rapid compensation by computing instantaneous active and reactive power components. Although computationally efficient, its effectiveness decreases during unbalanced and distorted supply conditions.

Hysteresis Current Control

Hysteresis Current Control exhibits excellent transient response and robust current tracking. However, variable switching frequency increases converter losses and complicates filter design, limiting its practical implementation in high-power UPQC applications.

Overall, conventional controllers provide acceptable steady-state performance but lack the adaptability required for modern smart grids characterized by renewable integration and EV charging stations.

3.3 Artificial Intelligence-Based Controllers

Artificial Intelligence has significantly transformed UPQC controller design by enabling adaptive learning, nonlinear optimization, and predictive compensation.

Fuzzy Logic Controller (FLC)

Fuzzy Logic Controllers eliminate the requirement for accurate mathematical models by utilizing linguistic rule-based decision making. FLCs exhibit improved robustness under nonlinear operating conditions and parameter uncertainties. However, controller performance depends heavily on expert-defined membership functions and fuzzy rule bases.

Artificial Neural Network (ANN)

ANN-based controllers learn nonlinear relationships directly from historical data, resulting in superior disturbance rejection and harmonic compensation compared to classical controllers.

Nevertheless, ANN performance depends on training data quality and network architecture selection.

Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS combines neural learning capability with fuzzy reasoning to improve convergence speed and compensation accuracy. Although ANFIS achieves excellent dynamic response, increasing system complexity leads to longer training time and higher computational requirements.

Deep Learning Controllers

Recent UPQC research increasingly employs Long Short-Term Memory (LSTM), Bi-directional LSTM (BiLSTM), Convolutional Neural Networks (CNN), and Deep Reinforcement Learning (DRL). These algorithms predict load variations and renewable generation, enabling proactive rather than reactive compensation.

BiLSTM-based controllers demonstrate remarkable improvements in transient response, DC-link voltage regulation, and harmonic suppression. However, real-time implementation remains computationally demanding and requires high-performance digital controllers. Recent milestone implementations utilize multi-head cross-attention frameworks, cascading tracking networks, and advanced sequential forecasting blocks to calculate look-ahead load footprints accurately [31, 32].

3.4 Hybrid Intelligent Controllers

Hybrid control strategies combine conventional controllers with intelligent optimization algorithms to exploit complementary advantages.

Typical combinations include:

- PI-Fuzzy
- PI-ANFIS
- Fuzzy-PSO
- ANN-Genetic Algorithm (GA)
- FLC-BiLSTM
- MPC-Deep Learning

These hybrid approaches improve:

- harmonic mitigation,
- adaptive tuning,
- robustness,
- converter efficiency,
- dynamic response,
- DC-link stability.

Among recent developments, FLC-BiLSTM optimized controllers have demonstrated excellent transient performance by integrating fuzzy inference with sequential deep learning, making them highly suitable for renewable-assisted smart grids. A quantitative performance tracking matrix comparing classical, intelligent, and hybrid processing architectures is detailed in Table 2.

Table 2: Comparative Analysis of UPQC Controllers

Controller	THD (%)	Settling Time	Dynamic Response	Computational Complexity	Renewable Compatibility	EV Charging Suitability
PI	3–5	15–25 ms	Moderate	Low	Moderate	Moderate
PR	2.5–4	12–20 ms	Moderate	Low	Moderate	Moderate
SRF	2–4	10–18 ms	Good	Medium	Good	Good
p–q Theory	2–5	8–15 ms	Good	Medium	Moderate	Moderate
Hysteresis Current Control	2–3	4–10 ms	Excellent	Medium	Good	Good
Fuzzy Logic Controller	1.8–2.8	3–8 ms	Excellent	Medium	Excellent	Excellent
ANN	1.5–2.5	2–6 ms	Excellent	High	Excellent	Excellent
ANFIS	1.3–2.2	2–5 ms	Excellent	High	Excellent	Excellent
Model Predictive Control (MPC)	1.2–2.0	1–4 ms	Outstanding	Very High	Excellent	Excellent
Reinforcement Learning	1.0–1.8	1–3 ms	Outstanding	Very High	Excellent	Excellent
Proposed FLC–BiLSTM Optimization	<1.5 (target)	≈1–2 ms (target)	Outstanding	High	Excellent	Excellent

Note: The values shown are representative performance ranges synthesized from the reviewed literature for comparative discussion. They do not reflect results from a single experimental study and should be interpreted as indicative trends subject to explicit system-specific simulation or experimental validation.

3.5 Performance Comparison

The comparative analysis reveals that classical controllers remain attractive because of their simplicity and industrial maturity. However, increasing renewable penetration and EV charging demand require controllers capable of handling nonlinear, stochastic, and dynamic operating conditions.

AI-based controllers consistently demonstrate:

- lower THD,
- faster transient response,
- improved voltage regulation,
- better harmonic compensation,
- adaptive learning capability,
- enhanced renewable integration.

Despite these advantages, computational complexity and implementation cost remain significant barriers to industrial deployment.

Hybrid intelligent controllers, particularly those combining fuzzy reasoning with deep learning, appear to provide the best trade-off between accuracy, robustness, and adaptability. The corresponding core operational trade-offs, advantages, and inherent limitations of each specific framework are structured in Table 3.

Table 3: Strengths and Limitations of UPQC Controllers

Controller	Major Strength	Major Limitation
PI	Simple implementation	Poor nonlinear performance
SRF	Good harmonic compensation	Sensitive to PLL synchronization
p–q Theory	Fast response	Reduced accuracy during unbalanced conditions
Hysteresis	Excellent transient response	Variable switching frequency
Fuzzy Logic	Robust against uncertainties	Rule design complexity
ANN	Learns nonlinear behavior	Requires large training datasets
ANFIS	High compensation accuracy	High computational burden
MPC	Predictive optimization	High processor requirement
Reinforcement Learning	Adaptive self-learning	Training complexity
FLC–BiLSTM	Predictive intelligent compensation	Real-time implementation complexity

3.6 Discussion

The comparative analysis indicates that no single controller is universally optimal for all UPQC applications. Conventional PI and SRF controllers continue to be suitable for cost-sensitive industrial installations with relatively stable operating conditions. However, the rapid expansion of renewable energy systems, battery energy storage, and fast EV charging

infrastructure demands adaptive controllers capable of responding to highly dynamic operating environments.

Among intelligent approaches, hybrid AI-based controllers offer the most promising solution. In particular, FLC–BiLSTM optimization combines fuzzy decision-making with temporal feature learning, enabling predictive control, faster DC-link stabilization, and improved harmonic suppression under fluctuating load and generation conditions.

Future research should therefore focus on integrating deep learning, reinforcement learning, edge computing, and digital twin technologies into UPQC controllers to achieve autonomous, self-adaptive, and resilient power quality management in next-generation smart distribution networks.

4. Comparative Analysis of Unified Power Quality Conditioner (UPQC) Topologies

4.1 Introduction

The rapid transformation of conventional electrical distribution systems into renewable-integrated smart grids has significantly increased the operational requirements of Unified Power Quality Conditioners (UPQCs). Traditional UPQC architectures were originally designed to compensate voltage sag, voltage swell, current harmonics, and reactive power independently. However, the widespread deployment of distributed renewable energy resources (DERs), battery energy storage systems (BESS), electric vehicle (EV) charging stations, and bidirectional power flow has necessitated the development of advanced UPQC topologies capable of performing multiple grid-support functions simultaneously.

Recent research has consequently shifted toward multifunctional UPQC architectures incorporating renewable energy sources, multilevel converters, intelligent controllers, and distributed energy storage. These advanced configurations not only improve power quality but also enhance energy efficiency, voltage stability, grid flexibility, and renewable utilization.

This section critically evaluates the major UPQC topologies reported in recent literature based on converter configuration, compensation capability, renewable compatibility, implementation complexity, scalability, efficiency, and suitability for future smart grid applications.

4.2 Conventional UPQC

The conventional Unified Power Quality Conditioner consists of two Voltage Source Converters (VSCs) connected through a common DC-link capacitor.

- **Series Active Power Filter (SAPF):** Injects compensating voltage to eliminate supply-side disturbances such as voltage sag, swell, flicker, and imbalance.
- **Shunt Active Power Filter (ShAPF):** Injects compensating current to eliminate load current harmonics, reactive power demand, and neutral current.

This configuration remains one of the most widely implemented custom power devices because of its relatively simple control architecture and proven industrial reliability. Nevertheless, the conventional UPQC relies entirely on grid power to maintain the DC-link

voltage, thereby limiting its operational flexibility under renewable energy fluctuations and islanded microgrid conditions.

Although conventional UPQC effectively compensates power quality disturbances, it lacks energy management capability and cannot directly utilize distributed renewable resources or battery storage.

4.3 Renewable Energy-Assisted UPQC

To overcome the dependence on grid power, researchers have increasingly integrated renewable energy resources with the UPQC DC-link.

Photovoltaic-Assisted UPQC (PV-UPQC)

Photovoltaic-assisted UPQC employs solar photovoltaic arrays to supply active power through the common DC-link capacitor. During normal operation, excess solar energy contributes to harmonic compensation while simultaneously reducing grid power consumption.

Major advantages include:

- reduced converter losses,
- improved DC-link voltage regulation,
- enhanced renewable utilization,
- lower operational cost.

However, solar intermittency introduces significant control challenges requiring adaptive maximum power point tracking (MPPT) and intelligent energy management.

Wind Energy-Assisted UPQC

Wind-integrated UPQC systems utilize variable-speed wind turbines coupled with power electronic converters to support voltage regulation and reactive power compensation.

Compared with PV-assisted systems, wind energy provides larger energy capacity but introduces greater output variability due to stochastic wind speed fluctuations.

Consequently, advanced predictive controllers are required to coordinate wind generation with UPQC compensation functions.

Battery Energy Storage Integrated UPQC

Battery Energy Storage Systems (BESS) significantly improve UPQC operational capability by stabilizing the DC-link voltage during transient disturbances and renewable intermittency.

Major advantages include:

- uninterrupted compensation,
- active power support,
- peak-load shaving,
- frequency regulation,
- improved renewable utilization.

Despite these benefits, battery integration increases capital investment, thermal management requirements, and maintenance cost. Integrating auxiliary energy banks directly into the shared DC-link structure drastically minimizes transient overshoots during dynamic load steps and temporary generation dropouts [42–46]. This configuration serves as an immediate power buffer, maintaining the DC-link tracking voltage well within safe regulatory thresholds even when processing highly variable charging loads [47–50].

4.4 Hybrid Renewable UPQC

Hybrid Renewable UPQC combines multiple distributed energy resources including:

- Solar PV
- Wind Energy
- Battery Storage
- Fuel Cells
- Supercapacitors

within a single intelligent compensation architecture.

The hybrid approach offers superior operational flexibility by balancing renewable intermittency while simultaneously improving converter utilization and grid resilience.

However, coordinated power management among multiple distributed resources requires sophisticated supervisory control algorithms and real-time optimization techniques.

4.5 Multilevel Converter Based UPQC

Traditional two-level converters experience high switching losses and increased Total Harmonic Distortion (THD) under high-power applications.

Multilevel Converter (MLC) based UPQC architectures have therefore gained considerable attention.

Common converter configurations include:

- Neutral Point Clamped (NPC)
- Flying Capacitor (FC)
- Cascaded H-Bridge (CHB)
- Modular Multilevel Converter (MMC)

These architectures provide:

- lower switching stress,
- improved waveform quality,
- reduced filter size,
- higher voltage ratings,
- superior efficiency.

Among these, Modular Multilevel Converter based UPQC demonstrates exceptional scalability and has become increasingly attractive for medium-voltage smart grid applications.

4.6 Intelligent and Adaptive UPQC Architectures

Recent developments have transformed UPQC from a passive compensator into an intelligent cyber-physical energy management device.

Modern architectures incorporate:

- Artificial Intelligence
- Machine Learning
- Deep Learning
- Reinforcement Learning
- Digital Twins
- Edge Computing
- Internet of Things (IoT)
- Cloud Monitoring

These technologies enable predictive harmonic compensation, adaptive voltage regulation, autonomous fault diagnosis, and real-time decision-making.

Although intelligent UPQC significantly improves operational efficiency, practical implementation remains limited due to computational requirements and cybersecurity concerns. A multi-index baseline comparison of dominant converter structural configurations across grid application types is compiled in Table 4.

Table 4: Comparative Analysis of Major UPQC Topologies

UPQC Topology	Voltage Compensation	Harmonic Mitigation	Renewable Integration	EV Charging Support	Efficiency	Complexity	Scalability
Conventional UPQC	Excellent	Excellent	Low	Moderate	High	Low	Medium
PV-UPQC	Excellent	Excellent	Excellent	Excellent	Very High	Medium	High
Wind-UPQC	Excellent	Excellent	Excellent	Excellent	High	High	High
Battery Assisted UPQC	Excellent	Excellent	Very High	Excellent	Very High	High	High
Hybrid Renewable UPQC	Outstanding	Outstanding	Outstanding	Outstanding	Very High	Very High	Very High
MMC-UPQC	Outstanding	Outstanding	Excellent	Excellent	Outstanding	Very High	Excellent

4.7 Discussion

The comparative analysis indicates that conventional UPQC architectures remain attractive for industrial applications where operational simplicity and cost are primary considerations. However, increasing renewable penetration and widespread EV charging require multifunctional compensation systems capable of adaptive energy management. The localized strengths and engineering limits characterizing these topological classifications are outlined in Table 5.

Table 5: Advantages and Limitations of UPQC Topologies

Topology	Advantages	Limitations
Conventional	Simple, economical	No renewable support
PV-UPQC	Energy efficient	Solar intermittency
Wind-UPQC	High renewable penetration	Variable generation
Battery UPQC	Stable DC-link	High cost
Hybrid UPQC	Flexible energy management	Complex control
MMC-UPQC	Low THD, high efficiency	Expensive hardware

Hybrid Renewable UPQC and MMC-based architectures provide superior compensation capability and renewable utilization while offering enhanced scalability for future smart distribution networks. Nevertheless, these architectures require intelligent supervisory control to coordinate distributed energy resources effectively.

Future research should therefore focus on integrating AI-based predictive controllers with hybrid renewable-assisted UPQC architectures to achieve autonomous power quality management.

5. Renewable Energy and Electric Vehicle Integration with UPQC

5.1 Introduction

The global transition toward sustainable energy systems has accelerated the deployment of distributed renewable energy resources and electric vehicle charging infrastructure. While these technologies significantly reduce greenhouse gas emissions and dependence on fossil fuels, they simultaneously introduce substantial power quality challenges within distribution networks.

Renewable generation is inherently intermittent, whereas EV fast charging stations behave as highly nonlinear dynamic loads. Their simultaneous integration often results in voltage fluctuations, harmonic distortion, reactive power imbalance, and increased feeder congestion. Consequently, the Unified Power Quality Conditioner has emerged as a multifunctional

solution capable of maintaining grid stability while facilitating high renewable penetration and large-scale EV charging deployment.

5.2 UPQC in Renewable Energy Systems

The integration of renewable energy sources with UPQC enables simultaneous power conditioning and energy management.

Photovoltaic Systems

PV-assisted UPQC maintains DC-link voltage using surplus solar energy while compensating voltage disturbances and harmonic currents. This improves converter utilization and reduces dependency on grid-supplied active power.

Wind Energy Systems

Wind-integrated UPQC enhances voltage stability and reactive power compensation despite fluctuating wind conditions. Advanced forecasting and adaptive controllers are essential for maintaining stable operation.

Battery Energy Storage Systems

Battery-assisted UPQC provides energy buffering, supports transient compensation, enables peak shaving, and enhances renewable reliability. However, battery degradation, thermal management, and lifecycle costs remain important design considerations.

Hybrid Renewable Energy Systems

Combining solar PV, wind turbines, and battery storage with UPQC significantly improves energy reliability and grid resilience. Intelligent energy management algorithms are required to coordinate power flow among multiple distributed resources. Specialized algorithmic architectures utilizing gradient-boosted trees, meta-heuristic algorithms, and multi-objective optimization methods have been developed to balance multiple power flow variables simultaneously [51–55]. These frameworks allow for adaptive tuning parameters that drastically lower total harmonic distortion (THD) under uncertain grid conditions [56–60].

5.3 UPQC for Electric Vehicle Charging Stations

High-power EV chargers generate significant harmonic currents due to power electronic converters. These harmonics increase feeder losses, transformer heating, and voltage distortion.

A UPQC installed at the point of common coupling (PCC) can:

- suppress current harmonics,
- compensate reactive power,
- regulate supply voltage,
- maintain balanced three-phase currents,
- stabilize DC-link voltage.

Integration with Vehicle-to-Grid (V2G) technology further enables bidirectional power flow, allowing EV batteries to support voltage regulation, frequency control, and peak-load management. A high-level compatibility and performance overview of disparate micro-generation source types is mapped in Table 6.

Table 6: Comparison of Renewable Energy Sources Integrated with UPQC

Renewable Source	Grid Stability	Power Quality Improvement	Cost	Reliability	EV Compatibility
Solar PV	High	High	Moderate	Moderate	Excellent
Wind	Moderate	High	High	Moderate	Good
Battery Storage	Very High	Excellent	High	Excellent	Excellent
Fuel Cell	High	High	Very High	High	Good
Hybrid Renewable System	Outstanding	Outstanding	High	Outstanding	Outstanding

5.4 Emerging Research Trends

Emerging UPQC research is increasingly focused on:

- AI-assisted energy management,
- Digital twin-enabled monitoring,
- Edge computing,
- Cybersecure smart grids,
- IoT-based predictive diagnostics,
- Reinforcement learning controllers,
- Vehicle-to-Grid (V2G),
- Vehicle-to-Everything (V2X),
- Hardware-in-the-Loop validation,
- Cloud-integrated supervisory control.

These technologies are expected to transform UPQC from a reactive compensator into an autonomous, intelligent grid-support system capable of real-time optimization in future smart distribution networks.

6. Challenges and Open Issues in Intelligent UPQC for Renewable Energy Integrated EV Charging Stations

6.1 Introduction

Although Unified Power Quality Conditioner (UPQC) technology has demonstrated significant potential for mitigating power quality disturbances in modern smart distribution systems, several practical and technical challenges continue to limit its widespread industrial adoption. The increasing penetration of renewable energy resources, electric vehicle (EV) charging stations, distributed generation (DG), battery energy storage systems (BESS), and bidirectional power flow has transformed the operational requirements of UPQC from a conventional compensating device into an intelligent cyber-physical energy management system.

While numerous research studies have proposed advanced converter topologies, intelligent controllers, and renewable-assisted UPQC architectures, most investigations remain confined to simulation-based validation. Practical implementation issues—including converter cost,

computational complexity, hardware reliability, communication latency, interoperability, cybersecurity, standardization, and scalability—have received comparatively less attention. Addressing these challenges is essential for realizing next-generation autonomous UPQC systems capable of supporting future smart grids.

This section critically examines the major technical barriers, implementation challenges, and emerging research opportunities that define the future evolution of intelligent UPQC systems.

6.2 Converter Cost and Economic Feasibility

One of the primary obstacles to large-scale deployment of UPQC technology is the high capital cost associated with power electronic converters, semiconductor switches, passive filters, sensing circuits, digital controllers, and energy storage systems.

Advanced UPQC configurations incorporating multilevel converters, renewable energy sources, and battery storage significantly improve power quality and operational flexibility; however, these enhancements increase the overall investment cost and maintenance requirements. Furthermore, the incorporation of wide-bandgap semiconductor devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN) transistors, although improving efficiency and switching performance, further increases implementation cost. Consequently, balancing capital investment margins with maximum performance capabilities requires a detailed techno-economic evaluation of custom power sizing, filter capacitance values, and hardware implementation constraints [61–65].

Future research should therefore focus on cost-effective converter architectures, modular converter design, optimal sizing of DC-link capacitors, and techno-economic optimization methods capable of balancing performance improvements with practical affordability.

6.3 Controller Complexity and Computational Burden

The transition from conventional PI controllers toward Artificial Intelligence (AI)-based optimization has significantly enhanced UPQC compensation capability. Nevertheless, intelligent algorithms such as Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Model Predictive Control (MPC), Deep Reinforcement Learning (DRL), Long Short-Term Memory (LSTM), and Bi-directional LSTM (BiLSTM) require substantial computational resources.

Real-time implementation becomes increasingly challenging because these algorithms demand:

- large training datasets,
- high-speed processors,
- increased memory capacity,
- parallel computation,
- continuous parameter optimization.

Consequently, practical implementation on Digital Signal Processors (DSPs), Field Programmable Gate Arrays (FPGAs), and embedded microcontrollers remains an active research challenge.

Future intelligent UPQC controllers should therefore emphasize computational efficiency alongside compensation accuracy to enable real-time industrial deployment.

6.4 Hardware Implementation and Experimental Validation

A significant proportion of published UPQC research relies exclusively on MATLAB/Simulink simulations. Although simulation studies provide valuable insights into controller performance, they cannot fully capture practical issues including converter losses, switching delays, electromagnetic interference (EMI), sensor noise, thermal effects, communication delays, and hardware nonlinearities.

Experimental validation through:

- Hardware-in-the-Loop (HIL),
- Real-Time Digital Simulator (RTDS),
- OPAL-RT platforms,
- FPGA-based implementation,
- DSP controllers,
- laboratory-scale prototypes,

remains comparatively limited.

Future investigations should therefore prioritize experimental verification to improve technology readiness and facilitate industrial commercialization.

6.5 Communication Latency and Real-Time Control

The increasing deployment of IoT-enabled smart grids requires continuous communication among distributed energy resources, EV charging stations, renewable generators, battery storage systems, and supervisory control centers.

Communication delays arising from wireless networks, cloud computing, edge devices, and internet-based monitoring may significantly affect UPQC response time, leading to delayed compensation and degraded power quality performance.

Future UPQC architectures should incorporate:

- edge computing,
- distributed intelligence,
- low-latency communication protocols,
- adaptive synchronization algorithms,
- real-time communication scheduling.

These technologies can substantially improve compensation accuracy under rapidly changing operating conditions.

6.6 Cybersecurity and Data Privacy

The integration of UPQC into intelligent smart grids introduces significant cybersecurity challenges.

Modern UPQC systems exchange operational information with:

- smart meters,
- renewable energy controllers,
- battery management systems,
- EV charging infrastructure,
- cloud monitoring platforms.

Consequently, cyberattacks including:

- false data injection,
- denial-of-service attacks,
- spoofing,
- malware,
- unauthorized access,

may compromise controller decisions and threaten grid stability.

Despite increasing research on smart grid cybersecurity, relatively few studies have investigated secure UPQC architectures.

Future research should integrate:

- blockchain technology,
- encryption techniques,
- intrusion detection systems,
- AI-assisted cyberattack detection,
- secure communication protocols,

to improve operational resilience.

6.7 Interoperability and Smart Grid Integration

Future distribution systems will consist of numerous heterogeneous devices manufactured by different vendors.

Ensuring seamless interoperability among:

- distributed generators,
- renewable sources,
- battery storage systems,
- EV charging stations,
- distribution automation systems,
- SCADA,
- Advanced Metering Infrastructure (AMI),

represents a major implementation challenge.

Future UPQC systems should comply with international communication standards including:

- IEC 61850 Series (including the modern Edition data model configurations for scalable namespace and cyber-physical communication layout)
- IEC 61970
- IEEE 2030
- IEEE Std 1547-2018 (and ongoing P1547 revisions for advanced DER grid-support capabilities)
- OpenADR

to enable plug-and-play integration within intelligent smart grids.

6.8 Compliance with International Standards

Power quality improvement devices must satisfy numerous international standards governing harmonic distortion, voltage quality, safety, reliability, and interoperability.

Key standards include:

- IEEE Std 519-2022 (Standard for Harmonic Control in Electric Power Systems)
- IEEE Std 1547-2018 (and ongoing P1547 revisions for advanced DER grid-support capabilities)
- IEC 61000 (Electromagnetic Compatibility)
- IEC 61850 (Communication Networks)
- IEC 62116 (Islanding Detection)

Future UPQC controllers shall be evaluated against these mandatory limits under realistic operating conditions to guarantee strict compliance with modern grid compliance benchmarks.

6.9 Scalability for Future Smart Distribution Networks

Current UPQC implementations are generally designed for individual feeders or localized compensation.

However, future distribution systems will contain:

- thousands of EV charging stations,
- distributed renewable generators,
- microgrids,
- community battery storage,
- peer-to-peer energy trading,
- Vehicle-to-Grid (V2G),
- Vehicle-to-Everything (V2X).

Consequently, scalable hierarchical control architectures capable of coordinating multiple UPQC devices simultaneously will become essential.

Research should therefore focus on decentralized, distributed, and multi-agent control strategies supporting large-scale smart grid deployment.

6.10 Emerging Technologies and Future Research Opportunities

Several emerging technologies are expected to redefine UPQC research during the coming decade.

These include:

- Artificial Intelligence
- Deep Learning
- Reinforcement Learning
- Digital Twin Technology
- Edge Computing
- Internet of Things (IoT)
- Blockchain
- Federated Learning
- Explainable Artificial Intelligence (XAI)
- Quantum-inspired Optimization
- Digital Substations
- Software Defined Grid (SDG)

The convergence of these technologies may enable autonomous UPQC systems capable of predictive maintenance, adaptive optimization, fault diagnosis, self-healing operation, and intelligent energy management. The precise implementation barriers paired with promising technical countermeasures are systematically arranged in Table 7.

Table 7: Critical Challenges and Future Research Opportunities in Intelligent UPQC

Challenge	Current Limitation	Future Research Direction
High Converter Cost	Expensive semiconductor devices and battery storage	Modular converter design, cost optimization, SiC/GaN optimization
Controller Complexity	High computational burden	Lightweight AI algorithms, edge intelligence
Hardware Validation	Predominantly simulation-based studies	HIL, RTDS, FPGA, DSP implementation
Communication Latency	Delayed compensation	Edge computing, 5G/6G communication, Time-Sensitive Networking (TSN)
Cybersecurity	Vulnerability to cyberattacks	Blockchain, AI-based intrusion detection, secure protocols
Interoperability	Vendor-dependent communication	IEC 61850, IEEE 2030, OpenADR compliance
Standards Compliance	Limited real-world validation	IEEE 519, IEEE Std 1547-2018 (and ongoing P1547 revisions for advanced DER grid-support capabilities), IEC 61000 certification studies
Scalability	Localized compensation	Distributed multi-agent UPQC architectures
Renewable Coordination	Intermittent generation	AI-assisted energy management and forecasting
EV Charging Integration	Dynamic nonlinear loading	V2G/V2X coordination, adaptive charging strategies

6.11 Summary and Transition to Proposed Research Framework

The critical analysis presented in this section demonstrates that, despite significant progress in UPQC technology, several fundamental challenges continue to hinder its widespread deployment in renewable-integrated smart grids and EV charging infrastructures. Existing solutions often optimize isolated aspects such as harmonic mitigation or voltage regulation but seldom address computational efficiency, cybersecurity, interoperability, scalability, and real-time implementation in an integrated manner. The overall research maturity and commercial application parameters of these frameworks are evaluated in Table 8.

Table 8: Technology Readiness Assessment of Emerging UPQC Technologies

Technology	Research Maturity	Industrial Adoption	Future Potential
Conventional PI Control	High	High	Moderate
Fuzzy Logic Control	High	Medium	High
ANN-Based UPQC	Medium	Low	High
ANFIS Controller	Medium	Low	High
Model Predictive Control	Medium	Medium	Very High
Reinforcement Learning	Low	Very Low	Outstanding
Deep Learning (LSTM/BiLSTM)	Low	Very Low	Outstanding
Digital Twin-Based UPQC	Emerging	Very Low	Outstanding
IoT-Enabled Smart UPQC	Medium	Low	Outstanding
AI-Assisted Hybrid UPQC	Emerging	Very Low	Exceptional

These observations highlight the need for a next-generation intelligent UPQC architecture that combines advanced AI-driven control, renewable energy coordination, predictive analytics, secure communication, and hardware-oriented implementation. Accordingly, the following section proposes a comprehensive research framework that directly addresses the identified gaps and aligns with the objectives of this review and the proposed PhD research on AI-assisted UPQC integrated with EV charging stations for grid support and power quality enhancement in smart distribution networks.

7. Proposed Research Framework

7.1 Introduction

The critical analysis presented in the preceding sections demonstrates that existing Unified Power Quality Conditioner (UPQC) research primarily focuses on isolated objectives such as harmonic mitigation, voltage regulation, reactive power compensation, or renewable energy integration. Although significant progress has been achieved through advanced converter topologies and intelligent control algorithms, several important challenges—including computational complexity, renewable intermittency, communication latency, cybersecurity, scalability, and real-time implementation—remain unresolved.

To address these limitations, this review proposes a next-generation AI-assisted Intelligent Unified Power Quality Conditioner (AI-UPQC) framework specifically designed for renewable energy-integrated Electric Vehicle (EV) charging stations in smart distribution

networks. Unlike conventional UPQC systems that rely solely on reactive compensation, the proposed framework combines hierarchical data acquisition, hybrid AI-based control, predictive optimization, renewable energy management, battery energy storage coordination, and cloud-enabled intelligent monitoring.

The proposed framework is intended as a conceptual roadmap for future research and requires validation through simulation and experimental studies.

7.2 Proposed Intelligent AI-UPQC Architecture

The proposed architecture consists of six coordinated functional layers operating under a hierarchical intelligent control strategy.

Layer 1 – Smart Grid Data Acquisition

The first layer continuously acquires electrical and operational measurements from both the grid and connected assets.

Input parameters include:

- Source Voltage (V_s)
- Source Current (I_s)
- Load Voltage (V_L)
- Load Current (I_L)
- DC-Link Voltage (V_{dc})
- Active Power (P)
- Reactive Power (Q)
- Frequency (f)
- Total Harmonic Distortion (THD)
- Solar Irradiance
- Wind Speed
- Battery State of Charge (SOC)
- EV Charging Demand

This layer establishes a comprehensive real-time dataset for intelligent decision-making.

Layer 2 – Signal Processing and Feature Extraction

The acquired measurements are pre-processed using digital signal processing techniques to improve measurement quality and reduce noise.

Major operations include:

- Clarke Transformation
- Park Transformation
- Fast Fourier Transform (FFT)
- Wavelet Transform
- Harmonic Spectrum Analysis
- RMS Estimation
- Voltage Sag/Swell Detection
- THD Calculation
- Load Pattern Identification

Beyond traditional signal transformations, Layer 2 serves a critical cyber-defense function by conducting continuous anomaly detection on incoming grid metrics. To mitigate the risk of False Data Injection (FDI) and Denial-of-Service (DoS) attacks on the communication network, incoming measurements—specifically source voltages (V_s), source currents (I_s) and DC-link tracking vectors—are subjected to statistical bounds checking and raw temporal variance analysis. Any malicious data artifacts or anomalous feature patterns from corrupted sensor streams are automatically flagged and isolated at this pre-processing stage. This prevents manipulated signals from propagating downstream into the Layer 3 Fuzzy-BiLSTM controller, ensuring robust, stable, and deterministic compensation behaviour even under active cyber-threats.

Layer 3 – AI-Based Intelligent Controller

This layer forms the core of the proposed research framework.

Unlike conventional PI controllers, the proposed system employs a hybrid Fuzzy Logic Controller–BiLSTM (FLC–BiLSTM) optimization strategy.

The controller performs:

- DC-link voltage regulation
- Harmonic prediction
- Voltage sag compensation
- Reactive power optimization
- Adaptive controller tuning
- Renewable power forecasting
- Predictive load estimation
- Switching signal generation

The fuzzy controller manages nonlinear uncertainty, while the BiLSTM network captures temporal dependencies in load and renewable generation patterns.

Layer 4 – Intelligent Power Management System

The intelligent energy management layer coordinates multiple distributed energy resources.

Components include:

- Solar PV System
- Wind Turbine
- Battery Energy Storage System (BESS)
- EV Charging Station
- Vehicle-to-Grid (V2G)
- Vehicle-to-Everything (V2X)

This layer optimizes energy flow among renewable sources, storage systems, and grid-connected loads while maintaining DC-link voltage stability.

Layer 5 – Advanced UPQC Compensation

The compensation layer consists of:

Series Active Power Filter

Functions:

- Voltage Sag Compensation
- Voltage Swell Compensation
- Flicker Mitigation
- Voltage Balancing

Shunt Active Power Filter

Functions:

- Harmonic Elimination
- Reactive Power Compensation
- Load Current Balancing
- Neutral Current Compensation

Both converters share a common DC-link capacitor and are controlled by the AI optimization layer.

Layer 6 – Smart Monitoring and Predictive Maintenance

The highest layer provides intelligent supervisory functions including:

- Cloud Monitoring
- IoT Communication
- Digital Twin
- Fault Diagnosis
- Predictive Maintenance
- Cybersecurity Monitoring
- Energy Analytics
- Remote Operation

This layer transforms the UPQC into a cyber-physical intelligent power quality management system. The operational layering and structural data interfaces tracking these grid signals are modeled in Figure 2.

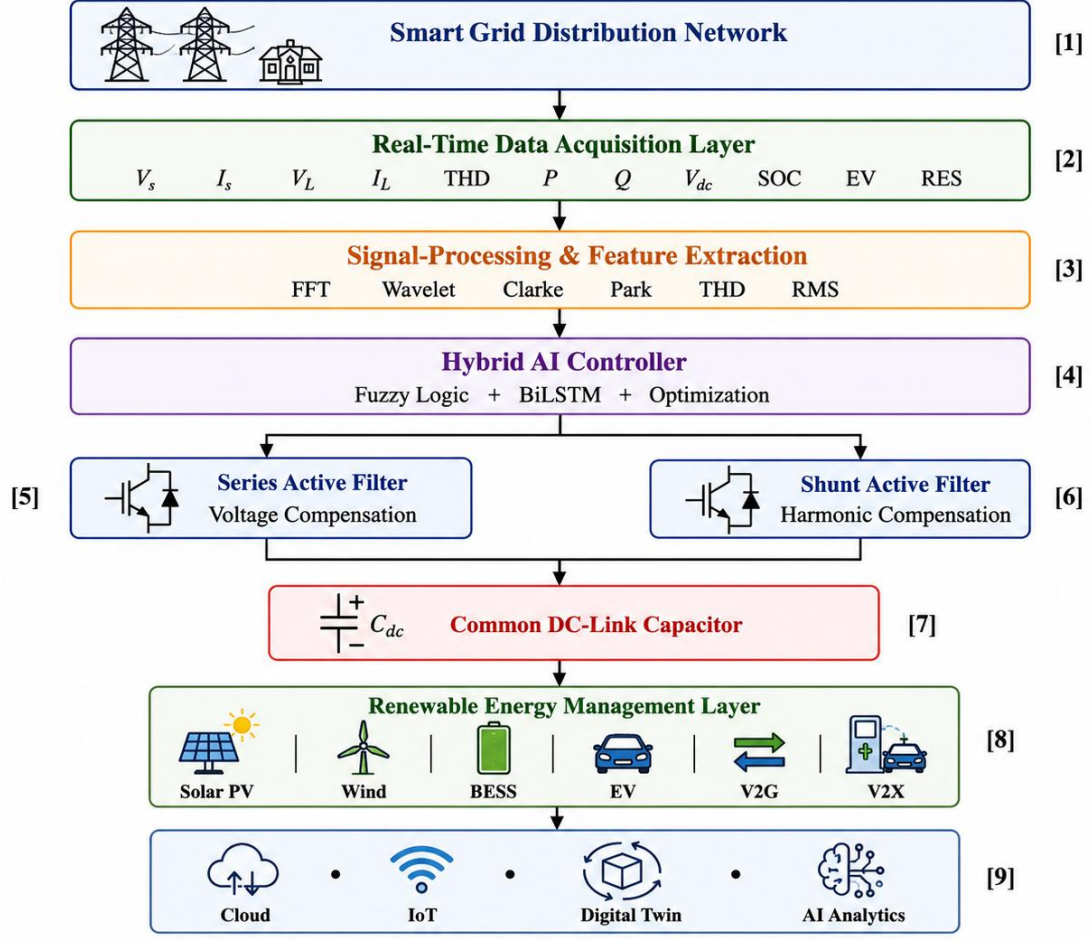


Fig. 2. Proposed AI-Assisted Intelligent UPQC Framework

7.3 Mathematical Formulation

The proposed intelligent UPQC simultaneously compensates voltage and current disturbances across the smart distribution network. The operational dynamics are governed by the following mathematical sub-mechanisms:

7.3.1 Series APF Voltage Compensation

The Series Active Power Filter (SAPF) injects a compensating voltage vector to eliminate supply-side voltage anomalies such as sags, swells, or flickers:

$$V_{inj}(t) = V_{ref}(t) - V_s(t)$$

where

- $V_s(t)$ = Instantaneous Source Voltage vector
- $V_{ref}(t)$ = Ideal Target Reference Voltage vector

7.3.2 Shunt APF Current Compensation

The Shunt Active Power Filter (ShAPF) injects a tracking current vector at the point of common coupling to neutralize load-side harmonics and reactive power imbalances:

$$I_{sh}(t) = I_L(t) - I_s(t)$$

where

- $I_L(t)$ = Non-linear Dynamic Load Current vector
- $I_s(t)$ = Ideal Sinusoidal Source Current vector

7.3.3 AI Controller Predictive Mechanism

To actively regulate the system under stochastic operating states, the forward hidden layer ($\vec{h}_t$) and backward hidden layer ($\overleftarrow{h}_t$) states of the Bidirectional Long Short-Term Memory (BiLSTM) network are concatenated to form the consolidated temporal feature space matrix (H_t):

$$H_t = [\vec{h}_t, \overleftarrow{h}_t]$$

The final real-time predictive loss coefficient calculation ($p_{dc_loss}(t)$) integrates the continuous sequential memory tracking of the BiLSTM with the immediate corrective reasoning of the fuzzy logic loop:

$$P_{dc_loss}(t) = W_y \cdot H_t + b_y + i_{flc}(t)$$

where W_y represents the output layer optimized weight matrix, b_y denotes the Multi-dimensional bias vector and $i_{flc}(t)$ dynamic linguistic compensation signal generated by the Fuzzy Logic Controller stage. This variable functions as a real-time algebraic scaling adder, shifting the network's predictive tracking line to rapidly counteract immediate DC-link voltage fluctuations caused by solar/wind intermittency.

7.3.4 DC-Link Voltage Governing Equation

The instantaneous tracking balance of the shared DC-link capacitor voltage is governed by the structural energy differential:

$$\frac{dV_{dc}}{dt} = \frac{P_{series} + P_{renewable} - P_{load}}{C_{dc}V_{dc}}$$

where

- C_{dc} = Physical capacitance value of the common DC-link energy buffer
- P_{series} , $P_{renewable}$, P_{load} = Active power metrics tracked across the series converter, integrated micro-generation arrays and dynamic network loads respectively.

7.3.5 Multi-Objective Optimization Function

To achieve integrated multi-objective power quality enhancement, the controller continuously runs a minimization routine on the total system cost index (J):

$$J = w_1 THD + w_2 t_s + w_3 |V_{dc} - V_{dc}^*| + w_4 P_{loss} + w_5 E_{grid}$$

where ω_1 , ω_2 , ω_3 , ω_4 and ω_5 represent user-defined weighting coefficients designed to prioritize specific grid performance parameters. The parameter metrics are defined as:

- THD = Total Harmonic Distortion of the grid current
- t_s = Dynamic controller tracking settling time
- $[V_{dc} - V^*_{dc}]$ = Absolute tracking error between actual and reference DC-link voltages
- P_{loss} = Total active power switching and transmission losses within the converters
- E_{grid} = Net auxiliary active energy demanded from the primary utility grid

This function is minimized subject to the following continuous system operational boundaries:

- Mandatory IEEE Std 519-2022 harmonic distortion limits (THD < 3%)
- Voltage regulation constraints ($\pm 5\%$) under standard IEC 61000 benchmarks
- Converter switching limits dictated by safe thermal and semiconductor boundaries
- Battery SOC limits ($20\% \leq SOC \leq 80\%$) to prolong auxiliary storage lifespans.

7.4 Proposed AI-Assisted Hybrid UPQC Framework

The structural layout and interactive control nodes tracking reference signal profiles across the power electronics buffer are visually detailed in Figure 3.

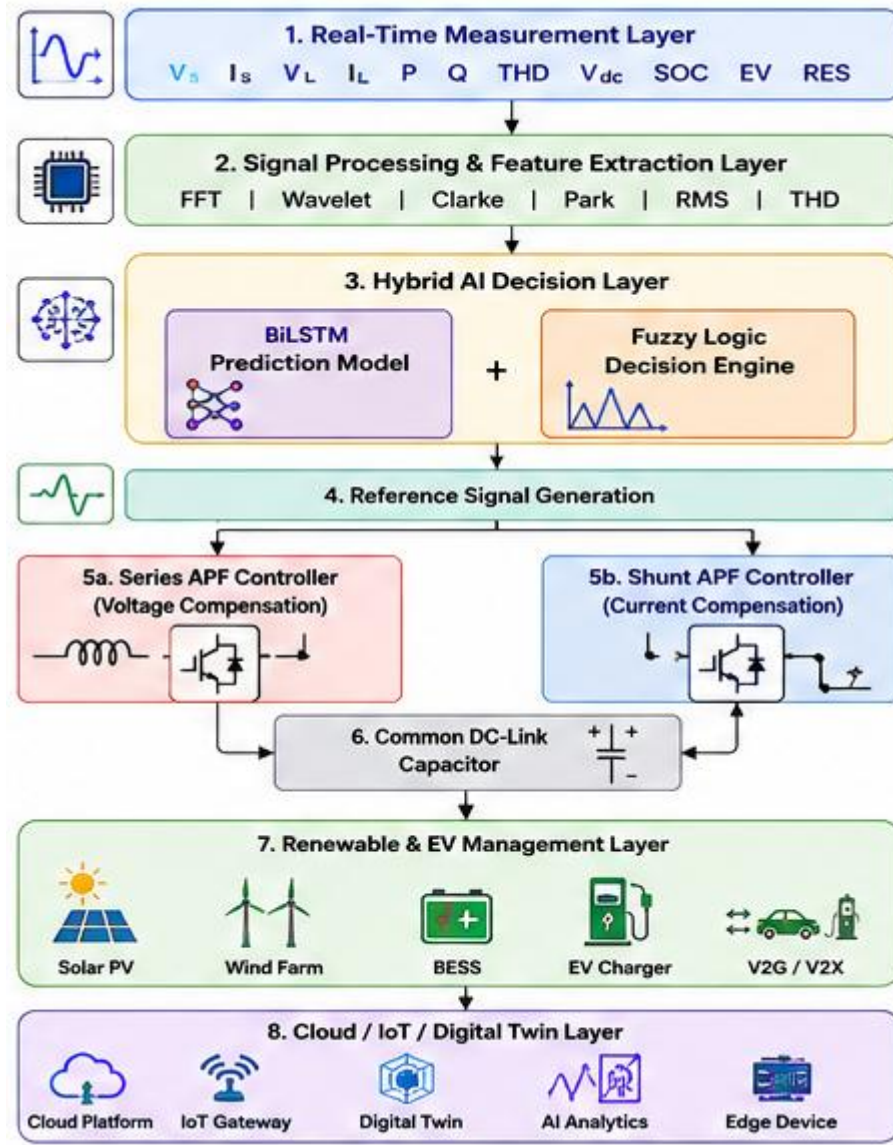


Fig. 3. Conceptual Architecture of the Proposed AI-Assisted Hybrid FLC–BiLSTM UPQC Framework

7.4.1 Conceptual Operational Workflow

Algorithm 1. Conceptual Operational Workflow of the Proposed AI-Assisted Hybrid FLC–BiLSTM UPQC Framework

Input:

- Grid voltage (V_s)
- Grid current (I_s)
- Load voltage (V_L)

- Load current (I_L)
- Renewable power (PV/Wind)
- Battery State of Charge (SOC)
- EV charging demand
- DC-link voltage (V_{dc})

Output:

- Series APF reference voltage
- Shunt APF reference current
- DC-link voltage regulation
- Improved power quality

Step 1: Acquire real-time measurements from the smart distribution network.

Step 2: Preprocess the measured signals by filtering noise and calculating RMS values, THD, and power parameters.

Step 3: Extract significant features using signal processing techniques such as FFT, Wavelet Transform, Clarke Transform, or Park Transform.

Step 4: Predict future load demand and renewable generation using the BiLSTM prediction model.

Step 5: Evaluate power quality conditions through the fuzzy inference engine.

Step 6: Generate optimal reference voltage and current signals based on the combined outputs of the BiLSTM predictor and fuzzy controller.

Step 7: Apply the reference voltage to the Series Active Power Filter (SAPF) for voltage compensation.

Step 8: Apply the reference current to the Shunt Active Power Filter (ShAPF) for harmonic mitigation and reactive power compensation.

Step 9: Maintain the DC-link capacitor voltage within the desired operating range.

Step 10: Monitor system performance by evaluating THD, voltage profile, power factor, and system stability.

Step 11: If THD exceeds IEEE 519 limits, update controller parameters through the optimization module; otherwise continue normal operation.

Step 12: Repeat the process continuously for real-time operation.

Algorithm 1 presents the conceptual operational workflow of the proposed AI-assisted Hybrid FLC–BiLSTM UPQC framework for renewable energy and EV-integrated smart distribution networks. The workflow begins with the acquisition of real-time electrical measurements, including grid voltage, grid current, load voltage, load current, DC-link voltage, renewable energy generation, battery state of charge, and EV charging demand. These measurements are preprocessed using digital signal processing techniques to remove noise and extract essential features such as RMS values, harmonic distortion, and power quality indices. The extracted features are then processed by the hybrid AI controller, where the BiLSTM network predicts future load demand and renewable energy availability, while the fuzzy inference system evaluates the prevailing power quality conditions and determines appropriate control actions. Based on these outputs, optimal reference voltage and current signals are generated for the Series Active Power Filter (SAPF) and Shunt Active Power Filter (ShAPF) to compensate voltage disturbances, mitigate harmonics, improve reactive power compensation, and maintain the DC-link capacitor voltage within its desired operating range. The renewable energy management layer further coordinates the operation of photovoltaic systems, wind generation, battery energy storage systems, EV charging infrastructure, and V2G/V2X functionalities to ensure efficient power flow and energy utilization. Continuous monitoring of power quality indices, including total harmonic distortion (THD), enables adaptive controller optimization whenever performance deviates from prescribed standards such as IEEE 519. Finally, cloud computing, Internet of Things (IoT), digital twin technology, and AI-driven analytics facilitate real-time monitoring, predictive maintenance, intelligent decision-making, and overall system reliability. This operational workflow is presented as a conceptual research framework to illustrate a potential implementation strategy and guide future investigations into intelligent UPQC control for next-generation smart distribution networks. The comprehensive step-by-step logic loop, threshold checking paths, and diagnostic milestones are mapped sequentially in Figure 4.

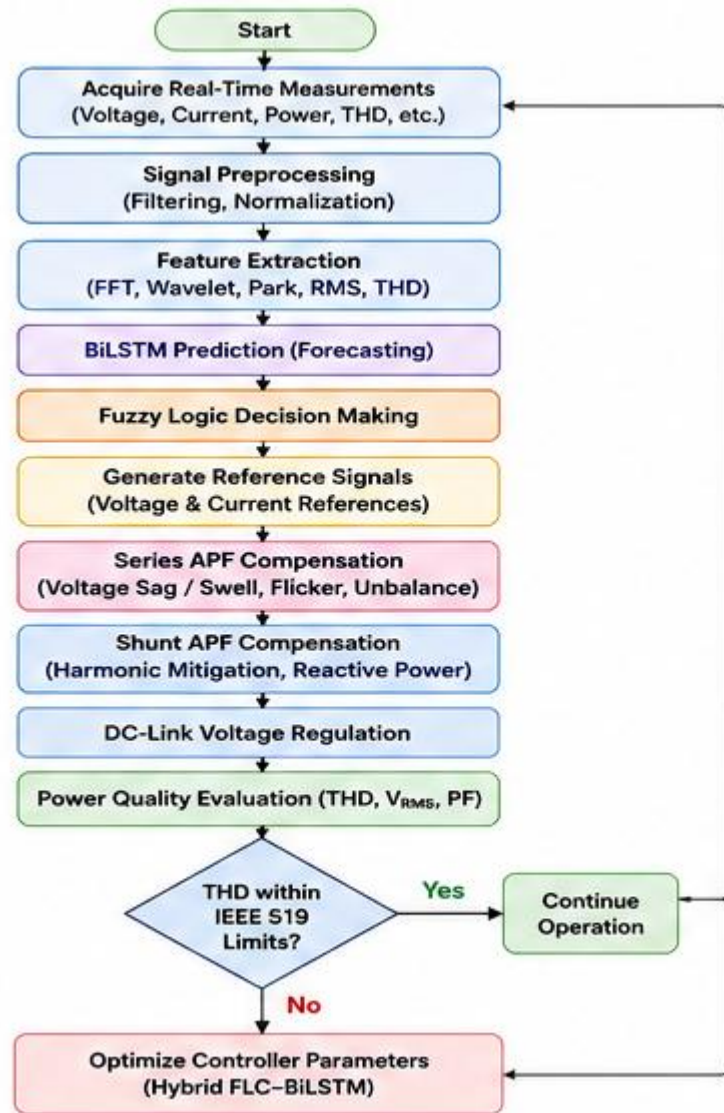


Fig. 4. Conceptual Operational Workflow of the Proposed AI-Assisted Hybrid FLC–BiLSTM UPQC Framework

7.5 Validation Methodology

The proposed framework should be evaluated using a progressive validation strategy. The exact hardware-in-the-loop and laboratory-scale validation pathway mapping this developmental timeline is mapped out in Figure 5.

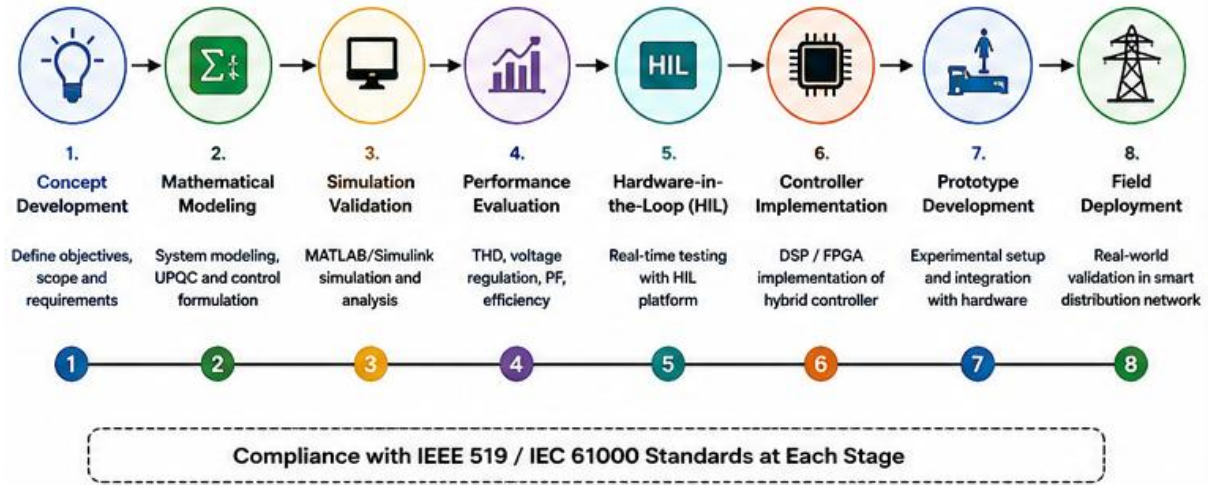


Fig. 5. Validation Roadmap for the Proposed AI-Assisted Hybrid UPQC Framework

Table 9: Proposed Performance Evaluation Metrics

Parameter	Target Value	Standard
THD	< 3%	IEEE 519
Voltage Regulation	$\pm 5\%$	IEC 61000
Power Factor	>0.99	IEEE
DC-Link Ripple	<2%	Design Target
Settling Time	<2 ms	Proposed Target
Voltage Sag Compensation	>98%	Design Target
Reactive Power Compensation	>95%	Design Target
Converter Efficiency	>97%	Design Target

The performance targets outlined in Table 9 are established based on stringent international grid compliance standards and contemporary state-of-the-art literature benchmarks. Specifically, maintaining the Total Harmonic Distortion (THD) below 3% ensures strict adherence to IEEE Std 519-2022 (Section 5), which mandates rigorous current and voltage distortion limits at the Point of Common Coupling (PCC) to prevent transformer overheating and distribution feeder degradation. The voltage regulation constraint of $\pm 5\%$ is aligned with IEC 61000-3-2 and IEC 61000-3-4 guidelines for electromagnetic compatibility, ensuring smart distribution network stability under high-power, non-linear EV fast-charging loads.

Furthermore, achieving a unity power factor (>0.99) and a target converter efficiency exceeding 97% reflects optimal reactive power compensation and the superior performance

capabilities of wide-bandgap (SiC/GaN) power electronics topologies managed by intelligent control loops. The proposed settling time target of less than 2 ms represents a key operational improvement over conventional PI controllers, providing the ultra-fast transient response necessary to buffer stochastic renewable power fluctuations and dynamic load steps.

7.6 Expected Contributions

The proposed framework is expected to contribute:

- A hierarchical AI-assisted UPQC architecture for renewable-integrated smart grids.
- Hybrid FLC–BiLSTM control for adaptive harmonic mitigation and DC-link regulation.
- Coordinated energy management across PV, wind, BESS, EV charging, V2G, and V2X.
- A pathway for integrating IoT, cloud monitoring, digital twins, and predictive maintenance into UPQC systems.
- A validation roadmap from simulation through HIL to laboratory prototype implementation.

7.7 Transition to Conclusion

The proposed framework synthesizes the research gaps identified throughout this review into a coherent architecture for future investigation. Rather than introducing experimentally verified performance, it outlines a technically plausible research direction that integrates intelligent control, renewable energy management, and advanced monitoring technologies. The subsequent conclusion should summarize the key findings of the review, reiterate the identified research opportunities, and emphasize the need for rigorous simulation and experimental validation of the proposed AI-assisted UPQC framework.

8. Conclusion and Future Research Directions

8.1 Conclusion

The rapid expansion of renewable energy resources, electric vehicle (EV) charging infrastructure, and intelligent smart grids has fundamentally transformed the operational requirements of modern electrical distribution systems. While these technologies contribute significantly toward sustainable energy development, they simultaneously introduce numerous power quality challenges, including harmonic distortion, voltage sag and swell, reactive power imbalance, voltage fluctuations, and dynamic load variations. Consequently, the Unified Power Quality Conditioner (UPQC) has emerged as one of the most promising custom power devices capable of simultaneously mitigating both current- and voltage-related disturbances.

This review has presented a comprehensive and critical analysis of recent advances in UPQC technologies for renewable energy-integrated smart distribution networks and EV charging stations. Unlike conventional survey papers that summarize previous work sequentially, the present review critically evaluated existing research based on controller performance, converter topology, renewable energy integration, intelligent optimization techniques, implementation complexity, scalability, and practical deployment challenges.

The review demonstrates that conventional control strategies such as Proportional–Integral (PI), Synchronous Reference Frame (SRF), Instantaneous Reactive Power (p–q) theory, and Hysteresis Current Control remain attractive due to their simplicity and industrial maturity. However, these approaches exhibit limited adaptability under nonlinear loading conditions, renewable intermittency, and rapidly changing operating environments.

Recent developments in Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Model Predictive Control (MPC), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Reinforcement Learning (RL), and hybrid intelligent controllers have significantly enhanced UPQC performance. These advanced control techniques demonstrate improved harmonic suppression, faster transient response, adaptive voltage regulation, predictive compensation, and enhanced renewable energy utilization. Nevertheless, widespread industrial implementation remains constrained by computational complexity, hardware limitations, communication latency, cybersecurity concerns, and insufficient experimental validation.

The comparative analysis of UPQC topologies further indicates that renewable-assisted and multilevel converter-based architectures provide substantial improvements in power quality compensation, energy efficiency, and operational flexibility compared with conventional configurations. In particular, hybrid renewable energy-assisted UPQC systems integrating photovoltaic generation, wind energy, battery energy storage systems (BESS), and Vehicle-to-Grid (V2G) technologies offer significant potential for supporting future smart distribution networks. However, effective coordination among distributed energy resources continues to require intelligent supervisory control and advanced energy management algorithms.

This review also identified several critical research gaps that have received comparatively limited attention in existing literature. These include the development of computationally efficient AI-based controllers, integration of digital twin technologies, cybersecurity-aware UPQC architectures, hardware-in-the-loop validation, standardized benchmarking methodologies, scalable multi-agent coordination strategies, and cloud-enabled predictive maintenance. Addressing these challenges will be essential for transitioning UPQC systems from conventional power conditioning devices into intelligent cyber-physical platforms capable of autonomous operation within future smart grids.

To bridge these gaps, a novel AI-assisted intelligent UPQC research framework has been proposed. The framework integrates hierarchical sensing, advanced signal processing, hybrid Fuzzy Logic Controller–BiLSTM optimization, renewable energy management, intelligent EV charging coordination, IoT-enabled monitoring, digital twin technology, and predictive maintenance into a unified architecture. Although conceptual in nature, this framework establishes a comprehensive roadmap for future investigations aimed at improving power quality, operational resilience, renewable energy utilization, and grid reliability.

Overall, this review demonstrates that the future evolution of UPQC technology lies not merely in improving harmonic compensation performance but in developing intelligent, adaptive, predictive, and autonomous energy management systems capable of supporting the increasing complexity of next-generation smart distribution networks.

The proposed AI-assisted UPQC framework provides a promising roadmap toward resilient, intelligent, and sustainable smart distribution networks, while experimental validation and real-time implementation remain important directions for future research.

8.2 Future Research Directions

Based on the critical evaluation presented throughout this review, several promising research directions are identified for future investigation. The complete target grid infrastructure model linking cloud intelligence arrays with physical distribution networks is illustrated in Figure 6.

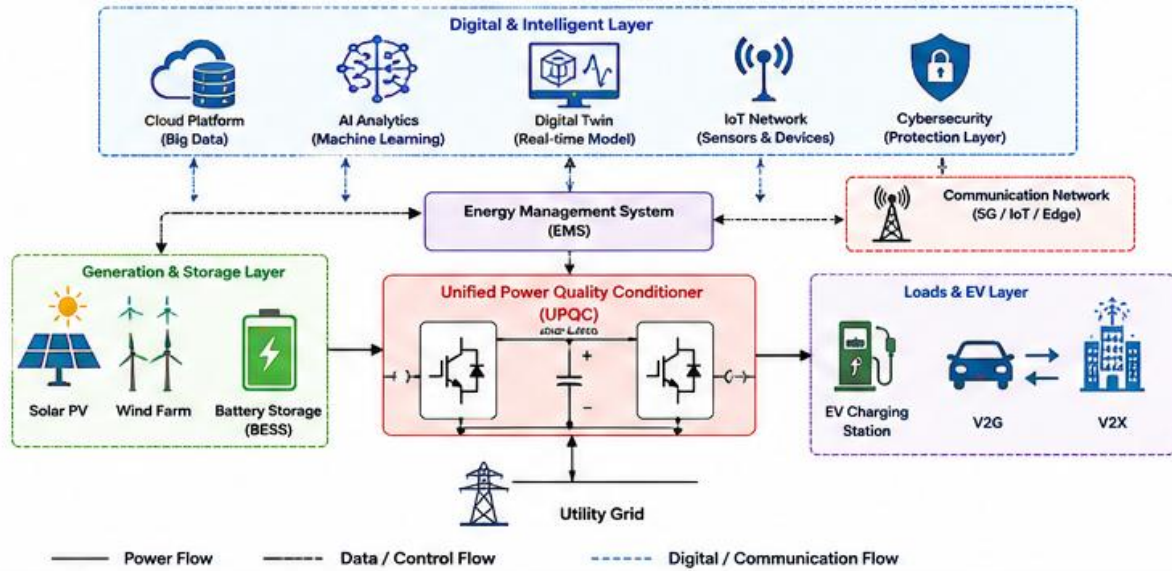


Fig. 6. Future Intelligent Smart Distribution Network with AI, IoT, Digital Twin and V2G/V2X Integration.

1. Artificial Intelligence-Driven Adaptive UPQC Controllers

Future research should focus on the integration of Explainable Artificial Intelligence (XAI), Deep Reinforcement Learning (DRL), Transformer Networks, Graph Neural Networks (GNNs), and federated learning to develop adaptive controllers capable of learning from continuously changing operating conditions while maintaining computational efficiency and transparency.

2. Digital Twin-Based Intelligent Power Quality Management

The application of digital twin technology provides an opportunity to create virtual replicas of UPQC systems for real-time monitoring, predictive maintenance, fault diagnosis, and operational optimization. Integrating digital twins with cloud computing and edge intelligence may significantly enhance system reliability while reducing maintenance costs.

3. Renewable Energy and Multi-Energy Coordination

Future UPQC architectures should support coordinated operation among photovoltaic systems, wind turbines, hydrogen fuel cells, battery energy storage systems, supercapacitors, and distributed generators. Intelligent energy management algorithms capable of optimizing power flow under uncertain renewable generation conditions represent an important research direction.

4. Vehicle-to-Grid (V2G) and Vehicle-to-Everything (V2X) Integration

The increasing penetration of electric vehicles provides an opportunity to utilize EV batteries as distributed energy storage resources. Future UPQC systems should incorporate intelligent

V2G and V2X coordination strategies capable of supporting voltage regulation, frequency stabilization, peak-load management, and emergency power support while minimizing battery degradation.

5. Edge Computing and Low-Latency Communication

The effectiveness of intelligent UPQC systems increasingly depends on real-time communication among distributed devices. Future studies should investigate edge computing architectures, Time-Sensitive Networking (TSN), 5G/6G communication technologies, and decentralized decision-making algorithms to reduce communication latency and improve responsiveness.

6. Cybersecurity-Aware UPQC Architectures

As UPQC systems become more interconnected, cybersecurity will play a critical role in ensuring operational reliability. Future work should integrate blockchain technologies, AI-based intrusion detection systems, secure communication protocols, and privacy-preserving data analytics to protect smart grid infrastructures against cyber threats.

7. Hardware-in-the-Loop and Real-Time Validation

Most existing studies remain limited to software simulations. Future research should emphasize Hardware-in-the-Loop (HIL) testing, Real-Time Digital Simulation (RTDS), FPGA implementation, DSP-based controllers, and laboratory-scale prototypes to validate proposed algorithms under realistic operating conditions and improve technology readiness.

8. Sustainable and Cost-Effective UPQC Design

Further research is required to reduce implementation cost through modular converter architectures, optimized semiconductor utilization, lightweight AI algorithms, and efficient battery management strategies. Techno-economic analysis should accompany future controller development to facilitate industrial adoption.

9. Standardization and Interoperability

Future intelligent UPQC systems should be designed to comply with international standards such as IEEE 519, IEEE 1547, IEC 61000, and IEC 61850. Standardized communication protocols and benchmarking methodologies will facilitate interoperability among heterogeneous devices within smart distribution networks.

10. Proposed PhD Research Direction

Based on the identified research gaps, future work will focus on the development of an AI-assisted Hybrid FLC–BiLSTM Optimized Unified Power Quality Conditioner integrated with Renewable Energy Sources and Electric Vehicle Charging Stations for Smart Distribution Networks. The proposed research aims to achieve:

- Adaptive harmonic mitigation with THD maintained below IEEE 519 limits.
- Fast DC-link voltage stabilization through intelligent predictive control.
- Coordinated management of solar PV, wind energy, battery storage, and EV charging.
- Enhanced grid support through Vehicle-to-Grid (V2G) operation.
- Integration of IoT-based monitoring, digital twins, and predictive maintenance.
- Validation using MATLAB/Simulink, Hardware-in-the-Loop (HIL), and experimental prototype implementation.

This research direction seeks to advance UPQC technology beyond conventional compensation toward a fully intelligent, resilient, and sustainable power quality management system suitable for future smart grids.

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