International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 5, October 2025, pp. 4477~4486
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i5.pp4477-4486

A comparative analysis of D-FACTS devices for power quality improvement in photovoltaic/wind/battery system

Manpreet Singh[1], Lakhwinder Singh[2]
[1]Electrical Engineering Department, Baba Banda Singh Bahadur Engineering College, IK Gujral Punjab Technical University, Punjab, India
[2]Electrical Engineering Department, Baba Banda Singh Bahadur Engineering College, Punjab, India

Article Info

Article history:

Received Mar 6, 2025
Revised Jun 30, 2025
Accepted Jul 12, 2025

Keywords:

Dynamic voltage restorer
Power quality
Total harmonic distortion
Unified power flow controller
Unified power quality conditioner

ABSTRACT

The identification and reduction of power quality events have become essential because of the growing interest in incorporating renewable energy sources to power system. The primary aim of this paper is to compare the performances of dynamic voltage restorer (DVR), unified power flow controller (UPFC) and unified power quality conditioner (UPQC) to improve power quality issues in grid-connected photovoltaic/wind/battery system by mitigating total harmonic distortion (THD). The results of the proposed research have been validated using MATLAB platform. The comparative analysis of DVR, UPFC, and UPQC in mitigating THD in a grid-connected PV/wind/battery system is presented in this paper. The comparative analysis of the results depicts that THD in voltage decreases from 51% to 44.67%, 20.94%, and 16% whereas THD in current decreases from 58% to 44%, 29.26%, and 22% after implementation of DVR, UPFC, and UPQC respectively in the proposed photovoltaic/wind/battery system. The effectiveness of the proposed system has been confirmed by comparing the results with already published techniques.

Corresponding Author:

Manpreet Singh
Department of Electrical Engineering, Baba Banda Singh Bahadur Engineering College, IK Gujral Punjab Technical University
Jalandhar, Punjab, India
Email: mnprtsingh95@gmail.com

1. INTRODUCTION

The sources of renewable energy become important because of environment degradation due to the consumption of fossil fuels. Solar and wind energy are the two most widely used green energy sources. But the main limitation of these two most used renewable energy sources is their dependent nature as their operation completely depends on the environmental factors such as availability of sunlight and wind [1]. There is occurrence of power quality issues (PQI) when these sources are integrated with the existing power system [2]. Despite the occurrence of PQI due to their grid-interconnection, these renewable energy sources are in demand at a present time as these provide better air quality, good public health, produce lesser greenhouse gases and are cost effective [3]. In the recent years, the use of renewable energy has begun to expand to almost every country, because of the short comings of the traditional energy sources, such as fossil fuel exhaustion, non-flexibility, ageing and also very low energy efficiency [4]. In a smart grid, the storage system is essential because load demand may sometimes exceed photovoltaic (PV) and wind turbine energy conversion system production. The power needed to fulfil load demand in the event of no generating power and to store extra power above and beyond load demand is taken into account while designing the size of the battery storage [5]. Because wind and PV systems rely on nature, their power inputs vary greatly as well. The power quality (PQ) improvement in the ac-bus and constant power at the DC-link are significant problems [6]. Distributed flexible AC transmission system (D-FACTS) devices improve various system parameters such as controllability, stability, and power transmission capacity. The D-FACTS devices also enhance the power system's performance. Dynamic voltage restorer (DVR), unified power flow controller (UPFC) and unified power quality conditioner (UPQC) are the most widely used D-FACTS devices used in smart grids with renewable energy sources [7]. Power flow control has become very important in smart power networks that need to include higher percentages of variable renewable energy sources. Power electronics components included in most of renewable energy sources introduce harmonics into grid-connected systems [8], [9].

Hatnapure and Chandrakar [10] reduced harmonics in order to regulate the performance of pulse width modulation based UPFC. A study is being conducted by Li *et al.* [11] to ascertain whether the UPFC can be implemented in the power grid in order to address the problems of increasing power supply capacity. Song *et al.* [12] done the analysis on the effects of grid structure characteristics and UPFC location on the needed capacity per transferred power flow. Jing *et al.* [13] examined the algorithm for power flow with a UPFC and the steady-state model of UPFC. Cai *et al.* [14] described the use of two UPFC projects in the electricity system: one is operating at 220 kV, while the other is building a 500 kV UPFC project. The viability and necessity of using UPFC were examined. Bhasin *et al.* [15] presented the performances of UPFC based controller for a single machine infinite bus power system. Lee *et al.* [16] suggested a novel topology by implementing a three-phase UPFC system using three single-phase transformers, as opposed to the two three-phase transformers used in the traditional UPFC topology, also known as series and parallel transformers. Siddula *et al.* [17] implemented fuzzy based UPFC to reduce PQI such as voltage sag, swell in the transmission lines. Hassan and Tuaimah [18] simulated the state model of UPFC using the 30-bus system of IEEE and utilized the Newton Raphson numerical analysis method to resolve system's load flow. An ideal approach for calculating the UPFC capacity is described by Shen *et al.* [19]. Nilsson *et al.* [20] presented the applications of UPFC and its variants.

Singh and Senroy [21] introduced a system for static synchronous compensator (STATCOM) and UPFC based on the holomorphic embedding technique, which is quick and adaptable. By using data mining and machine learning approaches, Angadi *et al.* [22] described how to estimate the system's severity under various load and situations both with and without a unified power flow controller. Through the use of line outage distribution factor, a suitable location for UPFC is determined by Vasudha *et al.* [23]. Harmonics generated with the operation of an induction furnace under fluctuating load have been reduced using distributed static synchronous compensator (DSTATCOM) and UPQC by Saggu *et al.* [24], [25]. Grid connection of sustainable energy sources presents PQI in the power system. D-STATCOM has been used to improve power quality in a grid connected wind energy system by Hussain *et al.* [26]. Malik and Sharma [27] implemented the three levels inverters to improve the PQI in hybrid photovoltaic-wind system. The enhancement of PQI in grid connected solar power system using UPQC has been implemented by Poongothai and Srinath [28]. Further, Sree and Ankarao [29] implemented an adaptive neuro-fuzzy inference system based controller to mitigate PQI in grid connected wind and solar system. Mishra *et al.* [30] proposed the grid-integrated photovoltaic system along-with lymphoblastoid cell lines filter for mitigating PQI. Chapala *et al.* [31] alleviated the PQI in solar-photovoltaic and battery integrated UPQC system integrated with grid. Further, PQI in grid-integrated photovoltaic system has been reduced by using series filter is developed by Hadi *et al.* [32]. Srilakshmi *et al.* [33] implemented the dynamic voltage restorer in power system with non-linear loads to improve power quality issues due to non-linear nature of loads.

Harmonics in the power system are one of the main issues with its operation. The energy supply may be interrupted if the harmonics can increase and reduce transmission line capacity. Consequently, D-FACTS devices are used to lower these harmonics. The main contribution of this paper is to address harmonic distortions in distributed generation system considering non-linear load. In this paper, the distributed generation system is considered by undertaking photovoltaic, wind power generation and power of the battery system, named as hybrid PV/wind/battery system. Simulink models of the proposed system with and without DVR, UPFC and UPQC are implemented. The comparison of performances of DVR, UPFC, and UPQC in proposed system is the novelty of this paper.

2. METHODOLOGY

2.1. Basic architectures and workings of DVR, UPFC, and UPQC

Dynamic voltage restorer is composed of step-up transformer, an AC filter, a pulse width modulation converter, and DC capacitor in the D-FACTS series. The system often employs DVR for voltage adjustment in the event of a voltage decrease. The phase-angle and the size of voltage drop affect active and reactive power. The load voltage causes a current spike when renewable energy sources are integrated to the grid. The DVR provides series voltage to the point of common coupling (PCC) to make up for the voltage loss. The voltage dips that happen during the integration of the solar panel with high active energy are taken into account by the phase correction [34]. Figure 1 displays the DVR's block diagram. The UPFC integrates a series compensator-static series synchronous compensator (SSSC) with a shunt compensator-STATCOM. These two compensators are connected via a DC connection element. On the other hand, UPQC integrates a series compensator DVR with a shunt compensator DSTATCOM via a common DC connection element [35]. Figure 2 shows the generalized block diagram of UPFC and UPQC.

There are two fully regulated inverters that make up the UPFC. A series inverter is linked to the transmission line by a series-transformer and a parallel inverter is coupled to the transmission line by a parallel-transformer. By altering the magnitude of added voltage and phase angle, which are generated by the series inverter, the real and reactive power of the transmission line can be managed [36]. The fundamental purpose of the parallel inverter is to provide the required power by the series inverter across the shared DC-link. Additionally, the parallel inverter also controls the reactive power by producing or absorbing it [37]. The working of UPQC is also similar to UPFC. Shunt inverter introduces the reactive current to improve the power factor, add harmonic current to improve the harmonics in the load current and inject negative and zero-sequence components to neutralize supply currents. It has the ability to regulate the DC-link voltage also [38]. Voltage compensation in the source is done by series inverter [39]. It also adds the required real power components to regulate the magnitude of load voltage and isolates the load bus from source voltage harmonics by injecting harmonic voltage [40].

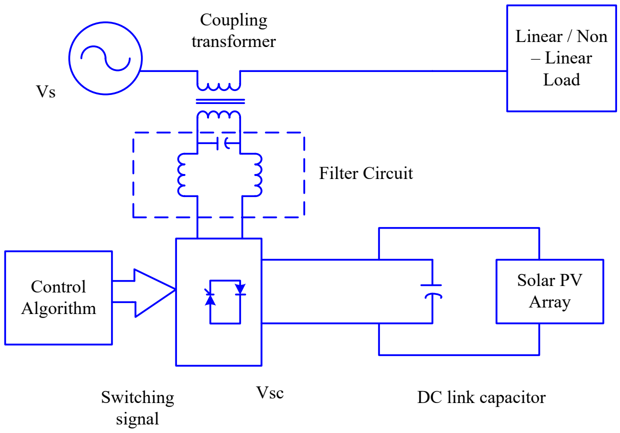

Figure 1. Block diagram of DVR

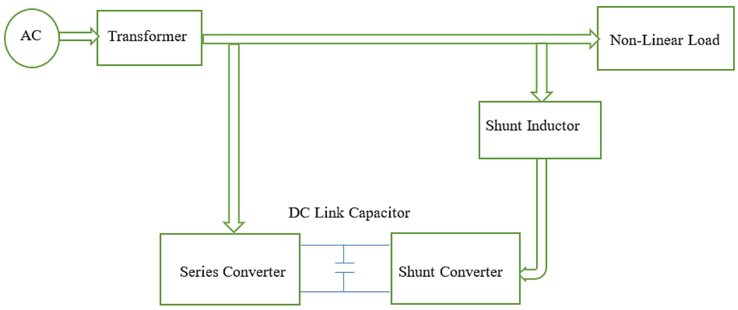

Figure 2. Generalized block diagram of UPFC and UPQC

2.2. Simulink models of the proposed system

The Simulink model of proposed PV/wind/battery system without any D-FACTS device is shown in Figure 3. To compare the performances of DVR, UPFC and UPQC in reducing total harmonic distortion (THD), four scenarios are simulated: i) hybrid PV/wind/battery system without any D-FACTS device, ii) hybrid PV/wind/battery system with DVR, iii) hybrid PV/wind/battery system with UPFC, and iv) hybrid PV/wind/battery system with UPQC. The MATLAB Simulink models of the non-linear load connected hybrid PV/wind/battery system without any compensation device and with compensation devices-DVR, UPFC and UPQC are shown in Figures 3, 4, 5 and 6, respectively. Simulation parameters used for the proposed system are given in Table 1 [41].

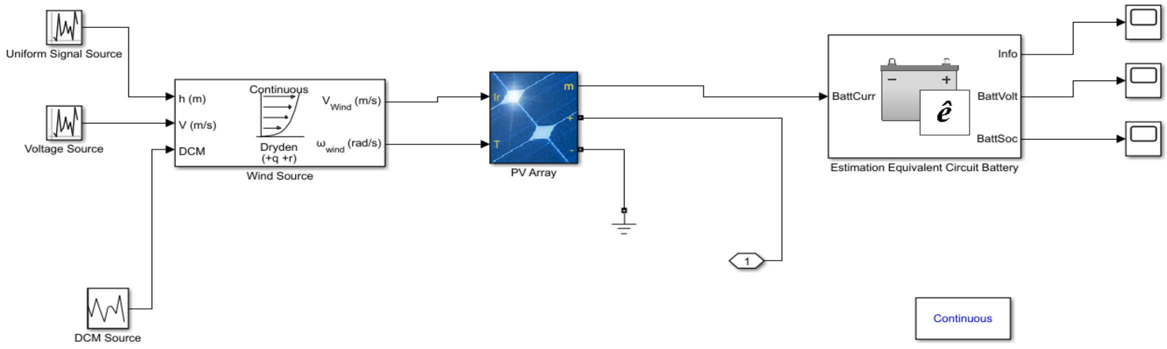

Figure 3. Simulink model of PV/wind/battery system without any compensation device

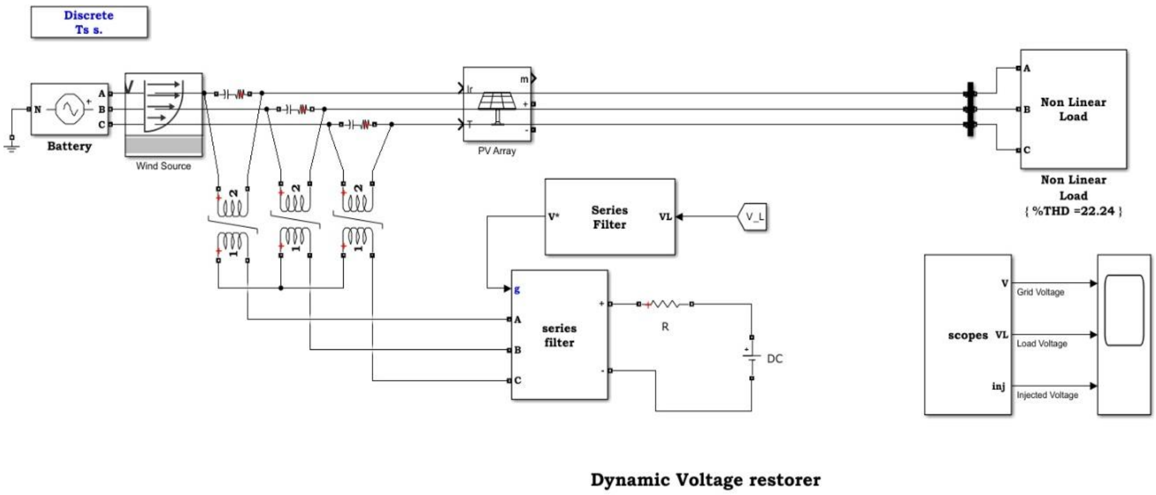

Figure 4. Simulink model of PV/wind/battery system with DVR

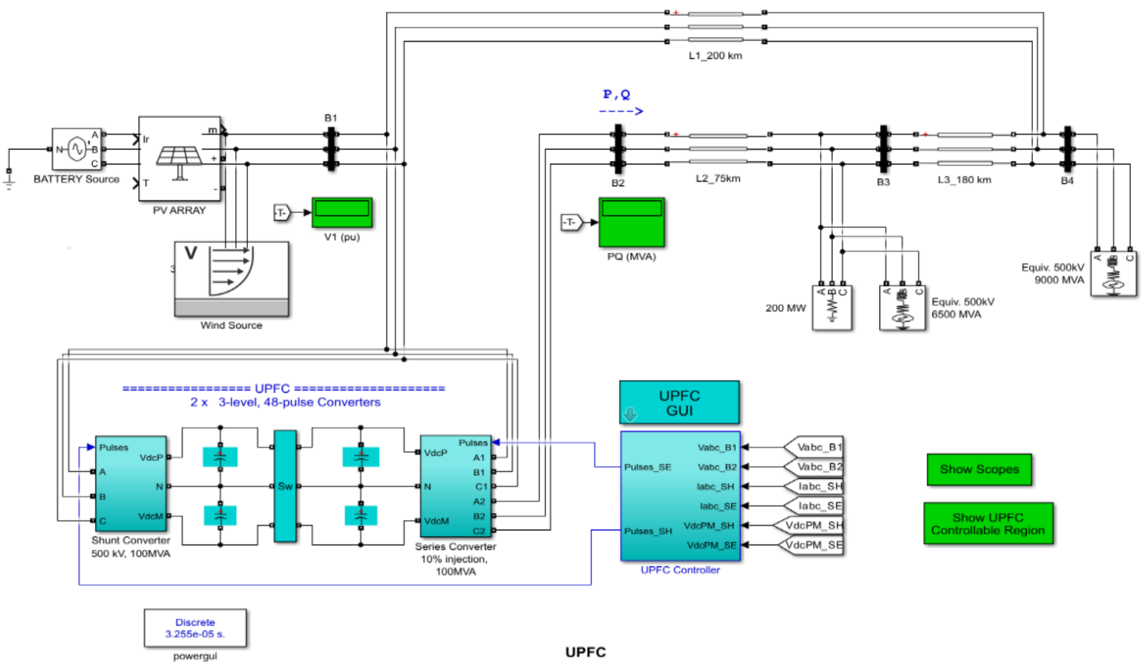

Figure 5. Simulink model of PV/wind/battery system with UPFC

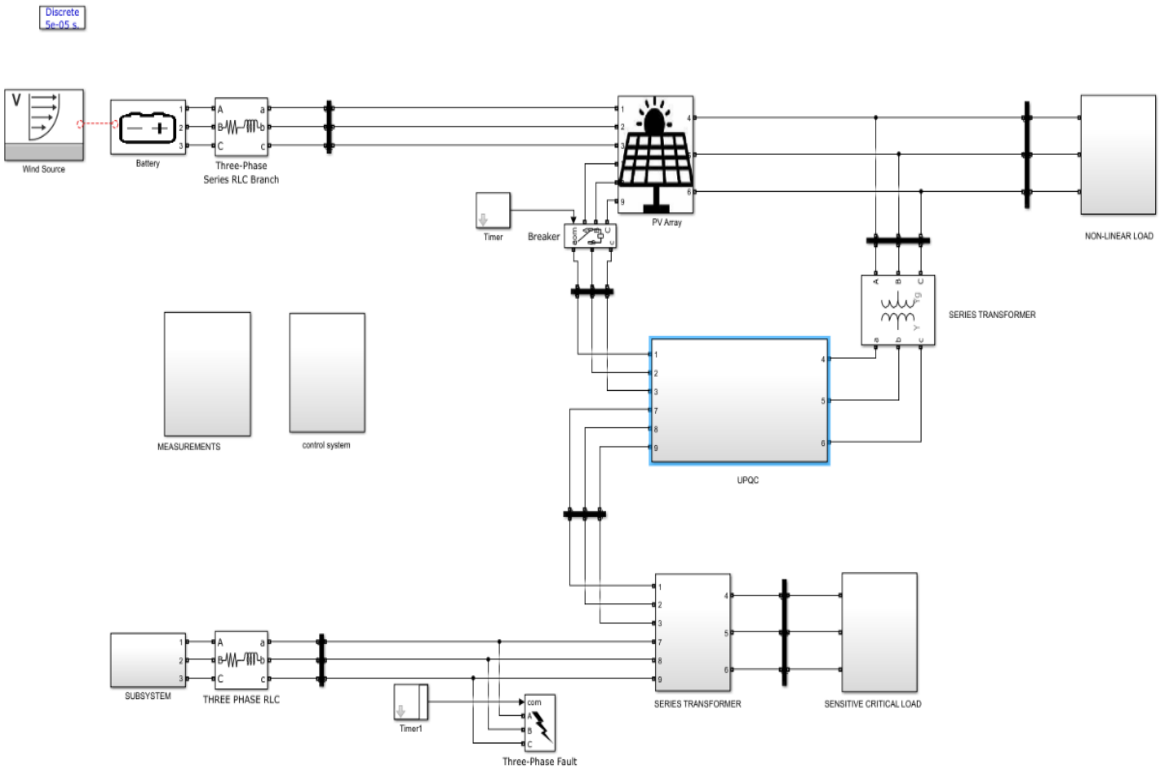

Figure 6. Simulink model of PV/wind/battery system with UPQC

Table 1. Simulation characteristics

Sr. No.	System	Characteristics	Values
1.	Wind turbine	Base torque (Nm)	8000
		Nominal mechanical output power (kW)	75
		The base power of the electrical generator (kW/pf)	75/0.9
		Base speed of wind (m/s)	10
2.	Photovoltaic	Irradiance	950
		Real power generated (kW)	30
3.	Connected grid	System phase voltage (V)	440
		System frequency (Hz)	50
4.	Non-linear load	Nominal system voltage (V)	440

3. RESULTS AND DISCUSSION

Before the integration of any compensation device in the hybrid PV/wind/battery system, the intimal values of THD measurements were obtained. The harmonics were produced into the system, because of the non-linear characteristics wind and solar energy sources. Figure 7 depicts the load voltage and current waveforms and their respective THDs of the proposed system without any compensation. Figure 8 shows the voltage and current waveforms with their respective THDs of the proposed system with DVR. THD levels were re-measured under the same operating conditions following the integration of the UPFC and UPQC into the system. Figure 9 and Figure 10 represent the load voltage and current waveforms along with their THD measurements of the proposed system with the implementation of UPFC and UPQC, respectively.

The outcomes of all the four scenarios showing comparative performances of DVR, UPFC and UPQC are summarized in Table 2. The comparison of results depicts that THD in voltage decreases from 51% to 44.67%, 20.94%, and 16% after implementation of DVR, UPFC, and UPQC respectively in the grid-integrated PV/wind/battery system. Further, THD in current decreases from 58% to 44%, 29.26%, and 22% after implementation of DVR, UPFC, and UPQC respectively in the grid-integrated PV/wind/battery system. The achieved results are also compared with the already published work [41] for the validation purpose.

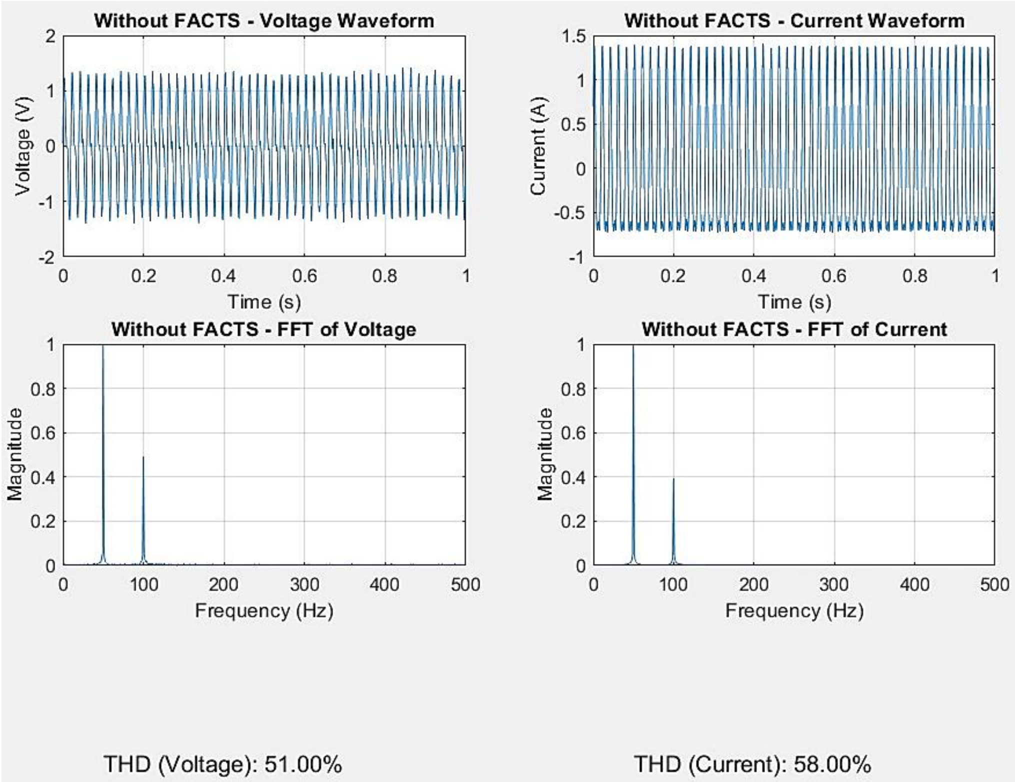

Figure 7. Load voltage, current waveforms and THD for grid connected PV/wind/battery system without any compensation

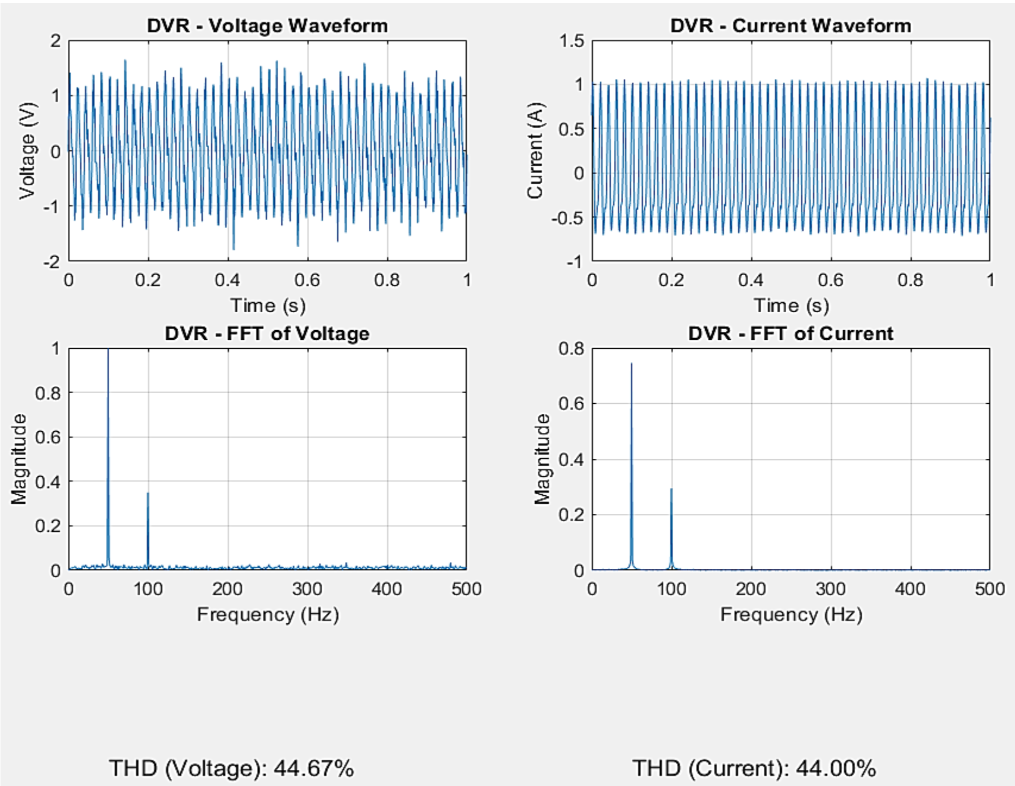

Figure 8. Load voltage, current waveforms and THD for grid connected PV/wind/battery system with DVR

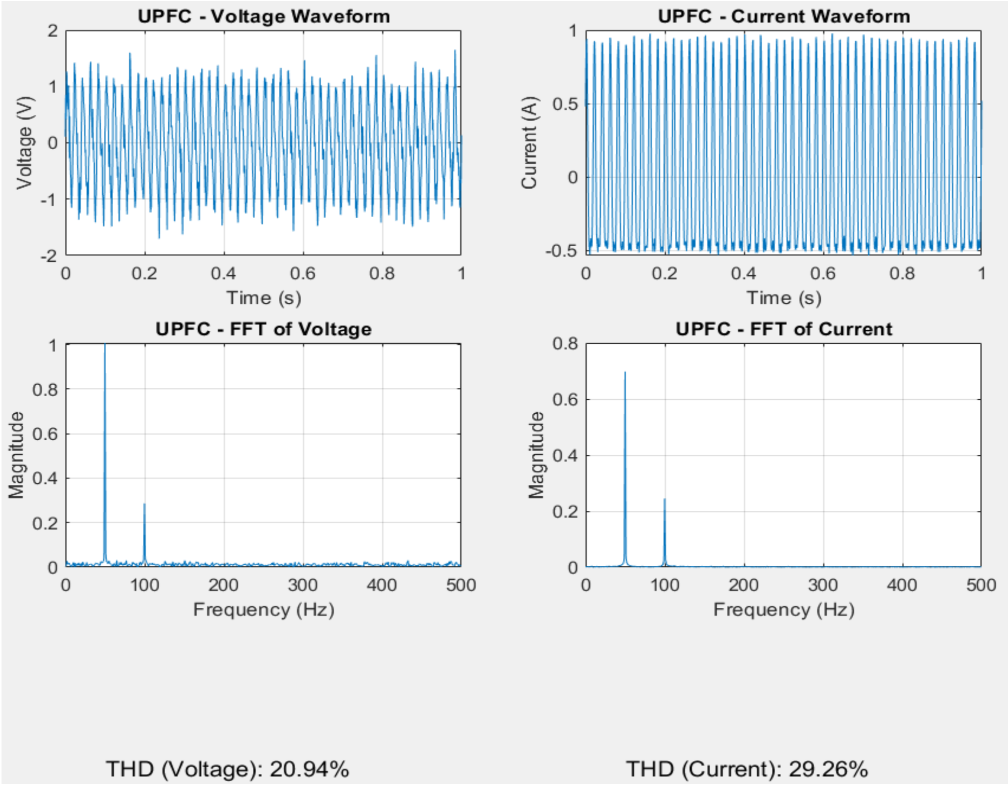

Figure 9. Load voltage, current waveforms and THD for grid connected PV/wind/battery system with UPFC

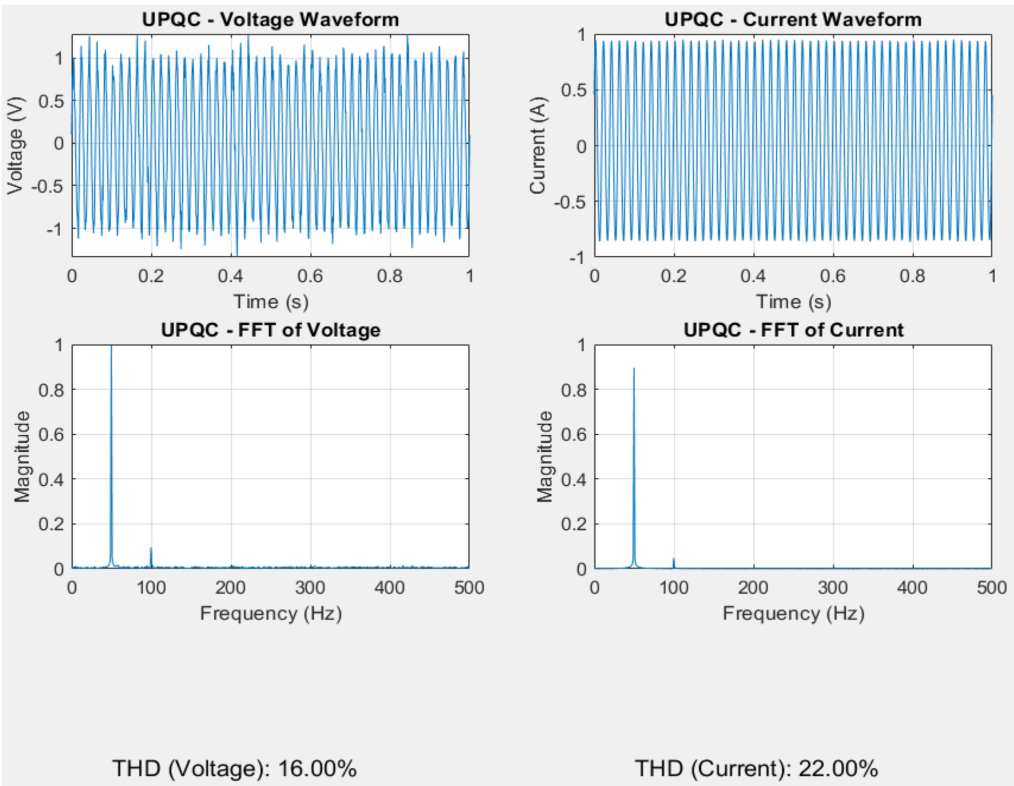

Figure 10. Load voltage, current waveforms and THD for grid connected PV/wind/battery system with UPQC

Table 2. Comparative analysis of D-FACTS devices in PV/wind/battery system

D- FACTS device	THD - Voltage (%)	THD - Current (%)
Without any compensation	51	58
DVR	44.67	44
UPFC	20.94	29.26
UPQC	16	22

4. CONCLUSION

In non-linear integrated PV/Wind/Battery system, the performances of DVR, UPFC and UPQC have been implemented and compared. In this paper, the design, simulation, and comparison of performances of DVR, UPFC, and UPQC in mitigating PQI in terms of THD has been discussed. It is obvious from the obtained results that the THD in voltage decreases from 51% to 44.67%, 20.94%, and 16% after implementation of DVR, UPFC, and UPQC respectively in the grid connected PV/wind/battery system. Further, THD in current decreases from 58% to 44%, 29.26%, and 22% after implementation of DVR, UPFC, and UPQC respectively in the grid connected PV/wind/battery system. Comparison of results validates the superior performance of UPQC over DVR and UPFC in terms of mitigation of THD. The achieved results are compared with the already published work for the validation purposes. Further the research can be performed on implementation of UPFC or UPQC with hybridized optimization techniques in solar/wind/battery/fuel cells or any other suitable combination of renewable energy systems.

ACKNOWLEDGMENTS

The authors are indebted to the I.K.G. Punjab Technical University Jalandhar, Kapurthala for providing the advanced research facilities for this research work.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Manpreet Singh	✓	✓	✓	✓	✓	✓			✓	✓				
Lakhwinder Singh		✓			✓	✓			✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] R. Venkatesan, C. Kumar, C. R. Balamurugan, and T. Senjyu, "Enhancing power quality in grid-connected hybrid renewable energy systems using UPQC and optimized O-FOPID," *Frontiers in Energy Research*, vol. 12, Jul. 2024, doi: 10.3389/fenrg.2024.1425412.

[2] A. H. A. Elkasem, S. Kamel, M. Khamies, and L. Nasrat, "Frequency regulation in a hybrid renewable power grid: an effective strategy utilizing load frequency control and redox flow batteries," *Scientific Reports*, vol. 14, no. 1, p. 9576, Apr. 2024, doi: 10.1038/s41598-024-58189-2.

[3] A. Ranjan and J. Choudhary, "Power quality enhancement in grid-connected energy system with UPQC using hybrid PSO-GWO optimization technique," *In book: Advances in Data-Driven Computing and Intelligent Systems*, 2024, pp. 23–37, doi: 10.1007/978-981-99-9531-8_3
[4] S. Choudhury and G. K. Sahoo, "A critical analysis of different power quality improvement techniques in microgrid," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 8, 2024, doi: 10.1016/j.prime.2024.100520.
[5] M. M. Gulzar, A. Iqbal, D. Sibtain, and M. Khalid, "An innovative converterless solar PV control strategy for a grid connected hybrid PV/wind/fuel-cell system coupled with battery energy storage," *IEEE Access*, vol. 11, pp. 23245–23259, 2023, doi: 10.1109/ACCESS.2023.3252891.
[6] P. K. Pandey, R. Kumar, V. Gupta, A. Kanungo, and S. Diwania, "An innovative hybrid controller-based combined grid-connected hybrid renewable energy system," *Electrical Engineering*, vol. 106, no. 6, pp. 7055–7072, Dec. 2024, doi: 10.1007/s00202-024-02363-2.
[7] B. H. Alajrash, M. Salem, M. Swadi, T. Senjyu, M. Kamarol, and S. Motahhir, "A comprehensive review of FACTS devices in modern power systems: Addressing power quality, optimal placement, and stability with renewable energy penetration," *Energy Reports*, vol. 11, pp. 5350–5371, Jun. 2024, doi: 10.1016/j.egyr.2024.05.011.
[8] P. S. Georgilakis and N. D. Hatziargyriou, "Unified power flow controllers in smart power systems: models, methods, and future research," *IET Smart Grid*, vol. 2, no. 1, pp. 2–10, Mar. 2019, doi: 10.1049/iet-stg.2018.0065.
[9] R. Kannan, B. Krishnan, K. Porkumaran, S. Prabakar, I. Elamvazuthi, and K. Srinivasan, "Power quality improvement using UPQC for grid integrated renewable energy sources," in *2020 8th International Conference on Intelligent and Advanced Systems (ICIAS)*, Jul. 2021, pp. 1–6, doi: 10.1109/ICIAS49414.2021.9642647.
[10] H. B. Hatnapure and V. K. Chandrakar, "Power quality improvement by using UPFC," in *2017 2nd International Conference for Convergence in Technology (I2CT)*, Apr. 2017, pp. 1014–1017, doi: 10.1109/I2CT.2017.8226282.
[11] P. Li, Y. Wang, C. Feng, and J. Lin, "Application of MMC-UPFC in the 500 kV power grid of Suzhou," *The Journal of Engineering*, vol. 2017, no. 13, pp. 2514–2518, Jan. 2017, doi: 10.1049/joe.2017.0780.
[12] P. Song, Z. Xu, F. Dou, and H. Cai, "Critical factor analysis and optimization method for placement and sizing of unified power flow controller," *Dianli Xitong Zidonghua/Automation of Electric Power Systems*, vol. 41, no. 13, pp. 168–175, 2017, doi: 10.7500/AEPS20161019006.
[13] W. Jing, T. Yong, X. Chang, C. Xinglei, W. Yi, and A. Ning, "Research on power flow algorithm of power system with UPFC," in *2018 International Conference on Power System Technology (POWERCON)*, Nov. 2018, pp. 2453–2457, doi: 10.1109/POWERCON.2018.8601661.
[14] H. Cai, L. Yang, H. Wang, P. Song, and Z. Xu, "Application of unified power flow controller (UPFC) in Jiangsu power system," in *2017 IEEE Power & Energy Society General Meeting*, Jul. 2017, pp. 1–5, doi: 10.1109/PESGM.2017.8274211.
[15] S. Bhasin, A. Bhargava, S. Verma, and V. Chaudhary, "Comparative simulation studies for hybrid power flow controller and UPFC based controller for SMIB system," in *2019 2nd International Conference on Power Energy, Environment and Intelligent Control (PEEIC)*, Oct. 2019, pp. 338–341, doi: 10.1109/PEEIC47157.2019.8976670.
[16] H.-J. Lee, D.-S. Lee, and Y.-D. Yoon, "Unified power flow controller based on autotransformer structure," *Electronics*, vol. 8, no. 12, p. 1542, Dec. 2019, doi: 10.3390/electronics8121542.
[17] S. Siddula, T. V. Achyut, K. Vigneshwar, and M. U. Teja, "Improvement of power quality using fuzzy based unified power flow controller," in *2020 International Conference on Smart Technologies in Computing, Electrical and Electronics (ICSTCEE)*, Oct. 2020, pp. 55–60, doi: 10.1109/ICSTCEE49637.2020.9276496.
[18] S. K. A. Al Hassan and F. M. Tuaimah, "Study impact of unified power flow controller on a transmission line performance under different loading conditions," *Journal of Engineering*, vol. 26, no. 2, pp. 176–192, Jan. 2020, doi: 10.31026/j.eng.2020.02.13.
[19] X. Shen, H. Luo, W. Gao, Y. Feng, and N. Feng, "Evaluation of optimal UPFC allocation for improving transmission capacity," *Global Energy Interconnection*, vol. 3, no. 3, pp. 217–226, Jun. 2020, doi: 10.1016/j.gloei.2020.07.003.
[20] S. Nilsson, S. Xu, B. Lei, Z. Deng, and B. Andersen, "Application examples of UPFC and its variants," *CIGRE Green Books*, pp. 1–61, 2020, doi: 10.1007/978-3-319-71926-9_15-2.
[21] P. Singh and N. Senroy, "Steady-state models of STATCOM and UPFC using flexible holomorphic embedding," *Electric Power Systems Research*, vol. 199, p. 107390, Oct. 2021, doi: 10.1016/j.epsr.2021.107390.
[22] R. V. Angadi, S. B. Daram, P. S. Venkataramu, and V. J. Manohar, "Data mining and machine learning technique in contingency analysis of power system with UPFC," *Distributed Generation & Alternative Energy Journal*, May 2022, doi: 10.13052/dgaej2156-3306.3751.
[23] D. Vasudha, D. N. C. Kotaiah, and D. K. R. Rani, "Development of static model for a current based UPFC," *International Journal of Electrical and Electronics Research*, vol. 11, no. 4, pp. 1183–1187, Dec. 2023, doi: 10.37391/ijeer-110440.
[24] T. S. Saggu, L. Singh, B. Gill, and O. P. Malik, "Effectiveness of UPQC in mitigating harmonics generated by an induction furnace," *Electric Power Components and Systems*, vol. 46, no. 6, pp. 629–636, 2018, doi: 10.1080/15325008.2018.1460641.
[25] T. S. Saggu, L. Singh, and B. Gill, "armonics mitigation in a steel industry using 11-level cascaded multilevel inverter-based DSTATCOM," *Canadian Journal of Electrical and Computer Engineering*, vol. 40, no. 2, pp. 110–115, 2017, doi: 10.1109/CJECE.2017.2681686.
[26] J. Hussain, M. Hussain, S. Raza, and M. Siddique, "Power quality improvement of grid connected wind energy system using DSTATCOM," *International Journal of Renewable Energy Research*, no. v9i3, 2019, doi: 10.20508/ijrer.v9i3.9802.g7717.
[27] M. Malik and P. R. Sharma, "Power quality improvement in hybrid photovoltaic and wind power system using 3 levels inverter," in *2020 International Conference on Advances in Computing, Communication & Materials (ICACCM)*, Aug. 2020, pp. 253–260, doi: 10.1109/ICACCM50413.2020.9212821.
[28] S. Poongothai and S. Srinath, "Power quality enhancement in solar power with grid connected system using UPQC," *Microprocessors and Microsystems*, vol. 79, p. 103300, Nov. 2020, doi: 10.1016/j.micpro.2020.103300.
[29] V. Sowmya Sree and M. Ankarao, "Power quality enhancement of solar–wind grid connected system employing genetic-based ANFIS controller," *Paladyn, Journal of Behavioral Robotics*, vol. 14, no. 1, Jun. 2023, doi: 10.1515/pjbr-2022-0116.
[30] D. P. Mishra, K. K. Rout, S. Mishra, M. Nivas, R. K. P. R. Naidu, and S. R. Salkuti, "Power quality enhancement of grid-connected PV system," *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 1, pp. 369–377, Mar. 2023, doi: 10.11591/ijpeds.v14.i1.pp369-377.
[31] S. Chapala, D. N. R. L., and D. T. R. Das, "Power quality enhancement in solar PV and battery integrated UPQC grid connected system," *International Journal of Electrical and Electronics Research*, vol. 11, no. 2, pp. 291–298, May 2023, doi: 10.37391/ijeer.110207.
[32] H. A. Hadi, A. Kassem, H. Amoud, and S. Nadweh, "Improve power quality and stability of grid - connected PV system by using series filter," *Heliyon*, vol. 10, no. 21, p. e39757, Nov. 2024, doi: 10.1016/j.heliyon.2024.e39757.
[33] B. Srilakshmi, K. S. Reddy, H. Mahadeva, and M. Gayathri, "Power quality improvement using dynamic voltage restorer," in

2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT), May 2018, pp. 558–561, doi: 10.1109/RTEICT42901.2018.9012583.
[34] N. Abas, S. Dilshad, A. Khalid, M. S. Saleem, and N. Khan, "Power quality improvement using dynamic voltage restorer," *IEEE Access*, vol. 8, pp. 164325–164339, 2020, doi: 10.1109/ACCESS.2020.3022477.
[35] H. Manoharan, S. Karuppannan, K. Chandrasekaran, and S. Barua, "Power quality improvement of grid-connected solar power plant systems using a novel fractional order proportional integral derivative controller technique," *IET Renewable Power Generation*, vol. 18, no. 15, pp. 3268–3284, Nov. 2024, doi: 10.1049/rpg2.13128.
[36] M. Dehghani, M. R. Yousefi, A. Mosavi, and A. Fathollahi, "Unified power flow controller: operation, modelling and applications," *SACI 2023 - IEEE 17th International Symposium on Applied Computational Intelligence and Informatics, Proceedings*, pp. 699–704, 2023, doi: 10.1109/SACI58269.2023.10158642.
[37] M. M. Haque, M. S. Ali, P. Wolfs, and F. Blaabjerg, "A UPFC for voltage regulation in low voltage distribution feeders with a DC-link ripple voltage suppression technique," *IEEE Transactions on Industry Applications*, vol. 56, no. 6, pp. 6857–6870, Nov. 2020, doi: 10.1109/TIA.2020.3023068.
[38] A. Qasim, F. Tahir, and A. Alsammak, "Voltage sag, voltage swell and harmonics reduction using unified power quality conditioner under nonlinear loads," *Iraqi Journal for Electrical and Electronic Engineering*, vol. 17, no. 2, pp. 140–150, Dec. 2021, doi: 10.37917/ijeee.17.2.16.
[39] A. Bindu, K. S. Kavin, N. Kumar, and S. Sharma, "Reinventing power quality enhancement: deep reinforcement learning control for PV-UPQC in microgrids," *Electrical Engineering*, vol. 107, no. 4, pp. 4979–4999, 2025, doi: 10.1007/s00202-024-02778-x.
[40] A. Heenkenda, A. Elsanabary, M. Seyedmahmoudian, S. Mekhilef, A. Stojcevski, and N. F. A. Aziz, "Unified power quality conditioners based different structural arrangements: a comprehensive review," *IEEE Access*, vol. 11, pp. 43435–43457, 2023, doi: 10.1109/ACCESS.2023.3269855.
[41] B. S. Goud and B. L. Rao, "Power quality enhancement in grid-connected PV/Wind/ Battery using UPQC: atom search optimization," *Journal of Electrical Engineering & Technology*, vol. 16, no. 2, pp. 821–835, Mar. 2021, doi: 10.1007/s42835-020-00644-x.

BIOGRAPHIES OF AUTHORS

Manpreet Singh is working as an assistant professor in electrical engineering at Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib, Punjab, India. He has obtained his B.Tech. (Electrical) in 2006 from Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib and M.Tech. (Electrical engineering) in 2013 from Guru Nanak Dev Engineering College, Ludhiana. His research interests include energy management, power quality improvement, smart grids and renewable energy systems. He can be contacted at email: mnprtsingh95@gmail.com.

Lakhwinder Singh is working as a dean academics and professor in electrical engineering at Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib, Punjab, India. He has obtained his B.E. (Electrical) in 1990 from Guru Nanak Dev Engineering College, Ludhiana, M.E. (Power systems) in 1995 from Punjab University, Chandigarh and Ph.D in 2009 from Punjab Technical University, Jalandhar. He is a member of IEEE, life member of the Indian Society for Technical Education and a fellow of the Institution of Engineers (India). He is the author of 72 technical papers published in national and international journals/conferences. His research interests include fuzzy logic, optimization techniques, power system operation and control, power quality improvement, smart grids and renewable energy systems. He can be contacted at email: b_lakh@yahoo.com.