Advanced Optimization of Switching Modulation Strategies for Improved Power System Stability in Distributed Generation-Enabled UPQC Frameworks

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Abstract: - An optimized Distributed Generation-based Unified Power Quality Conditioner (DG_UPQC) system is proposed to improve power quality in hybrid renewable energy environments. Integrated with solar and wind sources through a DC link, the system leverages two advanced control strategies—conventional PI-based vector modulation and an AI-driven Quality Controlled Evolution Strategy (QC_ES). Developed and simulated in the MATLAB/Simulink platform, the model is evaluated under nonlinear and unbalanced load conditions. The architecture incorporates a multi-port converter to ensure efficient direct power flow from the distributed energy sources. Pulse Width Modulation (PWM) signals, guided by the respective control strategies, are used to address voltage and current distortions. The study reveals effective harmonic compensation by both approaches, with the AI-based method slightly outperforming the conventional strategy in reducing Total Harmonic Distortion (THD). Results highlight the potential of intelligent modulation and hybrid energy integration in enhancing system efficiency, stability, and reliability. This model demonstrates a scalable solution for future smart grid applications focused on sustainable and stable power delivery.

Keywords: DG_UPQC, power quality, PI control, AI-based control, QC_ES, hybrid renewable energy, THD, smart grid, PWM, MATLAB/Simulink.

I. Introduction

Global energy systems are under pressure from rising demand due to industrial growth, tech advancements, and population increases. Renewables made up 29% of global electricity in 2022, projected to hit 42% by 2028. However, their intermittent nature causes 20%-30% variability in supply, challenging grid stability. Smart grids with AI offer solutions, potentially cutting CO_2 emissions by 500 million metric tons yearly by optimizing distribution and aiding net-zero goals [1]. AI enhances demand forecasting, DER management, and reduces operational and environmental costs [2][3]. It also improves grid routing and efficiency [4][5]. Power infrastructure is transforming via large-scale renewables, microgrids, and digital control systems. Intermittent RESs cause active power uncertainty and frequency shifts [6]. Smart grids offer superior generation, transmission, and economic performance [7], with real-time automation. High RE penetration cuts power losses and pollution but introduces PQ issues like voltage swings and harmonics [8]. Small DG units further support energy needs and grid restructuring [9].

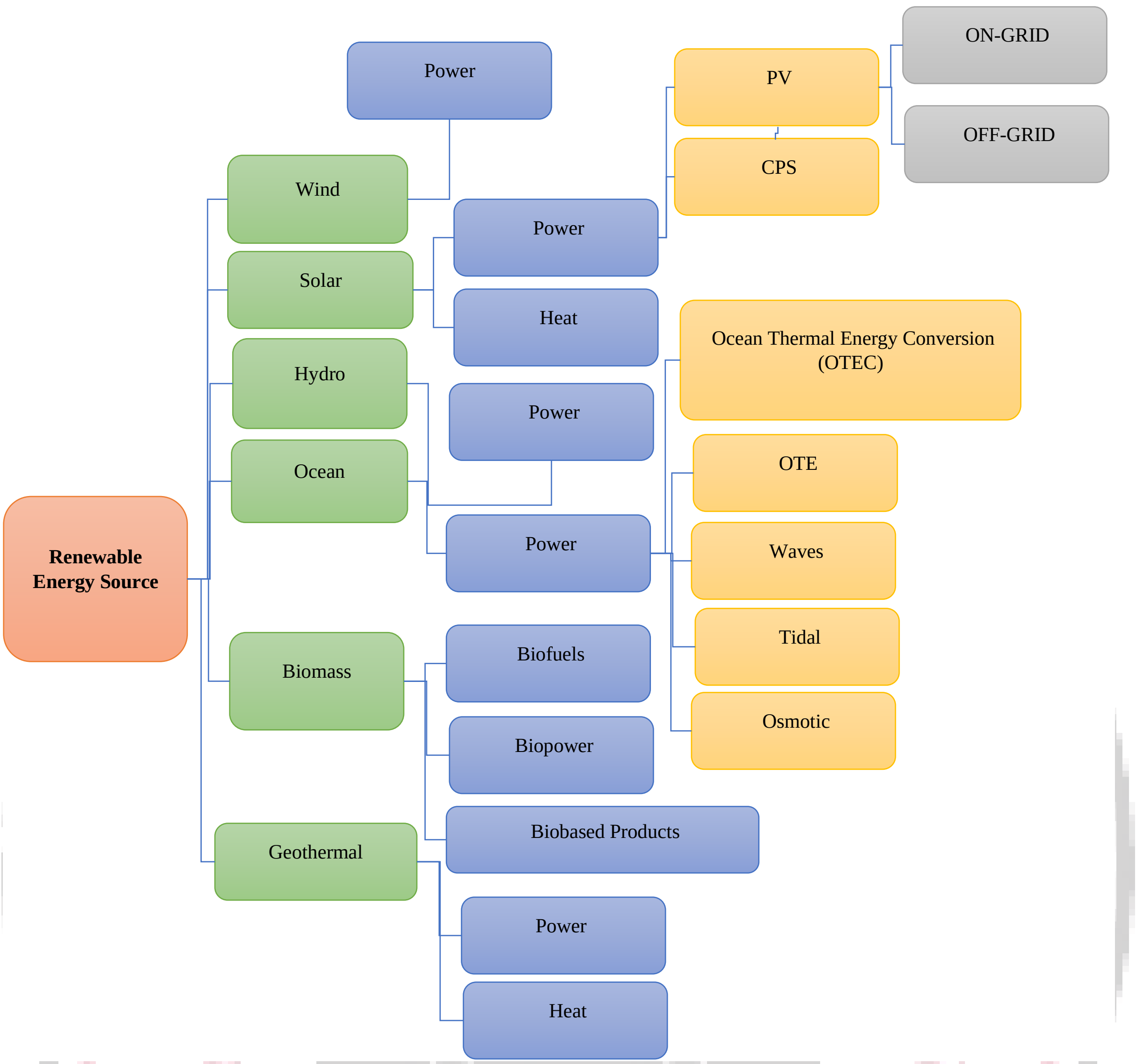


Fig 1 Different types of renewable energy sources within main utilizations.

The figure presents a detailed classification of Renewable Energy Sources (RESs) based on their primary types and specific utilizations. It categorizes sources such as wind, solar, hydro, ocean, biomass, and geothermal, showing how each contributes to energy production through power generation, heat, or the creation of bio-based products. For instance, solar energy can be harnessed for both power (via PV and CSP) and heat, with PV systems further divided into on-grid and off-grid applications. Ocean energy encompasses diverse technologies like OTEC, wave, tidal, and osmotic power, while biomass provides biofuels, biopower, and bioproducts. This diagram effectively highlights the versatility and scope of renewables in sustainable energy systems.

Distributed Generation (DG) involves small-scale energy sources like solar, wind, and biomass (≤10 MW) located near consumers, either standalone or grid-connected [10]. As renewable energy replaces fossil fuels due to rising demand and supportive policies, its variability poses challenges to grid reliability and power quality (PQ), requiring smart controls and flexible systems [11]. PQ issues now often arise from sensitive electronics and nonlinear loads, pushing utilities to maintain stable voltage and frequency amid stricter regulations [12]. Grid stability is also threatened by faults like short circuits, overcurrent, and overvoltage, which require robust protection systems [13]. The Unified Power Quality Conditioner (UPQC) addresses these issues by using dual inverters to correct voltage and current disturbances, enhancing grid performance in distorted environments [27]

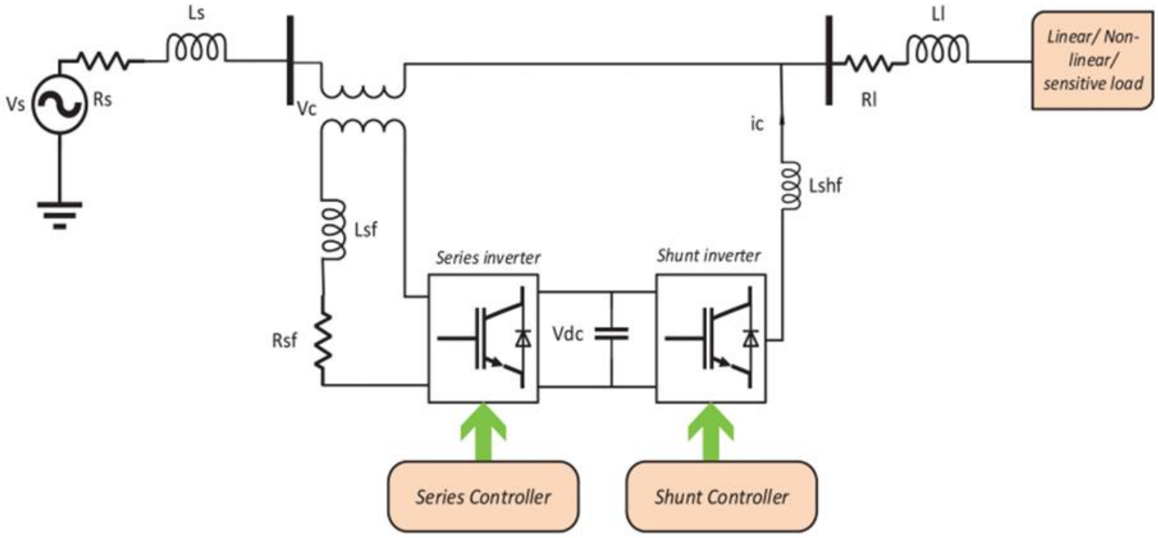


Fig 2 Typical structure of a unified power quality conditioner [14]

Figure 2 shows the structure of a Unified Power Quality Conditioner (UPQC), which includes a series and shunt inverter linked by a DC capacitor. The series inverter, via a coupling transformer, corrects voltage issues like sags, swells, and harmonics. The shunt inverter, connected parallel to the load, handles current harmonics, power factor correction, and load balancing. Together, they deliver stable, high-quality power to sensitive loads.

II. LITERATURE REVIEW

Smart grid technologies have revolutionized energy systems by enhancing energy management, demand response, renewable integration, and storage, though they also present technical, ethical, and operational challenges [15]. Traditional grids struggle to meet the growing complexity of urban energy demands, making smart microgrids a sustainable, efficient alternative [16]. Smart grids enable two-way communication, improving efficiency and reliability while raising concerns about data integrity and cybersecurity [17]. Digital control strategies, including real-time monitoring and distributed systems, are crucial for managing fluctuating energy supply and demand [18]. Urban areas, as major energy consumers, require smart planning, with Smart Grids playing a key role in Smart Cities through advanced metering, IoT, and renewable integration [19]. The shift to inverter-based renewable energy introduces grid stability issues, addressed through virtual inertia and advanced modeling [20]. Liberalized energy markets boost competition and consumer empowerment, positioning smart grids and microgrids as vital for reliable, eco-friendly power distribution [21]. Solar energy integration enhances grid efficiency but requires storage solutions and supportive policies to manage its intermittency [22]. The move to decentralized smart grids brings challenges like reduced inertia and grid instability, highlighting the need for robust architectures and further research [23]. Overall, the global transition to renewables is driven by sustainability, demanding advancements in smart grids, storage, and efficiency [24].

TABLE 1 Comparative Analysis of Smart Grids, Microgrids, and Renewable Energy Integration

Reference	**Focus Area**	**Key Contributions**	**Challenges Discussed**	**Insights**
Ranbir Singh et al. (2025) [28]	Smart grid technologies and implementation frameworks	Revolutionized energy systems; focus on data management, dynamic pricing, and reliability	Technical, ethical, and operational challenges	Continued exploration of smart grid functions and frameworks
Mohamed G. Moh Almihat et al. (2025) [29]	Smart microgrids in urban settings	Systematic review of smart microgrid technologies and real-world applications	Centralized grid limitations; urban demand complexity	Microgrids improve efficiency and resilience in urban energy systems
Venkatraman Ethirajan et al. (2025) [30]	Smart grid evolution and components	Two-decade synthesis; focus on data, pricing, and grid structure	Cybersecurity risks and communication challenges	Highlights advancements in energy systems and urban digital grids

Sarathkumar D et al. (2025) [31]	Digital control in smart grids and microgrids	Real-time monitoring, distributed control, adaptive systems	Integration of renewables and storage technologies	Scalable and adaptive frameworks are essential
Nuno Souza e Silva et al. (2025) [32]	Smart Cities and Smart Grids convergence	Energy trilemma approach; Smart City technologies	Electrification and infrastructure readiness	Smart grids are foundational for future urban planning
Paul Moore et al. (2025) [33]	Grid stability with RES and IBRs	Virtual inertia, grid modeling, system strength	Reliability risks with high RES; limited operator tools	Enhance control strategies and reduce curtailment
Subhojit Dawn et al. (2024) [34]	Smart grids and microgrids in deregulated markets	Market-driven efficiency, environmental gains	Distribution complexity in competitive markets	Smart integration aligns business goals with sustainability
Delwar Hussain et al. (2024) [35]	Solar energy in smart grids	28% efficiency gain, 18% CO_2 reduction in projects	Intermittency, voltage instability, policy gaps	Address storage, regulatory support, and technical readiness
Chibuike Peter Ohanu et al. (2024) [36]	Renewable integration in smart grids	DG focus; energy structure and inertia analysis	Instability and reduced inertia due to DG	Identifies key research gaps in smart grid-RER integration
Bahman Zohuri et al. (2023) [37]	Global energy transition and sustainability	Role of globalization; rise of renewables	Fossil fuel dependency, policy inertia	Policies and innovation must lead low-carbon transition

III. OBJECTIVES

• To design of a system with UPQC which is also fed by distributed generation resources which is hybrid solar wind energy system in MATLAB /SIMULINK environment
• To modify the control system of the UPQC Shunt device with slight modifications in its architecture that uses modified form of evolutionary technique that focuses on the quality assessment of the system under various loading Conditions.
• To analyze the power outcomes in the system with enhancement in the active power and balancing of available reactive power by using UPQC.

IV. RESEARCH METHODOLOGY

The DG_UPQC system is analyzed using MATLAB/SIMULINK, focusing on vector modulation-based control and system design. The proposed architecture includes a series and shunt active filter to enhance power quality by compensating voltage and current distortions. As shown in Fig. 5, the source voltage VsV_sVs may contain positive, negative, zero sequence components, and harmonics. The per-phase source voltage is given by:

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

To ensure the load voltage is purely sinusoidal, the series filter must produce:

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

The shunt filter compensates for harmonic current and reactive power, while maintaining DC link stability. The per-phase load current is:

$$i_{al} = I_{1pm} \cos(\omega t - \theta_1) + I_{a\,ln} + \sum_{k=2}^{\infty} i_{alk} = I_{ipm} \cos\omega t \cos\theta_1 + I_{1\,pm} \sin\omega t \sin\theta_1 + I_{a\,ln} + \sum_{k=2}^{\infty} i_{alk} \quad (3)$$

The shunt filter should generate:

$$I_{ah} = I_{1\,pm} \sin\omega t \sin\theta_1 + I_{a\,ln} + \sum_{k=2}^{\infty} i_{alk} \quad (4)$$

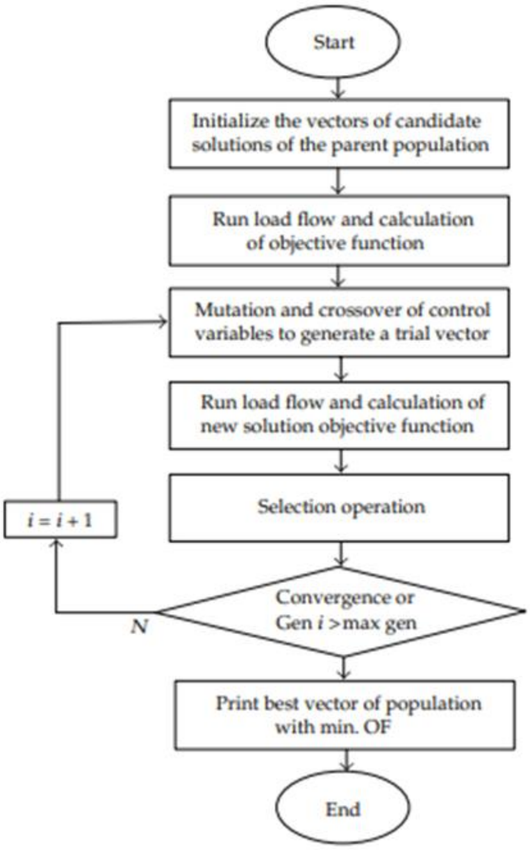
This results in a source current:

$$i_{as} = i_{al} - i_{ah} = I_{1\,pm} \cos\omega t \cos\theta_1 \quad (5)$$

This ensures the source current is purely sinusoidal and in phase. The system uses a PLL-based unit vector template to extract fundamental positive sequence components and generate reference signals for both filters. The series APF compensates voltage distortions via a hysteresis controller, while the shunt APF uses a QC_ES controller to maintain DC link current and correct current harmonics. The design also integrates a DC-DC converter and multi-port converters to regulate DC bus voltage, manage active power flow, and enhance overall power quality.

A. Control system Development

The control system for the DG_UPQC uses vector modulation with PI regulation and a simplified SVPWM approach. Voltage vectors are categorized into six sectors, but calculations are simplified by rotating all into Sector A, with sector-specific phase voltage relationships detailed in Table 3.1. To manage reactive and harmonic currents, the parallel converter operates as a current source in the dq frame. Optimization is achieved through the Quality Control Evolutionary Strategy (QC_ES), which evolves solutions via mutation and crossover to enhance power quality. The system interfaces with a 400V grid using a three-phase transformer, and converter dynamics are modeled using an average approach. A PWM controller compares reference and actual currents to produce gating signals, ensuring balanced and harmonic-free output.



Fig,.3 Flow chart of proposed QC_ES for converters in the DG_UPQC

The fig 6 shows the QC_ES algorithm, where candidate solutions are evolved through mutation, crossover, and selection until the best solution with the minimum objective function is found.

The DG modeling includes solar and wind energy systems within a hybrid setup. The **solar system** uses a PV-diesel configuration with inverter and battery, offering low operational costs, reduced emissions, and grid connectivity for selling excess power. The PV module is modeled using:

$$I_{pv} = I_{ph} - I_s\left(e^{q(V_{pv}+I_{pv}*R_S)/nKT} - 1\right) - (V_{pv} + I_{pv} * R_s)/R_{sh}) \quad (6)$$

Here, IpvI_{pv}Ipv is the PV output current, IphI_{ph}Iph is the solar-induced current, IsI_sIs is the diode saturation current, R_s and R_{sh} are series and shunt resistances, qqq is electron charge, KKK is Boltzmann constant, TTT is temperature, and V_{pv} is the voltage across the PV cell

and

$$I_{ph} = I_{sc} - k_i(T_c - T_r) * \frac{I_r}{1000} \quad (7)$$

Where I_{sc} is the short-circuit current at standard test conditions, k_i is the temperature coefficient, T_c and T_r are cell and reference temperatures, and I_r is the irradiance

For the wind system, both HAWTs and VAWTs are modeled, with HAWTs preferred for efficiency and VAWTs for low-speed, rooftop use. Power output is defined by:

$$P_{Turbine} = \frac{1}{2}\rho A C_p(\lambda, \beta)v^3 \quad (8)$$

where, ρ is the air density (typically 1.225 kg/m3), A is the area swept by the rotor blades (in m2), CP is the coefficient of power conversion and v is the wind speed (in m/s)

and torque by:

$$\lambda = \frac{\omega_m R}{v} \tag{9}$$

Where ω_m and R are the rotor angular velocity (in rad/sec) and rotor radium (in m), respectively. The wind turbine mechanical torque output $m\ T$
with the power coefficient CpC_pCp modeled as:

$$C_p = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-\left(\frac{21}{\lambda_i}\right)} \tag{10}$$

This empirical formula relates C_p to the adjusted tip-speed ratio λ_i and pitch angle β, key for optimizing turbine performance through MPPT. The system supports MPPT for optimal power extraction and is tested using MATLAB with realistic wind and solar parameters.

V. RESULTS AND OUTCOMES

A DG-UPQC model is developed in MATLAB-Simulink to improve power quality under unbalanced and nonlinear loads. Two control methods are tested: PI-based vector modulation and AI-based QC_ES. The system uses a multi-port converter for efficient direct power flow from the DG, enhancing performance and efficiency.

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

The DG_UPQC is connected to a line with a DC link powered by two hybrid renewable sources. To handle input variability, the load-end converter uses PWM signals controlled by a PI-based system. Analysis at loading points evaluates the UPQC's compensation performance under nonlinear load conditions with the DC link maintained by hybrid energy sources.

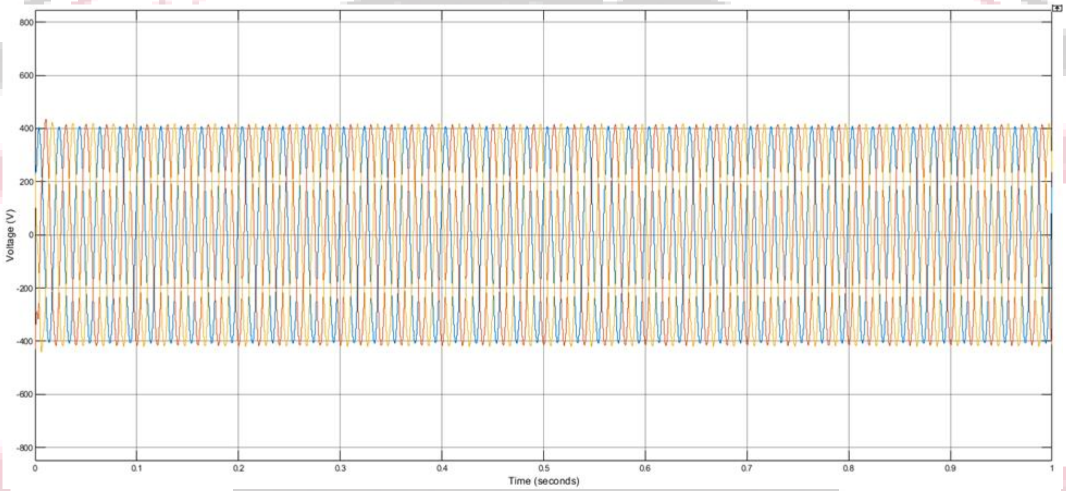


Figure 4: Three phase voltage available at the loading point of nonlinear load in system 1

Three phase voltage output available at the loading points is depicted in figure. The phase-to-phase voltage is approximately 400V in system 1.

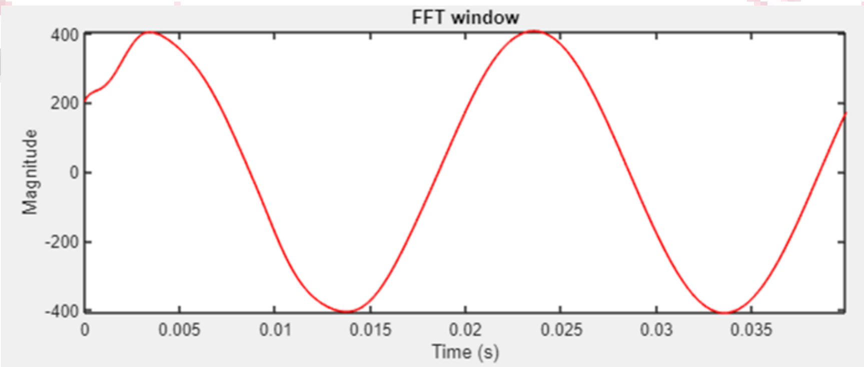


Figure 5: FFT analysis MATLAB window of voltage available at the loading point of nonlinear load in system 1

Figure 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.

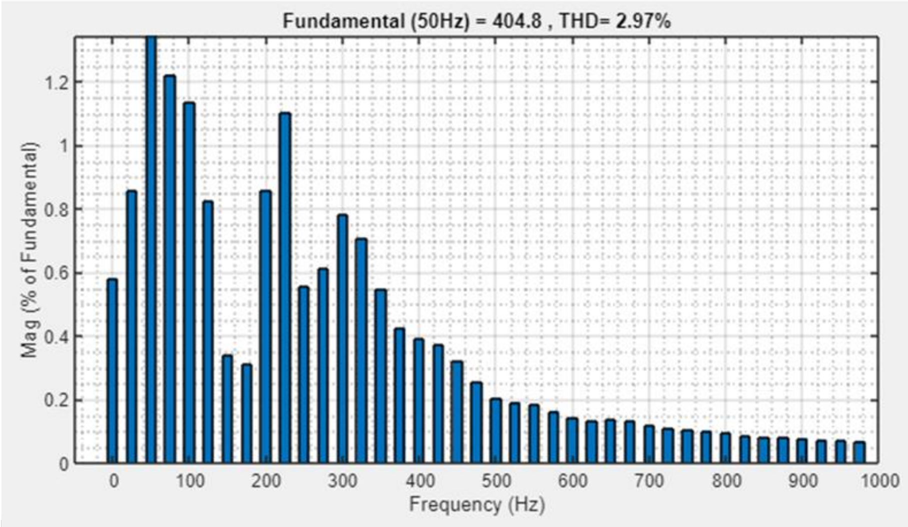


Figure 6: THD% in voltage available at the loading point of nonlinear load in system 1

The figure represents the THD% evaluation in the system 1 line voltage available at the nonlinear loading point that came out to be 2.97% when the DG_UPQC is driven by the vector-based PI regulation method of the control system.

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

Both DG_UPQC controller designs are tested under nonlinear loads, with quality analyzed through voltage and current distortion. One system uses AI-based switching with QC_ES to generate PWM signals, optimizing performance with hybrid energy inputs. A comparative analysis is performed to assess active power delivery and compensation, along with evaluating total harmonic distortion (THD) in voltage and current at the load points**.**

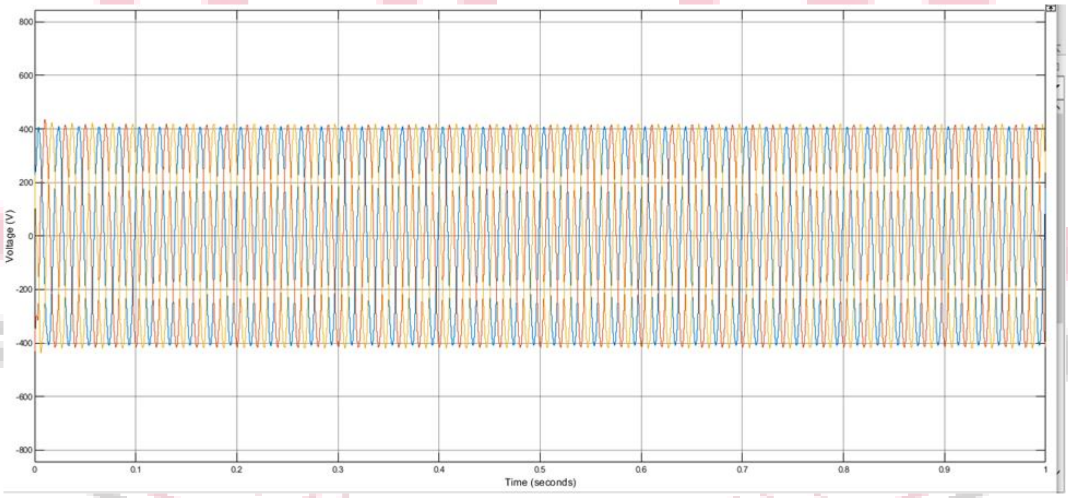


Figure 7: Three phase voltage available at the loading point of nonlinear load in system 2

Three phase voltage output available at the loading points is depicted in figure. The phase-to-phase voltage is approximately 400V in system 2

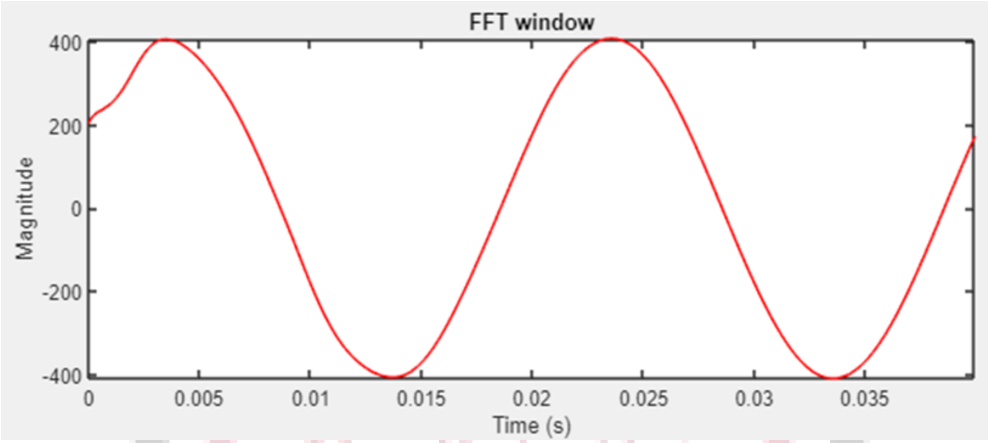


Figure 8: FFT analysis MATLAB window of voltage in line at the loading point of nonlinear load in system 2

Figure 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

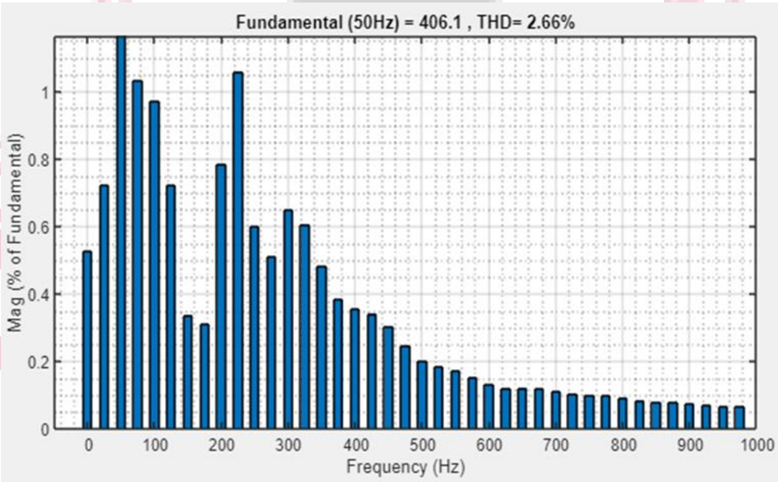


Figure 9: THD% in voltage at the loading point of nonlinear load in system 2

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

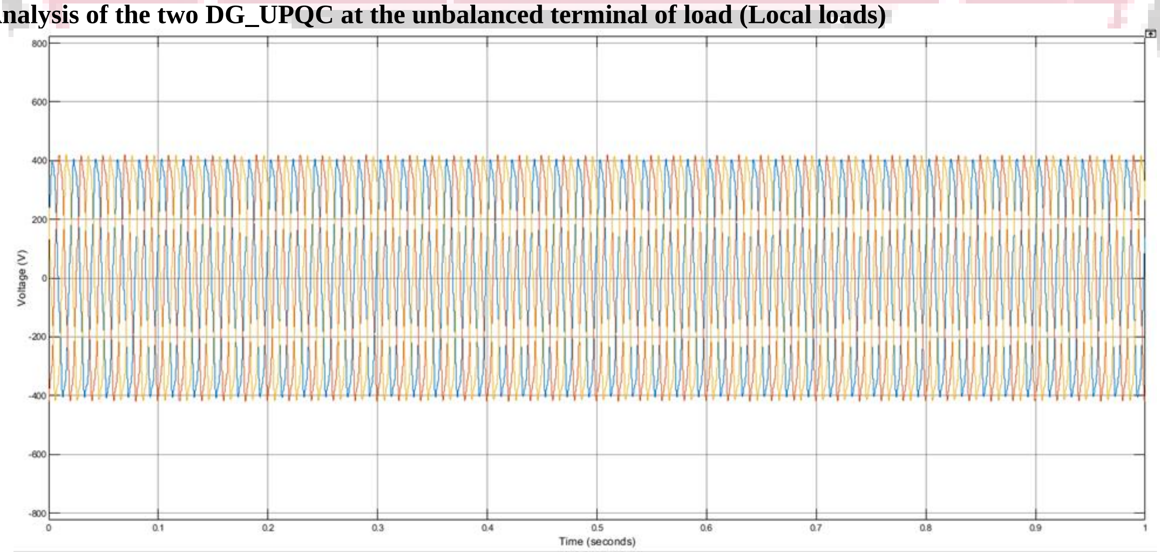


Figure 10: Voltage injected by the DG_UPQC at the unbalanced load terminal in system 1

Three phase voltage output available at the loading points where unbalanced load is connected is depicted in figure. The phase-to-phase voltage is same for all phases which is approximately 400V in system 1.

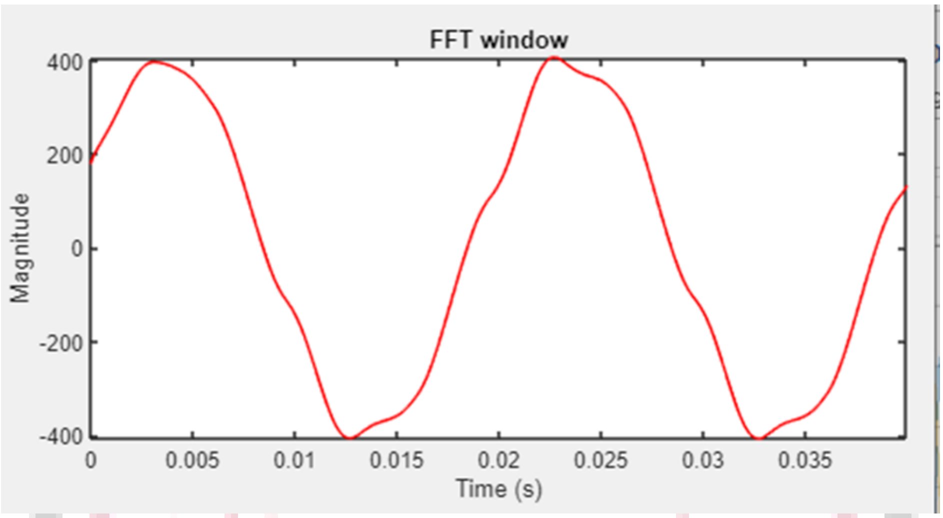


Figure 11: FFT analysis of the Voltage injected in line by the DG_UPQC at the unbalanced load terminal in system 1

Figure 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.

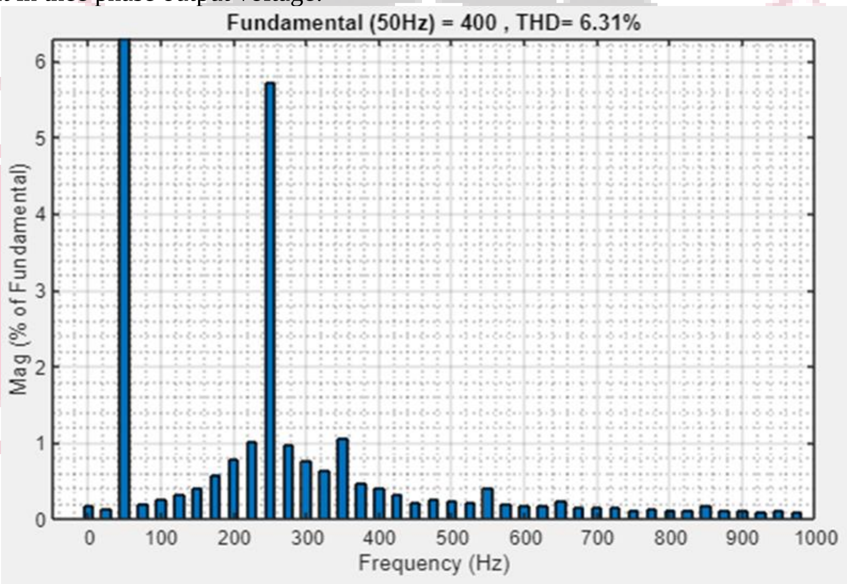


Fig. 12 THD % in the Voltage injected in line by the DG_UPQC at the unbalanced load terminal in system 1

The figure represents the THD% evaluation in the system 1 line voltage available at the unbalanced loading point that came out to be 6.31% when the DG_UPQC is driven by the vector-based PI regulation method of the control system.

Table 2 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%

The table presents a comparative analysis of DG_UPQC performance under unbalanced load conditions using two different control algorithms. System 1, driven by PI-based vector modulation, shows a load voltage THD of 6.31% and current THD of 7.07%. System 2, utilizing AI-based switching with QC_ES, slightly outperforms System 1 with reduced THD values—6.24% for voltage and 6.95% for current—indicating better harmonic compensation and power quality.

VI. CONCLUSION

The proposed DG_UPQC framework, integrated with hybrid renewable sources and advanced control strategies, successfully enhances power quality under nonlinear and unbalanced load conditions. Both PI-based and AI-based control methods demonstrated effective performance, with the AI-driven QC_ES system achieving slightly better results in minimizing voltage and current harmonics. The results confirm that intelligent modulation techniques significantly improve power compensation and harmonic mitigation, supporting the deployment of efficient and stable renewable-integrated power systems. The developed UPQC model effectively addresses power quality issues, but it offers significant potential for further enhancement. Future work can explore adapting the model from a right shunt to a left shunt configuration for broader applicability. Additionally, the current controller, proven effective in compensator design, can be advanced by developing a hybrid version of the algorithm. This indicates that the field of power quality compensators remains a promising area for ongoing research and commercial innovation.

REFERENCES

[1] P. Moriarty and D. Honnery, “What is the global potential for renewable energy?,” Renew. Sustain. Energy Rev., vol. 16, no. 1, pp. 244–252, 2012, doi: 10.1016/j.rser.2011.07.151.

[2] N. L. Panwar, S. C. Kaushik, and S. Kothari, “Role of renewable energy sources in environmental protection: A review,” Renew. Sustain. Energy Rev., vol. 15, no. 3, pp. 1513–1524, 2011, doi: 10.1016/j.rser.2010.11.037.

[3] J. Mohtasham, “Review Article-Renewable Energies,” Energy Procedia, vol. 74, pp. 1289–1297, 2015, doi: 10.1016/j.egypro.2015.07.774.

[4] M. Fatiha, M. Mohamed, and A. A. Nadia, “New hysteresis control band of an unified power quality conditioner,” Electr. Power Syst. Res., vol. 81, no. 9, pp. 1743–1753, 2011, doi: 10.1016/j.epsr.2011.05.003.

[5] A. Teke and M. Tümay, “Unified power quality conditioner: A literature survey,” Journal of Electrical Systems, vol. 7, no. 1. pp. 122–130, 2011.

[6] R. A. Wanjari, V. B. Savakhande, M. A. Chewale, P. R. Sonawane, and R. M. Khobragade, “A Review on UPQC for Power Quality Enhancement in Distribution System,” Proc. 2018 Int. Conf. Curr. Trends Towar. Converging Technol. ICCTCT 2018, pp. 1–7, 2018, doi: 10.1109/ICCTCT.2018.8550918.

[7] P. Deshpande, A. Shrivastava, and A. Khare, “Different modeling aspects and energy systems of unified power qualit conditioner (UPQC): An overview,” Int. J. Renew. Energy Res., vol. 3, no. 2, pp. 395–402, 2013.

[8] Yasmeena and G. T. R. Das, “A review of UPQC topologies for reduced DC link voltage with MATLAB simulation models,” 1st Int. Conf. Emerg. Trends Eng. Technol. Sci. ICETETS 2016 - Proc., 2016, doi: 10.1109/ICETETS.2016.7603075.

[9] F. Diner, “The analysis on photovoltaic electricity generation status, potential and policies of the leading countries in solar energy,” Renew. Sustain. Energy Rev., vol. 15, no. 1, pp. 713–720, 2011, doi: 10.1016/j.rser.2010.09.026

[10] M. K. Farooq and S. Kumar, “An assessment of renewable energy potential for electricity generation in Pakistan,” Renew. Sustain. Energy Rev., vol. 20, pp. 240–254, 2013, doi: 10.1016/j.rser.2012.09.042

[11] M. A. H. Mondal and M. Denich, “Assessment of renewable energy resources potential for electricity generation in Bangladesh,” Renew. Sustain. Energy Rev., vol. 14, no. 8, pp. 2401–2413, 2010, doi: 10.1016/j.rser.2010.05.006

[12] K. Manogna, P. Tejaswi, and G. Sujatha, “Sag and Swell mitigation and Power quality improvement in grid connected hybrid system using UPQC,” J. Phys. Conf. Ser., vol. 1362, no. 1, 2019, doi: 10.1088/1742-6596/1362/1/012075

[13] G. B. Ezhiljenekkha and M. Marsalinebeno, “Review of Power Quality Issues in Solar and Wind Energy,” Mater. Today Proc., vol. 24, no. July 2009, pp. 2137–2143, 2019, doi: 10.1016/j.matpr.2020.03.670

[14] S. Samal and P. K. Hota, “Power quality improvement by solar photo-voltaic/wind energy integrated system using unified power quality conditioner,” Int. J. Power Electron. Drive Syst., vol. 8, no. 3, pp. 1416–1426, 2017, doi: 10.11591/ijpeds.v8i3.pp1416-1426

[15] P. Oza, “Power Quality Enhancement in DFIG based Wind Power System using Fuzzy Controlled UPQC,” IJRAR-International J. Res. Anal. Rev., vol. 6, no. 2, pp. 70–74, 2019

[16] A. Amita and A. K. Sinha, “Power quality comparison of grid connected wind energy system with STATCOM and UPQC,” Proc. - 2nd Int. Conf. Intell. Circuits Syst. ICICS 2018, pp. 361–365, 2018, doi: 10.1109/ICICS.2018.00079

[17] K. Sarita and S. Member, “Power Enhancement With Grid Stabilization of Renewable Energy-Based Generation System Using UPQC-FLC-EVA Technique,” vol. 8, pp. 207443–207464, 2020, doi: 10.1109/ACCESS.2020.3038313

[18] S. Samal, P. K. Hota, and P. K. Barik, “Performance Improvement of a Distributed Generation System Using Unified Power Quality Conditioner,” Technol. Econ. Smart Grids Sustain. Energy, vol. 5, no. 1, 2020, doi: 10.1007/s40866-020-00095-3.

[19] J.Sandhya, “Performance Analysis of Three-Phase Solar PV Integrated UPQC Using Space Vector Technique,” J. Sci. Technol., vol. 5, no. Volume 5, pp. 140–148, 2020, doi: 10.46243/jst.2020.v5.i5.pp140-148.

[20] K. S. Srikanth, T. K. Mohan, and P. Vishnuvardhan, "Notice of Removal: Improvement of power quality for microgrid using fuzzy based UPQC controller," Int. Conf. Electr. Electron. Signals, Commun. Optim. EESCO 2015, vol. 4, no. 2, 2015, doi: 10.1109/EESCO.2015.7253882.
[21] M. W. Hyde, A. E. Bogle, and M. J. Havrilla, "Nondestructive characterization of PEC-backed materials using the combined measurements of a rectangular waveguide and coaxial probe," IEEE Microw. Wirel. Components Lett., vol. 24, no. 11, pp. 808–810, 2014, doi: 10.1109/LMWC.2014.2348496.
[22] S. C. Devi, B. Singh, and S. Devassy, "Modified generalised integrator based control strategy for solar PV fed UPQC enabling power quality improvement," IET Gener. Transm. Distrib., vol. 14, no. 16, pp. 3127–3138, 2020, doi: 10.1049/iet-gtd.2019.1939.
[23] S. Lakshmi and S. Ganguly, "Modelling and allocation of open-UPQC-integrated PV generation system to improve the energy efficiency and power quality of radial distribution networks," IET Renew. Power Gener., vol. 12, no. 5, pp. 605–613, 2018, doi: 10.1049/iet-rpg.2017.0525.
[24] Y. Bouzelata, E. Kurt, Y. Uzun, and R. Chenni, "Mitigation of high harmonicity and design of a battery charger for a new piezoelectric wind energy harvester," Sensors Actuators, A Phys., vol. 273, no. 2010, pp. 72–83, 2018, doi: 10.1016/j.sna.2018.02.023