Modification of Unified Power Quality Conditioner (UPQC) Architecture with Solar and Wind Based Distributed Generation at the DC Common Link

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Abstract: *The PQ (power quality) disturbances in distribution systems persist as a major challenge due to increasing consumer awareness and integration of renewable energy sources. The Unified Power Quality Conditioner (UPQC) is considered the most sophisticated custom power device that can simultaneously deal with disruptions in load current and supply voltage while performing functionalities such as load balancing, elimination of neutral current, power factor correction, and harmonic suppression. This article focuses on the DG-UPQC, where renewable sources like solar and wind are interfaced with the DC link through power electronic converters to enhance the resilience under varying operating conditions. Some of the notable improvements in the simulation results are an increase of 3.5% in active power transfer (from 37,780 W to 39,110 W), reactive power demand coming down to 52.85 Var, and power factor uplift to 0.96 from 0.91. Harmonic mitigation has been confirmed, where System 1 (vector modulation with PI regulators) reduced THD in voltage within 2.97-6.31% and THD in current within 12.45-7.07%. System 2 yields a better performance employing AI-based switching modulation via the Quality Control Evolutionary Strategy (QC_ES), reducing voltage THD to 2.66-6.24% and current THD to 10.45-6.95%. These studies suggest DG-UPQC with AI-based controllers to outweigh the conventional systems with PI controllers in matters of efficiency, stability, and PQ improvement. Future work can continue to be carried out toward other UPQC topologies, such as a left-shunt configuration, and hybrid control strategies merging traditional and intelligent approaches. A promising opportunity is available for researchers and practical applications of UPQC compensators.*

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

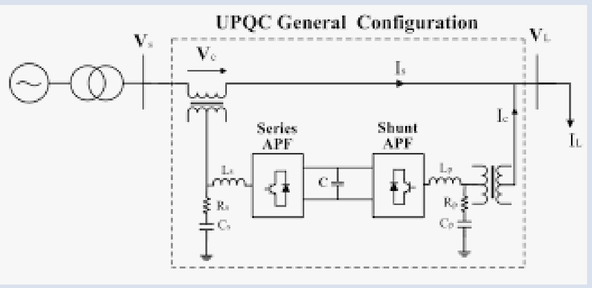

Figure 1: Unified Power Quality Conditioner

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

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

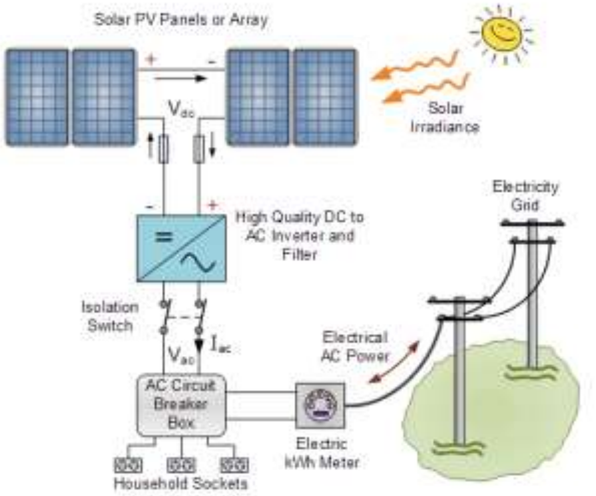

Figure 2: Solar Photovoltaic System Block Diagram

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.

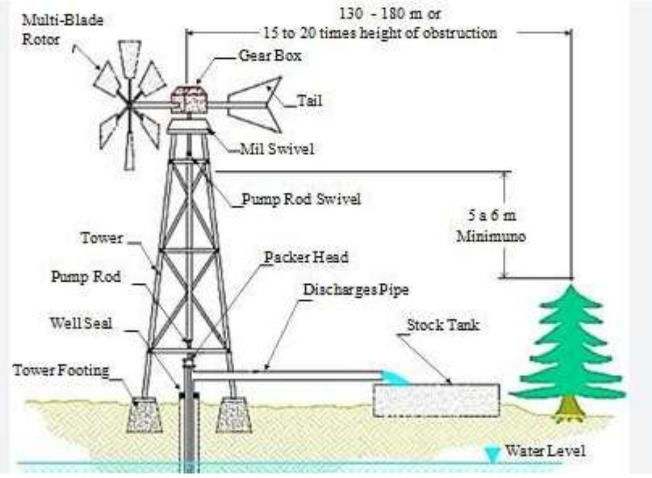

Figure 3 :Working Principle of Wind Turbine Systems

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. LITERATURE REVIEW

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.

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.

Table 1: BASED ON SOLAR AND 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;	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;

	assessed several operation modes (grid support with/without load, sag/swell/harmonics)					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	Single-stage three-phase PV-UPQC	Verified performance under load unbalance, PCC sags/swells,	Improved compensation and PV power utilization	Lab-scale test bench	Lab-scale validation downscaled; efficiency, thermal limits, and interaction with distribution

	power + current compensation; series converter handles voltage issues		irradiance variations			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

IV. PROPOSED METHODOLOGY

A. DG_DG_UPQC Working Equations and Design

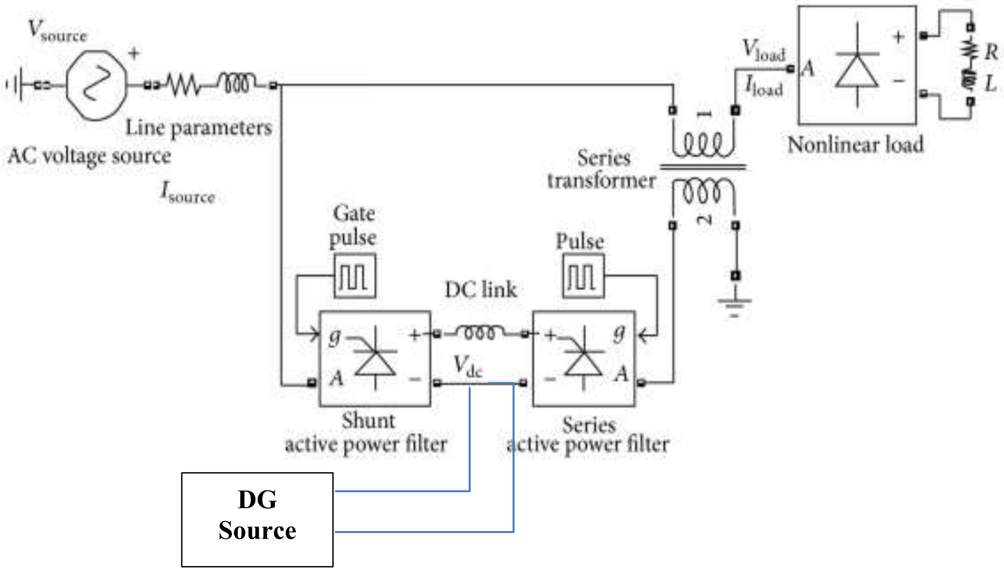

Figure 4: Proposed Architecture of the UPQC design

The equivalent circuit diagram of a Unified Power Quality Conditioner is shown in Figure 4. Vs is the supply voltage, V_{ac}, Iac are the series compensation voltage, the shunt compensation current, and V_{load} and I_{load} are the load voltage and current, respectively. The source voltage may contain negative, zero, and harmonic components. The per-phase voltage of the system can be described as

$$V_a = V_{1pa} + V_{1na} + V_{10a} + \sum_{k=2}^{\infty} V_{Ka}\sin(k\omega t + \theta_{Ka}) \qquad (1)$$

Algorithm Implementation

The evolutionary Strategy technique is an optimization method used in this control. At this load line, the power acts as the optimizing equation to keep good balance and make adjustments as the load changes. The flow chart for the optimization algorithm is shown below, which is implemented in MATLAB as governing equations and codes for generating pulses for each phase converter as well as the boosting pulses.

The contrast between QC-ES and classical ES lies in the fact that while classical ES depends on the variances of genes and selection as the driving forces, QC-ES explicitly chooses mutation lengths based on the control of the quality of the generated solutions. This approach supports the algorithm to adapt quickly to different search landscapes.

PV Module modeling

According to Ashok and Mukerji (2006), solar photovoltaic energy is abundantly available in nature and is, therefore, a clean and pollution-free source of power. Its output is highly dependent on geographical and environmental factors. PV technology is among the Renewable Source (RE) alternatives that would allow industrial countries to lessen dependency on fossil fuel-based conventional energy [4]. Figure 3.6 shows a diagram of the hybrid PV generation system consisting of a PV generator, diesel generator (DG), inverter, and battery storage system. Different configurations of PV/diesel-based hybrid systems with battery banks supported by a DG are studied to establish their possible advantages and effectiveness in supplying consumer load demands [5].

So PV cells always have one operating point where it just makes maximum power for a given set of values of current, I, and voltage, V, and this particular point corresponds to a resistance value given by V/I. A basic equivalent circuit of a PV cell is shown in Figure 5

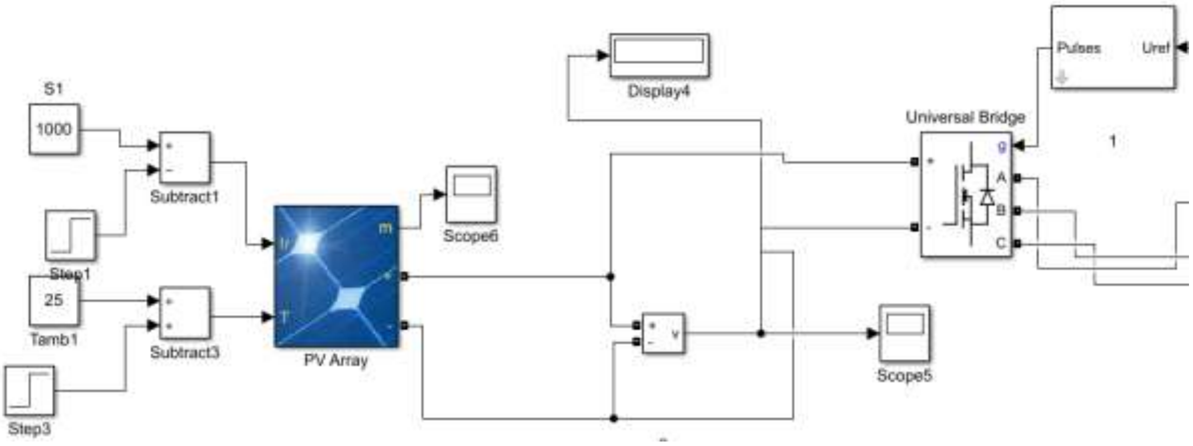

Figure 5 Modeled solar system

A cell series resistance (Rs) is connected in series with parallel combination of cellphotocurrent (I_{ph}),exponential diode (D), and shunt resistance (R_{sh}) , I pv and Vpv are the cells current and voltage respectively. It can be expressed as

$$I_{pv} = I_{ph} - I_s\left(e^{q(V_{pv}+I_{pv}*R_s)/nKT} - 1\right) - (V_{pv} + I_{pv} * R_s)/R_{sh} \qquad (2)$$

V. RESULT AND DISCUSSION

A. Case 1: Analysis of Voltage Current and Power Quality in the system 1 driving various loads

The hybrid renewable power plant feeds power to the DG_UPQC DC link, where disturbances are compensated by PWM-controlled converters using PI references under a nonlinear load, with analysis concentrated at loading points.

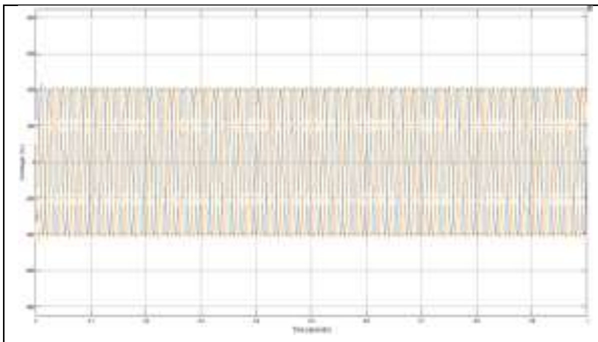

Figure 6: Three phase voltage available at the loading point of nonlinear load in system 1

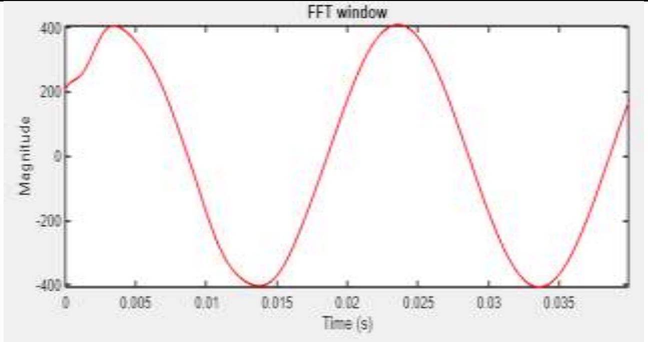

Figure 7: FFT analysis MATLAB window of voltage available at the loading point of nonlinear load in system 1

Three phase voltage output available at the loading points is depicted in figure 6. The phase to phase voltage is approximately 400V in system 1.The figure 7 shows the FFT plot for the voltage output analysis in system 1. This plot, in turn, is used to compute the harmonic content in the three-phase output voltage.

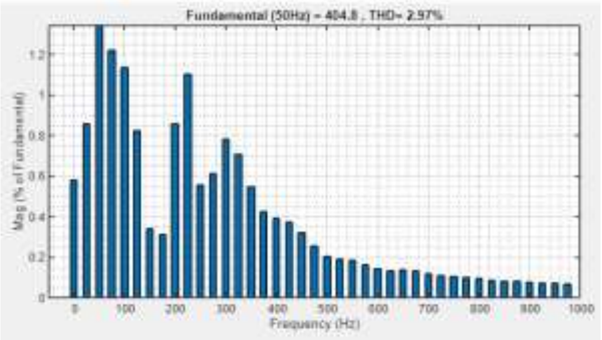

Figure 8: THD% in voltage available at the loading point of nonlinear load in system 1

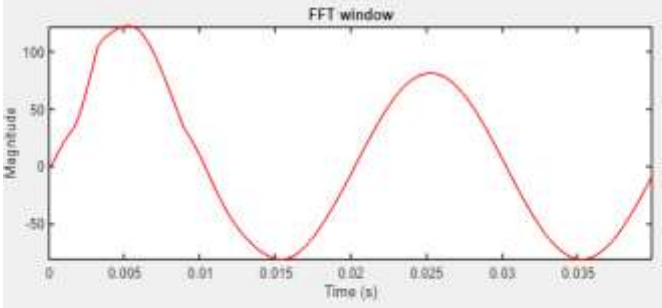

Figure 9: FFT analysis MATLAB window of current drawn at the loading point of nonlinear load in system 1

The figure 8 represents the THD% measurement done from the system 1 line voltage available at the nonlinear loading point, which got to be 2.97% when the DG_UPQC was driven by the vector based PI regulation method of the control system. The current being drawn in the nonlinear load terminal point in system 1 has been subjected to an FFT of the currents, depicted in the figure 9. Being further utilized for this cause is the harmonic content evaluation of the output current from the phase

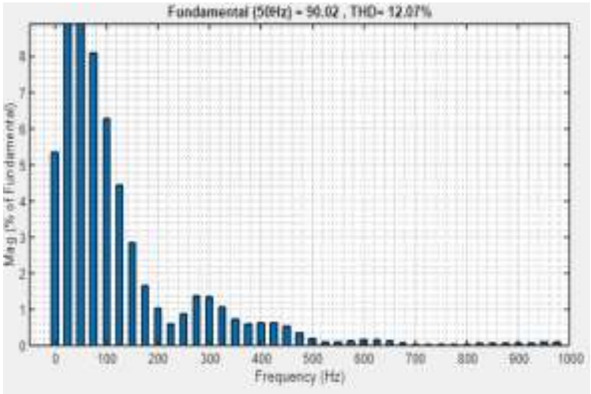

Figure 10: THD% in current drawn at the loading point of nonlinear load in system 1

In the figure 10, the THD% evaluation of the system 1 loading point came to 12.07 when the DG_UPQC is controlled by PI regulation technique based on the vector.

B. Case 2: Analysis of Voltage Current and Power Quality in the system 2 driving various loads

These hybrid-energy operated DG-UPQC controllers are taken under nonlinear loads by AI-Based QC-ES PWM modulation so that adaptive compensation, reliability, and better power quality, assessed on the basis of THD, and active power comparison at various points of load, could be ensured.

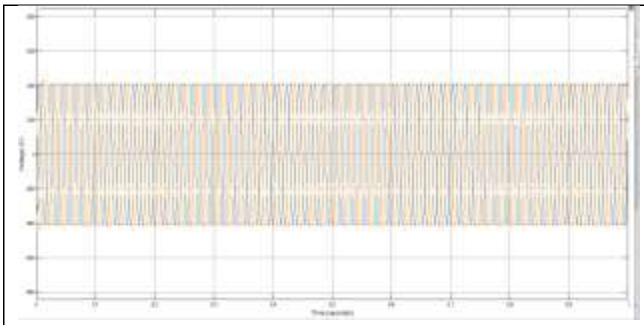

Figure 11: Three phase voltage available at the loading point of nonlinear load in system 2

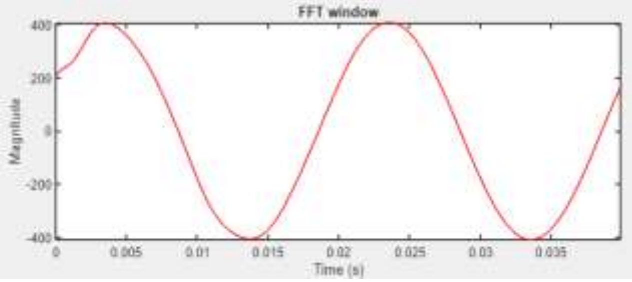

Figure 12: FFT analysis MATLAB window of voltage in line at the loading point of nonlinear load in system 2

Three phase voltage output available at the loading points is depicted in figure 11. The phase to phase voltage is approximately 400V in system 2. Figure 12 represents the FFT analysis of the voltage output in system 2. This is further utilized to evaluate the harmonic content in thee phase output voltage.

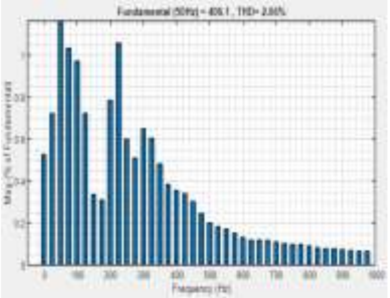

Figure 13: THD% in voltage at the loading point of nonlinear load in system 2

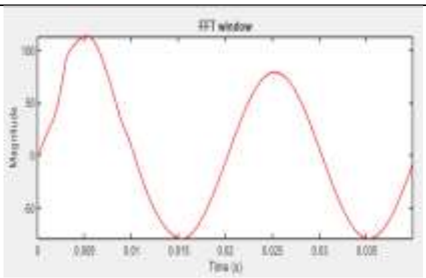

Figure 14: FFT analysis MATLAB window of current drawn at the loading point of nonlinear load in system 2

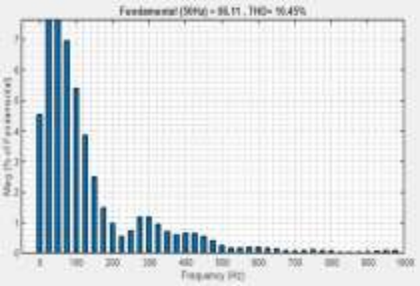

Figure 15: THD% in current drawn at the loading point of nonlinear load in system 2

The THD% was evaluated in system 1 line voltage at the nonlinear loading point, and the value came out to be 2.66% with DG_UPQC operation using the control system-based vector PI-regulation-method which is shown in figure 13. Figure 14 shows the FFT analysis of the current drawn at the nonlinear load terminal point in system 2. This is then used to study the harmonic content on the 3-phase output current for system 2 at the loading point. The figure 15 indicates the THD% evaluation in system 2 line current available at the nonlinear loading point which comes out to be 10.45% when DG_UPQC is operated by AI-based switching modulation with the QC evolution strategy method of control system.

Table 2: Comparative analysis of DG_UPQC with converters driven by different controlling algorithms

Parameters	System 1	System 2
Voltage (Volts)	400	
Active Power (W)	37780	39110
Power Factor Correction	0.91	0.96
Reactive Power (Var)	1649	52.85
Quality analysis at the loading points of nonlinear load		
THD% in load voltage	2.97 %	2.66%
THD% in load current	12.07%	12.45%

C. Analysis of the two DG_UPQC at the unbalanced terminal of load (Local loads)

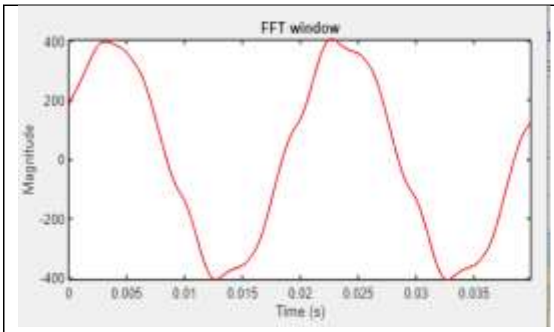

Figure 16: FFT analysis of the Voltage injected in line by the DG_UPQC at the unbalanced load terminal in system 1

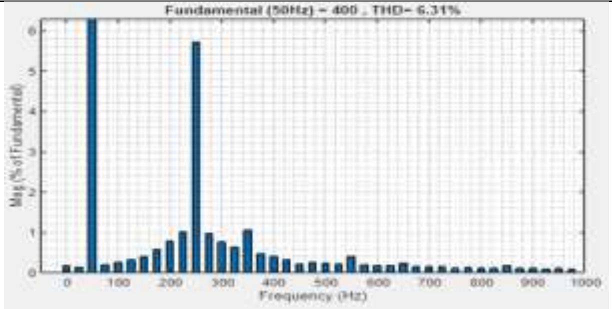

Figure 17: THD% in the Current drawn at the unbalanced load terminal in system 2

Figure 16 represents the FFT analysis of the voltage output in system 1. This is further utilized to evaluate the harmonic content in thee phase output voltage. Figure 17 presents the THD% evaluation in the system 2 line current at the unbalanced loading point, which came out to be 6.95% when the DG_UPQC was driven by AI-based switching modulation employing the QC_ES strategy.

Table 3: Comparative analysis of DG_UPQC with converters driven by different controlling algorithms at the unbalanced terminals

System Parameters	System 1	System 2
THD% in load voltage	6.31 %	6.24%
THD% in load current	7.07%	6.95%

V. CONCLUSION

This research presents a comprehensive investigation into power quality (PQ) challenges in distribution systems, emphasizing the growing complexity of maintaining PQ within acceptable limits due to increasing consumer demands and renewable energy integration. The power quality (PQ) phenomenon encompasses disturbances related to PQ in distribution systems. Following the ever-increasing customer demands for PQ and the integration of renewable energy sources, it is becoming challenging to keep PQ within permissible limits. The Unified Power Quality Conditioner (UPQC) is a very capable custom power device that can simultaneously mitigate disturbances in supply voltage and disturbances in load current while rendering other desirable functions such as load balancing, neutral current elimination, power factor correction, and harmonic suppression. To realize the DG-UPQC model for modern grid needs, solar and wind are interfaced at the DC link through power electronic converters, ensuring greater reliability and performance. The proposed system showed very good improvements like an increase of 3.5% in active power output (37,780 W-39,110 W), reduction in reactive power demand to 52.85 Var, and rise in power factor from 0.91 to 0.96. The THD analyses showed the effectiveness of the system with System 1 (vector modulation and PI regulators) reduced voltage THD to 2.97-6.31% and current THD to 12.45-7.07%, while System 2 (switching based on AI with QC_ES) takes the crown with voltage THD of 2.66-6.24% and current THD of 10.45-6.95%. This firmly establishes the supremacy of AI-based DG-UPQC over PI-based conventional methods for PQ enhancement and, consequently, for efficiency and stability of the system. The future work should involve other configurations of UPQC like left-shunt configuration, hybrid control strategies combining intelligent and conventional techniques, and even more advanced compensator designs to further enlarge the scope of research and real-life implementations.

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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