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Enhancing Power Quality in Microgrids with Integrated Distributed Energy Resources: A Comprehensive Analysis

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Abstract: - The conversion of electrical energy in microgrid systems presents challenges that can potentially impact Power Quality (PQ) through voltage variation, Total Harmonic Distortion (THD), and various other issues. This study assesses the power quality of a Microgrid (MG) that incorporates Distributed Energy Resources (DERs) in both On-grid and Off-grid operational modes. The MG test system is simulated employing the MATLAB/SIMULINK software, and load flow simulations are performed for four distinct scenarios. The findings indicate that the integration of the microgrid has a notable influence on the harmonic characteristics of current and voltage during Off-grid operation. One potential solution to this problem entails the deployment of a 3Φ harmonic filter, which has the capability to mitigate the magnitude of harmonics existing within the system efficiently.

Keywords: Harmonics, IEEE test system, THD, Harmonic Filter.

1. Introduction

In the context of evaluating PQ in the operation and control of resilient MG, it has been established that the integration of various DERs leads to the significant presence of non-linear characteristics within the system. The MG is composed of DERs that are interconnected based on their geographical locations. This interconnection introduces additional variables and equations, such as wind speed, humidity, solar irradiance level, meteorological conditions, temperature, and seasons. To ensure the steady and dependable functioning of microgrids, it is imperative to uphold PQ at a level that optimally satisfies users while minimizing the strain on Distributed Generators (DGs). Custom Power Devices (CPDs), such as the Dynamic Voltage Restorer (DVR), Active Power Conditioner (APC), Distribution Static Synchronous Compensator (DSTATCOM), and Active Voltage Conditioners (AVC), have been known for their advantageous role in enhancing PQ. These devices effectively address disturbances such as interruptions, voltage sag/swell, and harmonics (Jitender Kaushal et al., 2020). In (Y. Li et al., 2013) provide an overview of several PQ control strategies, such as advanced fuzzy power extraction control, inductively active filtering method, unified power quality conditioner (UPQC), and advanced reactive power compensation. These methods have demonstrated the significance of PQ control for both high and low levels of power systems, ensuring the satisfaction of power suppliers and customers. Regarding the improvement of PQ, one potential measure is the implementation of the UPQC, which serves to mitigate the effects of current and voltage harmonics (N. Gowtham et al., 2018). The utilization of CPDs is discussed in (B. S. Kumar et al., 2018), which demonstrates an extensive range of surveys conducted on PQ control to enhance customer satisfaction. Sparse signal decomposition using hybrid dictionaries can be employed to detect and classify PQ issues, considering different levels of noise (M.S. Manikandan et al., 2015). Static Var Compensation (SVC) and active filters can be utilized to maintain the three-phase current and power factor, thereby improving PQ with the use of reactive power correction (Y. Liu et al., 2018).

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The concept of microgrids involves the integration of DG units, such as micro-turbines, wind turbines, PV panels, fuel cells, and others, inside their respective geographical perimeters. The configuration of control, administration, and coordination in a typical microgrid context is recognized as a necessity at various levels of DERs and networks [Nikos Hatziargyriou et al., 2014]. The development of the active damping strategy, reduction in the size of the LC filter, and deployment of a robust fuzzy logic supervisor [F.S. Tidjani et al., 2017] can improve the PQ and power energy management dependability of an autonomous microgrid. The implementation of a new cost-function-based decentralized control technique for the compensation of current and voltage unbalance and harmonics at a common bus of loads is proposed to ensure PQ. This methodology is being compared to existing virtual impedance-based methods and is found to be more effective due to its ability to address the nonlinearities of inverters (J. Liu et al., 2019). The fuzzy droop control strategy is contrasted with current virtual impedance-based techniques in the development of a storage system for the direct current (DC) MG (Y. Mi et al., 2016). The regulation of grid-side power factor, reactive and active power flow, and THD can be accomplished through the implementation of a double-band hysteresis controller in grid-integrated DERs (V. Rajakumar et al., 2018). The potential for coordination among various storage devices can be improved through the deployment of Model Predictive Control (MPC) for load frequency regulation, as suggested by (M. Elsisi et al., 2018). The management of coordination between active power sharing and voltage regulation is accomplished through the use of droop control mechanisms inside the interconnected AC/DC MGs (S. Peyghami et al., 2018). In (P. Ray et al., 2022) examine the integration of PV systems with a UPQC in distribution networks. This study examines the influence of PV integration on PQ issues and evaluates the efficacy of the UPQC system in alleviating voltage variations, harmonic distortions, and load imbalances. Therefore, this study aims to conduct PQ analysis on an MG that is linked with multiple DERs and operates in On-grid and Off-grid modes. Furthermore, various controllers/compensators will be installed at critical locations within the MG to improve its PQ.

2. Problem definition

The presence of non-linear loads, such as equipment based on power electronics, gives rise to harmonic distortions, resulting in a degradation of PQ. CPDs, including AVR, UPQC, DVR, and D-STATCOM, among others, are adopted to ensure PQ for both power providers and customers. These devices are implemented to evaluate the operational efficiency of MG systems under the influence of various disturbances, such as THD, power factor, voltage sag/swell, frequency deviation, and unbalanced system conditions. The fundamental difficulty with microgrid systems is keeping the PQ parameters within reasonable limits. The voltage deviation stays within 10% of its nominal value as per IEEE Std. 1250-2011. Additionally, the allowable change in frequency deviation as per the IEEE Std. 1159–2009, should be limited to ±0.5 Hz. Furthermore, the THD of the current/voltage level should not exceed 5%, as outlined in the IEEE Std. 519–2014. In accordance with the IEC 60831-1/2 standard, it is imperative that the power factor is maintained at a level equal to or exceeding 0.9 in the system. The aforementioned issues highlight the need for implementing a proficient and reliable controller to ensure the preservation of optimal PQ in On-grid and Off-grid operational modes.

3. Proposed Methodology

The primary objective of this study is to carry out a thorough assessment of PQ in microgrid distribution systems. Specifically, the assessment focuses on the integration of DERs in two modes of operation: On-grid and Off-grid. To analyze PQ in DER modeling, the SIMULINK software tool is utilized. The simulation of a test system involves creating dynamic models of a PV system, wind turbine generator and diesel generator using SIMULINK. The Newton-Raphson method is adopted for power flow analysis to determine the current and voltage harmonics and to establish power flows and voltage profiles.

3.1 Test Case: IEEE 12-bus system

The study considers a standard IEEE 12-bus Radial Distribution System (RDS) with line and load data. Fig.1 presents the Single Line Diagram (SLD) of the IEEE 12-bus RDS, comprising 12 buses and 11 branches. The total reactive and active loads of the 12-bus system are 400kVAR and 435kW, respectively.

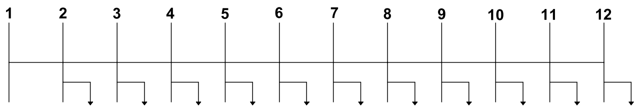

Fig.1: IEEE-12 bus RDS Single Line Diagram

3.1.1 Simulation Results of Base Case

The proposed system is simulated using the SIMULINK, and the results of the power flow simulation are obtained for the base case, in which the DG integration for static RL load is not taken into account.

Table 1 Summary of results for Base case

Bus No.	V_b in p.u	P_b in kW	Q_b in kVAR
1	1.000	427.56	397.49
2	0.9797	425.45	397.47
3	0.9897	363.67	335.78
4	0.9818	320.12	305.04
5	0.9719	263.39	251.50
6	0.9689	234.10	221.87
7	0.9663	215.49	208.34
8	0.9585	159.29	156.45
9	0.9512	118.58	114.72
10	0.9486	81.89	77.39
11	0.9478	49.39	43.42
12	0.9476	13.47	14.47

Table 1 shows lower voltage profiles at Bus no. 10, 11, and 12. Additionally, Columns Pb and Qb represent the values of real and reactive power flow at each bus. Due to the lower voltage profile observed at buses 10, 11, and 12, it has been recommended to install DGs at these buses.

Table 2 Results of Total Real and Reactive Line Losses

Total Real Line Losses in kW	17.95
Total Reactive Line Losses in kVAR	8.025

Table 2 shows the real line losses are 17.95kW and reactive line losses are 8.025kVAR of the system under consideration.

3.2 IEEE 12-bus MG system

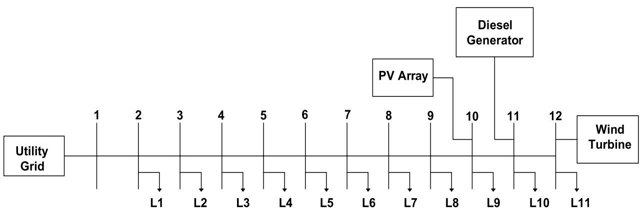

Fig.2: Illustrates the MG model concept

The study focuses on developing the MG model, using the IEEE 12-bus system. It includes wind turbines, diesel generators, and PV arrays at low-voltage buses, with a nominal voltage of 11 kV. The generator capacity is selected to ensure the MG system can function autonomously in case grid support is withdrawn. Table 3 presents comprehensive information on DERs. Fig.2 illustrates the MG model concept.

Table 3 Information on DERs

DERs	Specification	Interface
PV array	11kV,200kW	DC-AC Power Converter
Wind	11kV,250kW	Induction Generator
Diesel	11kV,100kVA	Synchronous Generator

4. Results and Discussions

The microgrid test system being analyzed is simulated using the MATLAB/SIMULINK software. Power flow simulations are carried out for four different scenarios as follows.

Case 1: In the On-grid mode, both the Grid and DERs are concurrently operational.

Case 2: The operation is limited to DERs exclusively, achieved by isolating the utility grid. This mode of operation is commonly called Off-grid mode. Within this configuration, a 500kVAR Star-type capacitor is connected at the PCC to fulfill the necessary reactive support.

Case 3: The operation of an Off-grid mode is considered, employing a 500kVAR capacitor of the Delta type.

Case 4: The operation of an Off-grid mode is examined, incorporating 3Φ Harmonic filters.

The THD of bus current, voltage, and VDI over all buses is measured and explained using load flow analysis as follows.

Case 1: In this scenario, DERs and utility resources are being utilized to supply power to various loads. The VDI for each bus is determined by analyzing the power flow of the simulated Microgrid. The THD values of the bus current and voltage were determined by employing an FFT analyzer. Subsequently, the acquired data was systematically arranged and represented in Table 4.

Table 4 Summary of results for Case-1

Bus No.	VDI	THD_I	THD_V
2	0.26	8.74	0.05
3	0.49	9.65	0.1
4	0.65	10.08	0.19
5	0.69	10.86	0.33
6	0.71	11.24	0.38
7	0.63	11.34	0.42
8	-0.19	11.73	0.6
9	-1.46	11.79	0.83
10	-2.21	11.65	0.95
11	-2.39	15.33	1
12	-2.54	11.22	1.02

The results obtained provide unambiguous evidence that by employing of Grid Support has effectively mitigated voltage fluctuations across all buses, resulting in an enhanced margin of steady-state voltage stability. In addition, it is observed that the harmonic voltage distortions of all buses remain within the prescribed limit of 5% as established by the IEEE 519-1992 standard for 11kV systems. Further, it is notable that the THDI exceeds 10% on several buses, necessitating careful consideration during the choice of compensators.

Case 2 & 3: The utility grid is effectively segregated by installing a 3Φ breaker. Consequently, only DERs responsible for meeting the energy demands of existing loads. To offer the necessary assistance for reactive power under isolated conditions, in the initial stage, a 500kVA capacitor of star configuration is connected at the PCC, and a simulation is conducted. The simulation was additionally performed with a Delta-type capacitor bank, and the findings of the capacitor bank for both configurations were recorded and presented in Table 5.

Table 5 Summary of results for Cases 2 & 3

Bus No.	VDI	THD_I	THD_V
2	3.85	22.07	21.87
3	3.46	22.1	21.85
4	3.63	22.1	21.83
5	3.58	22.1	21.82
6	3.52	22.08	21.83
7	3.42	22.05	21.81
8	2.82	21.98	21.84
9	1.42	21.9	21.75
10	0.72	21.82	21.77
11	0.42	22.04	21.73
12	0.31	22.05	21.77

In the absence of Grid Support does not significantly change the voltage variation at any buses, as evidenced by the data collected, which specifies that it remains under the acceptable threshold of 5%. The observed outcome can be obtained due to the presence of a capacitor bank that is connected at the PCC and is responsible for supplying the necessary reactive support. The presence of the electrical grid is of utmost importance due to the elevated levels of harmonic aberrations observed in both current and voltage, beyond the permitted thresholds. Hence, the utilization of a capacitor bank can improve the voltage profile; nevertheless, it is important to notice that the mitigation of harmonic distortions cannot be effectively accomplished without assistance from the power grid.

Case 4: In the current scenario, the installation of a three-phase breaker serves as an efficient means of isolating the electrical grid. As a result, only DERs are responsible for meeting the energy needs of existing loads. The utilization of a 500kVA three-phase harmonic filter at the PCC was necessitated due to the insufficient capacity of capacitor banks to effectively mitigate harmonic distortions. This filter is a composite of a single-tuned and a double-tuned filter. Subsequently, a simulation was conducted to evaluate its performance. In Table 6, the results are summarized.

Table 6 Summary of results for Case-4

Bus No.	VDI	THD_I	THD_V
2	4.36	13.46	13.08
3	4.15	13.52	13.08
4	4.17	13.53	13.07
5	3.95	13.56	13.07
6	3.79	13.57	13.07
7	3.88	13.56	13.07

8	2.99	13.53	13.07
9	1.71	13.49	13.07
10	0.79	13.44	13.07
11	0.65	14.46	13.07
12	0.37	13.18	13.07

The results reveal that the utilization of a 3Φ harmonic filter coupled at the PCC is an effective means of providing the required reactive support. Consequently, the absence of Grid Support does not have a substantial impact on the voltage variation observed at any of the buses. The adoption of a 3Φ harmonic filter instead of a capacitor bank, in contrast to the scenarios depicted in cases 2 and 3, can effectively mitigate current and voltage distortions.

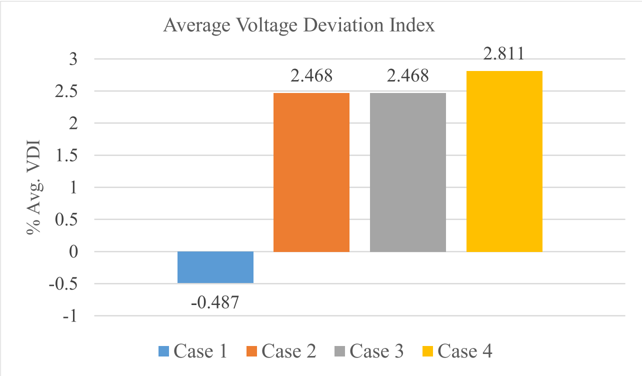

Fig. 3: The average value of the VDI

Fig.3 illustrates that the microgrid's average VDI values, both in the on-grid and Off-grid modes, are within permissible limits. The integration of DERs into an on-grid mode can improve the voltage quality of the system compared to a traditional system. Furthermore, the microgrid has the capability to regulate voltage levels within acceptable thresholds during Off-grid modes through the utilization of a capacitor bank, which serves as an adequate source of reactive power. To regulate the voltage and preserve the quality of the system's voltage, a 3Φ harmonic filter is employed as a substitute for the capacitor bank.

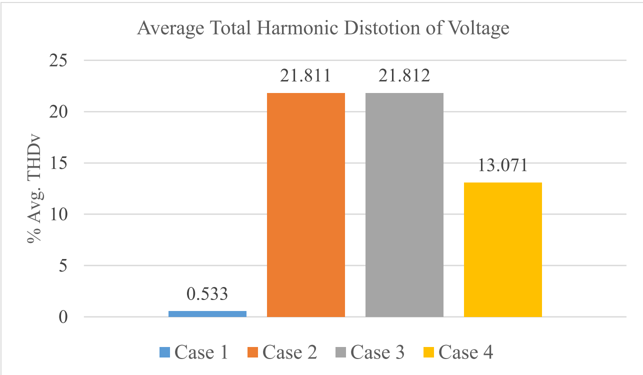

Fig. 4: The average value of the THD_V

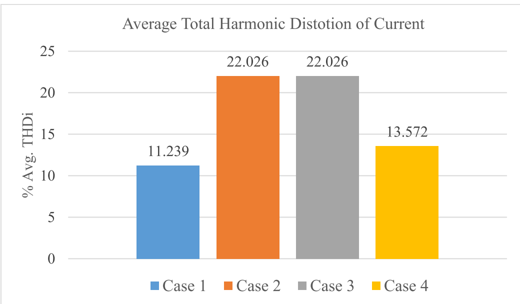

Fig. 5: The average value of the THD_I

The average THDV and THDI values for all the scenarios are shown in Fig.4 and Fig.5. The Grid-connected mode operation demonstrates an average THDV that remains under 5%. However, in the islanded mode, the average THDV experiences a rise, which is dependent upon the type of reactive power support employed. The utilization of star and delta-type capacitor banks supports reactive power resulting in an average THDV of 21.811%, which negatively affects the microgrid's electrical equipment. However, this issue can be mitigated by employing a 3Φ harmonic filter as a substitute for the capacitor bank, thereby reducing the THDV from 21.811% to 13.071%. Similarly, the average THDI dropped significantly from 22.026% to 13.572%.

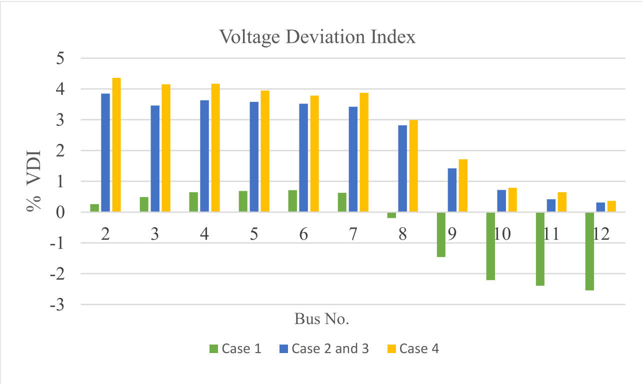

Fig. 6: VDI at the buses under different scenarios

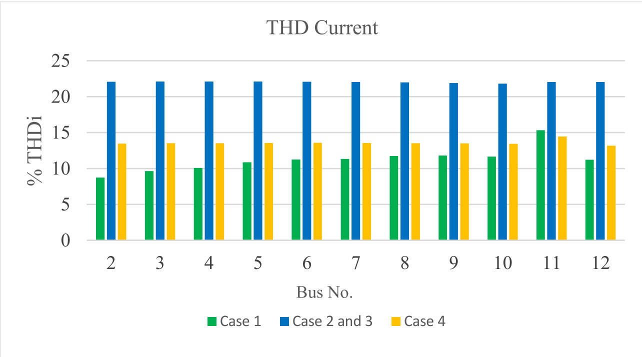

Fig. 7: Current THD at the buses under different scenarios

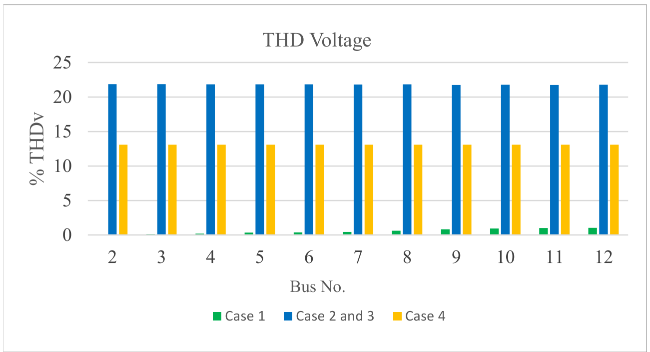

Fig. 8: Voltage THD at the buses under different scenarios

In Fig.6, VDI is depicted on all the buses under various scenarios. Meanwhile, Fig.7 and Fig.8 show Current and Voltage THD under different scenarios at all the buses. These figures reflect how VDI, THD_I, and THD_V affect all the buses under different scenarios. Moreover, this information is useful in determining an appropriate controller and its placement to mitigate the impact of harmonics within acceptable limits.

6. Conclusion

This paper discusses the importance of maintaining PQ in microgrid systems, specifically addressing the challenges related to voltage variation and total harmonic distortion. The study highlights the significant impact of current and voltage harmonics when microgrids are connected with DERs in on-grid and off-grid operations. The research suggests that current and voltage harmonics are more dominant during off-grid operation. The study proposes the use of a 3Φ harmonic filter as a feasible solution to mitigate harmonic concentration. The results indicate a significant reduction in the harmonic level, which improves the stability and effectiveness of microgrid operations overall.

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References

[1] Jitender Kaushal, Prasenjit Basak, “Power quality control based on voltage sag/swell, unbalancing, frequency, THD and power factor using artificial neural network in PV integrated AC microgrid, Sustainable Energy, Grids and Networks,” Volume 23, 2020, 100365, ISSN 2352-4677, https://doi.org/10.1016/j.segan.2020.100365

[2] Y. Li, T. K. Saha, O. Krause, Y. Cao and C. Rehtanz, "An Inductively Active Filtering Method for Power-Quality Improvement of Distribution Networks With Nonlinear Loads," in IEEE Transactions on Power Delivery, vol. 28, no. 4, pp. 2465-2473, Oct. 2013, doi: 10.1109/TPWRD.2013.2273941.

[3] Gowtham, N., & Shankar, S. (2017). UPQC: A Custom Power Device for Power Quality Improvement. Materials Today: Proceedings, 5(1), 965-972. https://doi.org/10.1016/j.matpr.2017.11.

[4] B. S. Kumar, S. Praveena and K. R. Kumar, "Power Quality Improvement using Custom Power Devices (AVC, DVR, APC)," 2018 International Conference on Current Trends towards Converging Technologies (ICCTCT), Coimbatore, India, 2018, pp. 1-5, doi: 10.1109/ICCTCT.2018.8551167

[5] M. S. Manikandan, S. R. Samantaray and I. Kamwa, "Detection and Classification of Power Quality Disturbances Using Sparse Signal Decomposition on Hybrid Dictionaries," in IEEE Transactions on Instrumentation and Measurement, vol. 64, no. 1, pp. 27-38, Jan. 2015, doi: 10.1109/TIM.2014.2330493.

[6] Y. -W. Liu, S. -H. Rau, C. -J. Wu and W. -J. Lee, "Improvement of Power Quality by Using Advanced Reactive Power Compensation," in IEEE Transactions on Industry Applications, vol. 54, no. 1, pp. 18-24, Jan.-Feb. 2018, doi: 10.1109/TIA.2017.2740840.

[7] Nikos Hatziargyriou, The microgrids concept, in: Microgrids: Architectures and Control, IEEE, 2014, pp. 1–24.

[8] F. S. Tidjani, A. Hamadi, A. Chandra, P. Pillay and A. Ndtoungou, "Optimization of Standalone Microgrid Considering Active Damping Technique and Smart Power Management Using Fuzzy Logic Supervisor," in IEEE Transactions on Smart Grid, vol. 8, no. 1, pp. 475-484, Jan. 2017, doi: 10.1109/TSG.2016.2610971.

[9] J. Liu, Y. Miura and T. Ise, "Cost-Function-Based Microgrid Decentralized Control of Unbalance and Harmonics for Simultaneous Bus Voltage Compensation and Current Sharing," in IEEE Transactions on Power Electronics, vol. 34, no. 8, pp. 7397-7410, Aug. 2019, doi: 10.1109/TPEL.2018.2879340.

[10] Y. Mi et al., "The fuzzy droop control design for storage system of DC microgrid," 2016 Chinese Control and Decision Conference (CCDC), Yinchuan, China, 2016, pp. 6100-6104, doi: 10.1109/CCDC.2016.7532092.

[11] Rajakumar, V., & Anbukumar, K. (2018). Enhancement of power quality using double-band hysteresis controller for the grid integrated renewable energy system. International Transactions on Electrical Energy Systems, 28(11), e2623. https://doi.org/10.1002/etep.2623

[12] Elsisi, M., Soliman, M., Aboelela, A. S., & Mansour, W. (2017). Improving the grid frequency by optimal design of model predictive control with energy storage devices. Optimal Control Applications and Methods, 39(1), 263-280. https://doi.org/10.1002/oca.2346.

[13] S. Peyghami, H. Mokhtari, P. C. Loh, P. Davari and F. Blaabjerg, "Distributed Primary and Secondary Power Sharing in a Droop-Controlled LVDC Microgrid With Merged AC and DC Characteristics," in IEEE Transactions on Smart Grid, vol. 9, no. 3, pp. 2284-2294, May 2018, doi: 10.1109/TSG.2016.2609853.

[14] P. Ray, P. K. Ray and S. K. Dash, "Power Quality Enhancement and Power Flow Analysis of a PV Integrated UPQC System in a Distribution Network," in IEEE Transactions on Industry Applications, vol. 58, no. 1, pp. 201-211, Jan.-Feb. 2022, doi: 10.1109/TIA.2021.3131404.