Power Quality Enhancement in Renewable-Integrated Smart Grids Using Unified Power Quality Conditioners: A Review

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Abstract: *Over the last few decades, renewable energy sources gained significant attention that still continues today. Whether it be for solar or wind energy, conventional analyses considered these as intermittent sources of power, causing several power-quality issues in the respective power systems, such as harmonics, voltage distortion, or stability. The UPQC has extremely convenient features, and so, it is considered a suitable custom power device offering mitigation for these disturbances; however, conventional setups of a UPQC cannot sufficiently remain adaptable under intermittency of the renewable source. Recently, major research has been directed to modifying UPQC configurations through the injection of distributed generation (DG) sources for renewable applications, mainly solar PV and wind energy, at the DC common link. This review paper attempts to discuss in detail the above-mentioned modifications with respect to their contributions for DC link voltage support, harmonic mitigation, load compensation, and overall system efficiency. A critical evaluation concerning the control strategies for series and shunt converters is conducted in terms of their application toward hybrid renewable-based UPQC systems. Afterwards, a comparative study on the investigated approaches is given with regard to their advantages and disadvantages, as well as current technological trends. Among others, this review identifies a few key research gaps regarding scalability, dynamic performance, and real-time implementation and discusses the future perspectives that appear promising toward designing robust and energy-efficient UPQC architectures for smart grid applications.*

Keywords: *Solar PV, Wind Energy, Distributed Generation, Power Quality, DC Link Integration , Smart Grid*

I. INTRODUCTION

The Unified Power Quality Conditioner is a custom power device that mitigates power quality issues related to voltage and current simultaneously [14]. By combining the functions of DVR and D-STATCOM, UPQC provides voltage stability [15], and reactive power support. Fast dynamic response and capability to mitigate multiple disturbances make it very much important for existing and future distribution systems [16].Figure 1. describes unified power quality conditioner

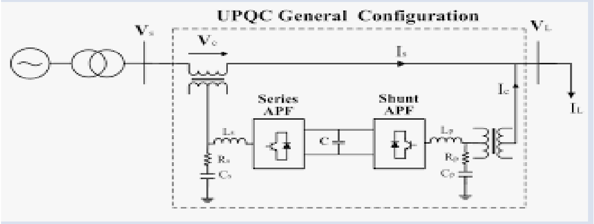

Figure 1: Unified Power Quality Conditioner

The basic configuration of a UPQC essentially comprises two voltage source converters (VSCs), one series and one shunt, interlinked by a common DC link-capacitor. The series converter, working together with series injection transformers [17], is connected between the source and the load. Its main function is to keep the voltage on the load-side at desired conditions by compensating for sags, swells, and distortions. The shunt converter operates in parallel with the load and carries out current-related compensations like for harmonics, unbalance, or reactive power demand [18]. The DC link acts as an energy storage element, maintaining constant voltage so that power can flow back and forth between the series and shunt converters optimally [19]. When operated in coordination, they serve as a very efficient power quality treatment. In more modern variations, the DC link could be associated with distributed generation resources, solar, or wind energy-based, thus further improving the UPQC and reducing the dependency on the utility grid [20].

Solar Photovoltaic Systems work on the principle of sunlight conversion into electricity by semiconductor materials, usually silicon. When sunlight, comprising photons, strikes the surface of the PV cell, the photons transfer energy to the electrons present in the semiconductor [32]. Such energy excites the electrons so that they can overcome the binding forces within the atoms and move freely in the material [33]. The movement is made use of by the solar cell, which has two layers of semiconductor forming a p-n junction: one having a positive charge, that is, p-type, and the other has a negative charge that is, n-type. The free electrons are pushed away by the electric field that exists at the junction toward an

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external circuit where they provide a flow of direct current (DC) [34].Figure 2 describes block diagram solar photovoltaic system.

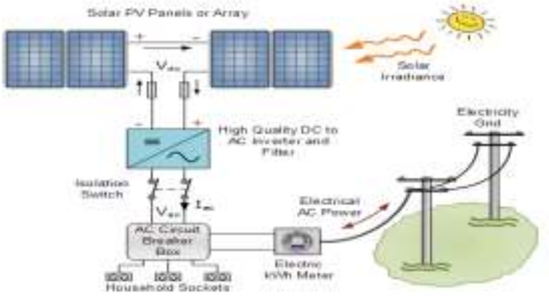

Figure 2: Solar Photovoltaic System Block Diagram

In order to increase power output, multiple PV cells are connected into modules, and several modules are combined into arrays. Because most electrical appliances and grid systems operate on the principle of alternating current (AC), an inverter is used to convert its DC output into AC [35]. In standalone systems, charge controllers and storage batteries may also be incorporated to regulate power flows and store energy when the system generates more power than it consumes. Thus, the choice of solar PV technology provides a clean, renewable, and efficient way to generate electricity, conserving nature for other uses [36].

Wind turbine systems work on the principle of transferring the kinetic energy of the wind into mechanical and then electrical energy. When wind passes over the blades, it causes lift, permitting the rotor to rotate [40]. The rotor transmits mechanical energy to a low-speed shaft connected to a gearbox. Because of an increase in the rotational speed in the gearbox, the high-speed shaft drives the generator. The generator produces the electrical energy, usually in the form of alternating current (AC), from this mechanical energy [41].Figure 3describes working principle of wind turbine systems.

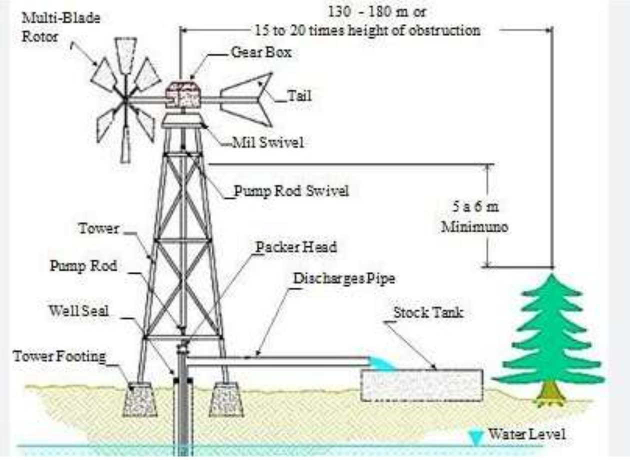

Figure 3 :Working Principle of Wind Turbine Systems

Modern wind turbines come with control and protection systems designed to optimize their performance. Yaw mechanisms turn the turbine into the wind, while pitch control adjusts the blades to either speed up the rotation or slow it down, generating more or less power [42]. For variable wind-speed operation, a power electronic converter stabilizes frequency and voltage before interfacing with the grid. In distributed generation, smaller wind turbines could be installed on a remote site, an industrial site, or in a residential area for local distribution [43].

II. INTEGRATION OF RENEWABLE ENERGY SOURCES WITH UPQC

In recent years, the integration of renewable energy into UPQC systems has been studied with greater sobriety to address power quality issues in modern grids. In reference [1], a Wind-PV integrated-UPQC with dual-compensation was proposed to tackle sag, swell, and harmonic distortions, as well as power factor correction for grid-connected distributed generation systems, even though the study remained on simulation-based methods with ideal assumptions. By contrast, in reference [2], a neural-network-based PV-Battery UPQC was proposed, and was shown to be better than the conventional SRF and p-q controls under nonlinear and unbalanced load conditions; however, its robustness and ability to mature during unseen disturbances and real-time uncertainties remained to be tested. In line with smart control, [3] introduced a PV-UPQC with multilevel inverters using resilient backpropagation neural networks and showed better dynamic responses, but it has never been benchmarked against adaptive or predictive control or considered grid code compliance. For the distribution level, [4] described a 10 kW PV-UPQC with the BESS support, together with design specification and PQ improvements, but the work appeared to emphasize much about feasibility and less on experimental validations. On a different note, [5] showed PV-integrated UPQC using series-shunt VSCs for sag, swell, and harmonic compensation; however, the paper confined itself mostly to preliminary conference presentations and never explored sensitivity or scalability issues. From the hardware standpoint, [6] designed and tested a single-stage PV-UPQC that tackled irradiance variation, unbalanced loads, and PCC voltage issues successfully, but validation was limited to lab-scale studies with no emphasis on efficiency or thermal analyses. Complementarily, [7] explored a PV-BESS-supported UPQC concept, demonstrating DC-link continuity and compensation support, but lacked detailed controller design and quantitative PQ performance metrics. [8] further continued with the PV-integrated UPQC with SRF-based control to improve PQ in distribution feeders but did not consider practical issues of grid-impedance variation, delays whatsoever. Regarding wind integration, [9] demonstrated that UPQC offers better conditioning performance than conventional converters in DFIG-based systems, but the models used were simplistic and excluded PV-wind hybrid coordination. Lastly, in [10], a PV-BESS grid-tied UPQC was proposed with emphasis on the reduction of THD and the benefits of energy storage, but only scant details of the architecture were provided and no reporting of field results were presented. Collectively, these studies signify an important step for renewable-integrated UPQC architectures while highlighting disparities of scaling, validation, robustness, and hybrid source coordination.

In recent years, research interests have expanded beyond UPQC-based configurations to consider other power quality (PQ) issues in PV-integrated distribution systems. [11] studied voltage fluctuations and flicker caused by small prosumer PV systems, proposing an impedance-of-feeder-based screening method, though test results were limited to local case data. [12] examined a large grid-connected PV plant with varying irradiance from a harmonic perspective but focused on compliance issues, while [13] gave an experimental evaluation of 26 commercial PV inverters to study efficiency-PQ trade-offs, without any real interaction with feeders. [14] compared several strategies for the control of PV microinverters at the device level, focusing on current quality without any validation at the feeder level. Simultaneously, by using hybrid deep learning, [15] classified PQ disturbances caused by PV, but it is not clear how robustly that would be deployed in real grid conditions. For mitigation of PQ effects using custom power devices, [16] studied D-STATCOM/UPQC in a PV-intensive grid, while [17] presented a UPQC supported by PV+BESS; both works proved PQ enhancements albeit kept within the simulation confines and latter got only limited hardware validation. Utility-oriented guidelines started to emerge such as those in [18], which provided flicker screening curves for PV interconnections, but these have to be calibrated for particular networks. More generic reviews, such as [19], detail actionable insights for PQ issues and mitigation practices but lack any form of quantitative validation. Hosting capacity assessment is a major theme in research [20] compared deterministic, stochastic, and time-series approaches under PQ and voltage constraints, and [21] showed how Volt/VAR-enabled PV inverters enhanced hosting, albeit all in modeled feeders. Likewise, [22] compared traditional and advanced inverter controls, showing the benefits of voltage regulation but ignoring interharmonic issues. Data-driven approaches for PQ research considered by [23] used feeder fingerprints for PQ anomaly detection; [24] utilize deep learning for Volt/VAR control, which yielded PQ enhancements but left concerns on controller generalization hanging; [25] stressed coordinated Volt/VAR-Watt settings for smart inverters but their findings reported in preprint were not validated either hardware-in-the-loop or in the field. Taken together, these studies show a gamut of approaches, including inverter control, intelligent PQ detection, hosting capacity assessments, and UPQC modifications, yet mostly suffer from common limitations such as reliance on simulations, narrow experimental scope, and inadequate attention to real-world grid dynamics.

III. WIND ENERGY SYSTEMS FOR GRID SUPPORT

Besides PV integration, the stabilization of the grid using wind-based systems, especially in relation to doubly-fed induction generators (DFIGs) for frequency and voltage support, has attracted much research attention. [26] proposed a predictive controller for the grid-side converter of DFIGs to quickly provide active-power support during islanding, enhancing frequency nadir and settling time, but the work was never extended to experimental investigations, being only tested through small-scale simulations. Complementarily, [27] studied the modal interactions related to inertial and primary frequency support of DFIGs, finding that while it is beneficial to electromechanical damping, there could be negative repercussions on converter control-mode stability, though experimental evidence was missing. At the data-driven methods side, [29] developed an additional controller for short-term frequency regulation with tuning by particle swarm optimization; [30] studied the temporary frequency support based on active power in wind farms along with wake effects-both remaining in the simulation domain and considered some simplified assumptions. Liu et al. [30] further came into the picture with their adaptive virtual inertia combined with droop control that is metaheuristically tuned to enhance frequency stabilization but is yet to demonstrate real-time implementation and online adapting capability. At the voltage level, [31] achieved reactive voltage control of wind farms through a modified Tabu search, though the application of the technique was limited to steady-state compliance without consideration of frequency-voltage dynamics. On the other hand, [32], [33] showed STATCOM-based support for LVRT and PQ in wind plants but hinged on simplified case studies lacking a systematic approach to device sizing, multi-fault interaction, or multiple grid codes. [34] Provided a broader standpoint, reviewing LVRT enhancement techniques (crowbar, DC chopper, reactive support) but mostly at the conceptual/simulation level. [35] gave a quantification of reactive-power limits for wind plants during voltage support events, though considering capability curves as static and without coordination with frequency headroom. From a perspective of compliance, [36] evaluated grid-forming wind turbines under grid codes and pointed to capability gaps but offered little benchmarking; [37] on the other hand, proposed a new grid-forming control for PMSG turbines to deliver fast frequency response with MPPT, still yellow-paper status and thus not validated on hardware. More extensive system-level intervention was provided by Anderson et al. [38], developing wind integration in mini-grids for resilience and black-start-like services but reviewed case studies rather than standardized testing regimes. From the dynamical viewpoint of wind farms, [39] went on to provide adjoint-optimized flow control with free-vortex wake models to smooth power output, while aerodynamic simplifications limit grid-scale impact; [40] developed a graph-neural-network accelerator for 3D wake modeling, a significant step forward toward better farm-scale power prediction for smoothing and dispatch; however, it was trained on steady-state CFD alone, without transient validation. These works thus represent the growing promise of wind-based DFIG and PMSG systems for PQ, frequency, and voltage support but indicate the persisting gaps in hardware validation, scalability, and proper integration with realistic grid codes and large-scale dynamics.

Table 1: WIND ENERGY SYSTEMS FOR GRID SUPPORT

Ref	Work Description	Technique Used	Key Findings	Results	Dataset/Setup	Limitations
[1]	Proposed a Wind–PV integrated UPQC with dual-compensation; assessed several operation modes (grid support with/without load, sag/swell/harmonics)	Dual-compensation UPQC, simulation	Improved PQ indices and power factor in grid-connected DG	Enhanced voltage/frequency stability; improved THD & power factor	Simulation of grid-connected DG with Wind & PV models	Simulation-centric; no hardware validation; control relies on idealized measurements and fixed parameters; robustness under fast irradiance/wind transients and DC-link stress not experimentally verified
[2]	Developed a neural-network–controlled PV–Battery fed UPQC; compared against SRF and p–q control under nonlinear/unbalanced loads and voltage sags/swells	Neural-network control, SRF, p–q method	Maintained grid-current THD <5% (IEEE-519)	Effective PQ improvement under nonlinear/unbalanced loads	Simulation with PV–Battery integrated grid system	Trained controller generalization to unseen grid events and cyber-physical uncertainties not proven; no HIL/real-time test; battery sizing & lifecycle impacts on DC-link stability not addressed
[3]	Studied PV-integrated UPQC using a multilevel inverter with resilient backpropagation NN for control; targeted harmonics/voltage deviations	Multilevel inverter, Resilient backpropagation NN	Improved dynamic response and harmonic mitigation	Reduced voltage deviations and THD	Simulation with PV-integrated UPQC system	Lacks comparison with adaptive/robust/predictive controls; grid codes and ride-through requirements not evaluated; only simulation metrics reported
[4]	Outlined integration of a 10 kW PV system via UPQC (with BESS support) to improve voltage profile and PQ	PV-BESS supported UPQC	Improved voltage profile and PQ at distribution level	Improved voltage stability; PQ enhancement at feeder level	Simulation/design study with 10 kW PV and 20 kVA UPQC	Primarily design/feasibility exposition; limited quantitative validation; controller tuning, MPPT–UPQC coordination, and DC-link energy management not deeply analyzed
[5]	Demonstrated PV-integrated UPQC for PQ enhancement using series–shunt VSCs with common DC link	Series–shunt VSCs, common DC link	Mitigated sag, swell, and harmonics	Voltage and current quality improvement	Simulation of PV-UPQC system	Brief conference study; no extended sensitivity analysis; scalability to multi-bus feeders not discussed
[6]	Designed and tested a three-phase single-stage PV-UPQC; shunt converter extracts PV power + current compensation; series converter handles voltage issues	Single-stage three-phase PV-UPQC	Verified performance under load unbalance, PCC sags/swells, irradiance variations	Improved compensation and PV power utilization	Lab-scale test bench	Lab-scale validation downscaled; efficiency, thermal limits, and interaction with distribution protection not reported
[7]	Investigated UPQC supported by PV + BESS for grid PQ mitigation; BESS backs up when PV under-produces	PV + BESS supported UPQC	DC-link support and continuity of compensation conceptually demonstrated	Improved PQ in simulation; BESS supports PV shortfall	Simulation with PV + BESS integrated UPQC	High-level performance investigation; lacks controller detail, BESS control bandwidth vs. DC-link ripple analysis; no quantitative THD/flicker/voltage unbalance results
[8]	Presented design & performance of a three-phase PV-integrated UPQC; covers control (SRF-like) and disturbance tests	SRF-based control	Improved PQ under canonical disturbances	Reduced sag, swell, and harmonic effects	Simulation with three-phase PV-UPQC system	Focused on canonical disturbances; no study of grid-impedance variation, communication delays; minimal hardware details

[9]	Compared UPQC-based conditioning vs. normal converter for DFIG/wind systems	UPQC-based conditioning	UPQC superior in voltage/harmonic mitigation for wind energy	Improved voltage and harmonic performance	Simulation with DFIG/wind system	Simplified wind/DFIG models; limited controller robustness assessment; lacks hybrid PV–wind coordination and realistic grid-event profiles
[10]	Proposed grid-integrated PV with BESS feeding UPQC to enhance PQ; emphasized energy buffering + conditioning	PV + BESS integrated UPQC	Reduced THD and improved PQ	Improved voltage/current quality under simulation	Simulation of PV+BESS-UPQC system	Abstract/extended summary; incomplete architecture specifics; no field trial results
[11]	Investigated voltage fluctuations and perceptible flicker (Pst/Plt) caused by small prosumer PV systems on LV feeders; proposed practical screening workflow relating feeder impedance, plant size, and background flicker	High-resolution field data analysis, screening workflow	Identified key factors affecting flicker; proposed PV screening methodology	Improved assessment of flicker risk on LV feeders	Several months of high-resolution field data from LV feeders	Single-country data; sensitive to local irradiance/cloud dynamics; may not generalize without re-tuning
[12]	Performed harmonic analysis for a large grid-connected PV plant; assessed current/voltage THD under varying irradiance and inverter operating points	Harmonic analysis, PV plant modeling	Quantified harmonic contributions and compliance vs. limits	Provided benchmark for PV plant harmonic performance	Large grid-connected PV plant simulation/measurements	Limited disclosure of inverter control and grid impedance; constrained replicability, weak-grid extrapolation
[13]	Experimental comparison of 26 commercial PV inverters; efficiency vs. harmonic emissions across operating ranges	Experimental lab testing	Trade-offs between conversion efficiency and PQ	Comparative efficiency/harmonic performance	Laboratory test bench	Lab conditions only; real-feeder interactions (resonance, background distortion) not covered
[14]	Analyzed four control strategies for dual-boost single-stage PV microinverter; compared current quality and THD	Linear control, FCS-MPC, flatness-based, sliding-mode	Device-level control affects THD; strategy comparison	Identified optimal control strategy for current quality	Microinverter test setup	Grid-support (Volt/VAR, Volt/Watt) and feeder-level PQ impacts not validated
[15]	Proposed hybrid deep-learning classifier with wavelet features to automatically recognize PV-related PQ disturbances	Hybrid deep learning, wavelet transform	Automatic recognition of PQ events	Improved classification of PQ disturbances	Curated PV PQ datasets	Validated only on curated datasets; real-plant deployment, class imbalance, sensor noise robustness not tested
[16]	Evaluated PV-rich grid PQ issues and compared mitigation via D-STATCOM/UPQC under different penetration	D-STATCOM, UPQC simulation	Quantified voltage profile and THD improvements	Simulation showed voltage/THD enhancement	PV-rich grid models under various penetration	Simulation-based; controller limits, thermal constraints, cost/size trade-offs not experimentally verified
[17]	Designed PV+BESS-supported UPQC; mitigated sags/swells/harmonics with DC-link support from renewables	PV+BESS-UPQC	Demonstrated DC-link support; simultaneous PQ mitigation	Reduced voltage sags/swells and harmonics	Simulation of PV+BESS-UPQC system	Controller performance under fast irradiance ramps and converter saturation not fully stress-tested in hardware
[18]	Utility-facing flicker screening guideline for PV interconnections (Screen H)	Summation laws, practical screening curves	Provides method for estimating aggregate flicker Pst	Improved utility-level flicker assessment	Guideline document; industry data	Not peer-reviewed; requires utility-specific calibration; conservative for smart-inverter fleets

[19]	Practice-oriented overview of PQ in grid-connected PV: harmonics/flicker sources, mitigation via active/reactive power controls	Review, technical article	Summarized PQ challenges and mitigation approaches	Narrative insights; code compliance context	Literature and field practice	Lacks quantitative validation or feeder case studies
[20]	Benchmarked methods to compute PV hosting capacity (HC) with voltage/PQ constraints on LV network	Deterministic, stochastic, time-series HC analysis	Compared HC computation methods	Method comparison results for LV network	LV network model	Does not integrate advanced inverter PQ services into HC quantification

IV. MODIFICATION OF UPQC ARCHITECTURE USING DC COMMON LINK

Recent studies have increasingly investigated different architectures of the Unified Power Quality Conditioner (UPQC) with renewable sources connected directly to the DC link with the intent of providing better PQ support in the distribution grid. [41] have analyzed a Wind–PV-fed UPQC and concluded that sharing the DC link among the converters offers some benefits in voltage regulation and harmonic appreciation; however, their results were mostly from simulations and were not validated with the fast dynamics of renewable sources. [42] extended these by furnishing the DC bus with PV and battery storage using a neural-network-based controller, achieving THD reduction and sag/swell compensation while acknowledging battery support as a stabilizing influence for the DC link, yet delineating unanswered questions in sizing and robustness under unforeseen events. Similarly, [43] proposed an MPC strategy for PV-integrated UPQC under double compensation, showing improved dynamic response and DC-link management but limited to pre-print simulation results without the hardware demonstration of MPPT–MPC interaction. [44] analyzed MMC-based UPQC alternative with altered DC-link architecture presenting superior PQ mitigation, yet without a detailed review of capacitor sizing or thermal limitations under renewable intermittency. [45] proposed a decoupling control design for series and shunt converters sharing the DC link, giving optimization-based insights without demonstration on renewable-supplied DC buses. Similarly, [46] had likewise proposed a Modulated-UPQC topology for AC microgrids with respect to the DC consideration, while never explicitly addressing PV/Wind coupling or storage operation. [47] demonstrated PV-fed UPQC designs for single and three-phase systems on the integration side to show PQ enhancements under distortion, and [48] stressed that embedding BESS ensures continuous compensation, though both were still limited in their experimental outlooks. Singh [49], in 2022, revisited PV-UPQC control, refining PLL-less and pq-theory approaches for better DC-link regulation; yet, he observed a dearth of field-level or hardware-in-the-loop testing. Lastly, [50] brought together D-STATCOM/UPQC-linked PQ enhancements in PV-rich grids while stressing DC-link stability, though again limiting their studies to the simulation side. Together, these works point toward strong promise in renewable-integrated UPQC systems for mitigation of sag/swell, THD, and DC-link voltage stabilization; hence, challenges remain in experimental validation, dynamic DC-link sizing, and system resilience to fast PV/wind fluctuations.

V. CONCLUSION

In this review the evolution of UPQC architectures with special consideration of renewable-assisted formations, wherein solar and wind-based distributed generations are connected at the common DC link are studied. Conventionally, UPQC has been touted as the most effective solution to eliminate voltage fluctuations, distortions in current, and issues in reactive power in distribution networks. In contrast, the dependency on supply from the grid or on bulky storage has included a serious bottleneck during their adaptation with a renewable-dominant system. Recent trends in research show that embedding photovoltaic and wind sources at the DC link stabilizes the voltage, thereby decreasing the needs for auxiliary storages and in turn, making overall energy utilization become more efficient. Also, the control techniques applied to both shunt and series converters, from classical control to modern optimization and intelligent techniques, have improved PQ compensation capability under variable renewable conditions. The hybrid architectures using PV–wind and PV–battery have been found to support increased reliability and resilience against intermittency issues. Nonetheless, most of the existing literature remains simulation-based, with scarcely any experimental validation, thus creating a gap between the theoretical advancement and practical applications. Thus, dynamic energy management, robustness in real-time control, cost perspectives, and large-scale penetration in smart grids need to be studied further. From the literature reviewed, it is evident that renewable-integrated UPQC systems will provide a promising pathway for achieving both integration of sustainable energy and better power quality. However, the greatest challenge for future research in this area is to try to bridge the gap that currently exists between theoretically appealing concepts and their implementation in the field.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

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