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Enhancement of large PV-integrated grid stability using an advanced UPQC

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ABSTRACT

This paper presents an enhancement to the stability of large PV-integrated grids using an advanced power quality control system. The proposed unified power quality conditioner (UPQC) system control technique combines synchronous reference frame (SRF) theory and modified unit vector template generation (MUVTG), supplemented by an additional proportional-integral-derivative (PID) controller to regulate reactive power flow to the grid. The results indicate a reduction in the total harmonic distortion (THD) levels. The study also demonstrates the system's stability for different harmonic orders and various cases of voltage sag and swell, in compliance with IEEE standards. The proposed approach effectively addresses power quality issues and achieves a THD of 0.30%, meeting the IEEE-519 standards using MATLAB Simulink.

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1. INTRODUCTION

The integration of solar photovoltaic arrays into electrical grids has significantly increased due to their provision of clean, renewable energy [1]. However, large-scale solar plants connected to the grid face challenges in maintaining stable electricity generation due to power quality problems, such as voltage sags, swells, and harmonic distortions [2], [3]. These issues compromise the reliability and performance of the systems, underscoring the need for effective mitigation technologies [4]. Unified power quality conditioners (UPQC) have emerged as a promising solution, capable of addressing multiple power quality problems [5]-[8]. Integration of a 1.5 MW solar photovoltaic system, designed to overcome power quality problems [9].

UPQC system utilizes a blend of synchronous reference frame (SRF) theory and modified unit vector template generation (MUVTG), combined with a proportional-integral-derivative (PID) controller for effective reactive power flow control [10], [11]. SRF theory aids in synchronizing control signals with the grid voltage waveform, ensuring precise control under variable grid conditions [12], [13]. MUVTG is employed to generate reference templates that align accurately with specific grid disturbances, facilitating effective compensation [14], [15]. The PID controller is integral to the system's performance, regulating reactive power flow to the grid, providing robust and dynamic responses, and ensuring system stability across varying conditions and loads [16]-[18]. The integration of these technologies aims to reduce total harmonic distortion (THD) levels, meet industry standards, and enhance grid performance, ultimately promoting the use of renewable energy through advanced power quality management.

2. LITERATURE REVIEW

A comprehensive literature review is essential for examining the integration of a 1.5 MW solar photovoltaic array with advanced power quality control systems to adherence the benchmarks like THD levels and IEEE-519 standards is crucial for maintaining industry compliance. The fault tree analysis [19] is utilized to identify critical faults in large-scale grid-connected PV systems, such as solder bond failures and interconnect issues. A fault diagnostic technique [20] using signal excitation was developed to detect and identify defective modules in large-scale PV installations, improving fault detection and operational reliability.

Integrating a UPQC with a PV system [21], was proposed using a hybrid maximum power point tracking technique and d-q control to enhance power quality and clean energy generation. UPQC linked with PV and battery energy systems, to stabilize voltage and minimize distortions, significantly reducing THD and improving power factor [22]. Power quality concerns are addressed in grid-connected PV systems with a UPQC, achieving effective voltage harmonic mitigation and grid synchronization [23]. Enhanced UPQC [24], utilizes distributed generation to supply reactive power assistance to the grid, using advanced control methods for better load management and system stability to improve resistance against voltage sags, verified through simulations in MATLAB-Simulink [25]. These studies collectively contribute to advancing PV system reliability and power quality management, crucial for sustainable energy development.

As of June 30, 2023, the National Solar Mission is an initiative by India to promote solar energy, achieving 70.10 GW of installed capacity, which can surpass 500 GW according to the ministry of new and renewable energy India. The intermittent nature of solar energy can cause stability issues when integrated with the conventional electric grid. Photovoltaic systems must adhere to grid integration IEEE standards ensuring safe and efficient photovoltaic system integration into the grid.

The literature review primarily focuses on power quality enhancement, with limited consideration of voltage stability under dynamic grid conditions. Additionally, there is limited research on the integration of large-scale PV systems into the grid. This paper addresses power quality disturbances in the distribution system and regulates the reactive power flow into the grid. The main features of the proposed method include:
- Reduction of power quality issues: Mitigates voltage sag, swell, and harmonic disturbances caused by both linear, non-linear loads and different faults under various scenarios using UPQC.
- Integrates the 1.5 MW photovoltaic system into the grid using the UPQC, ensuring a constant DC voltage despite voltage power quality issues and harmonics.
- Steady power supply: Ensures consistent power delivery to the grid, even during PV power generation and voltage fluctuations, enhancing distribution network stability.
- Maintains a THD below 5% at the point of common coupling (PCC).

3. PROPOSED METHODOLOGY

The research focuses on large-scale 1.5 MW solar photovoltaic array that is integrated with the grid using UPQC to address several power qualities concerns that are often encountered in grid-integrated solar energy systems which includes voltage sags, voltage swells, and harmonic distortions. Figure 1 shows the simulation model of proposed system.

3.1. System design

The design of the UPQC is essential, as it requires connecting the solar photovoltaic array system to a common DC link. This involves choosing the correct ratings for the DC capacitor and voltage for the DC bus. The details for the 1.5 MW photovoltaic modules and mathematical model of UPQC with grid are considered in the proposed system [26]. The control technique for the UPQC system combines SRF theory and MUVTG.

3.2. Synchronous reference frame theory

Using the SRF-based control strategy, the proposed controller manages the shunt APF, as shown in Figure 2. The SRF method calculates the desired source currents from the load currents by applying a dq0-to-abc transformation [24].
- Synchronization with grid voltage: SRF theory ensures that control signals match the grid's voltage waveform. This means that the control signals Vref and Iref are in synchronization with the grid voltage Vgrid. Mathematically, this can be represented as (1) and (2).

$$V_{ref}(t) = V_{grid}(t) \quad (1)$$

$$I_{ref}(t) = I_{grid}(t) \quad (2)$$

- Reference signal generation: Mathematically, the reference signals can be represented as (3) and (4).

$$V_{ref}(t) = V_{grid}(t) + \Delta V \quad (3)$$

$$I_{ref}(t) = I_{grid}(t) + \Delta I \quad (4)$$

- Enhanced control accuracy: By transforming AC quantities into a rotating reference frame (d-q frame), SRF theory simplifies the control of AC signals. This transformation is represented by (5) and (6).

$$V_d = V_{grid} \cos(\theta) + V_{grid} \sin(\theta) \quad (5)$$

$$V_q = -V_{grid} \sin(\theta) + V_{grid} \cos(\theta) \quad (6)$$

- Harmonic mitigation: The theory aids in the detection and compensation of harmonics in the power system. This compensation can be represented mathematically as (7).

$$V_{comp} = V_{grid} - V_{hormonic} \quad (7)$$

- Voltage and current regulation: SRF theory ensures precise regulation of voltage and current waveforms. This regulation is represented mathematically as (3) and (4).

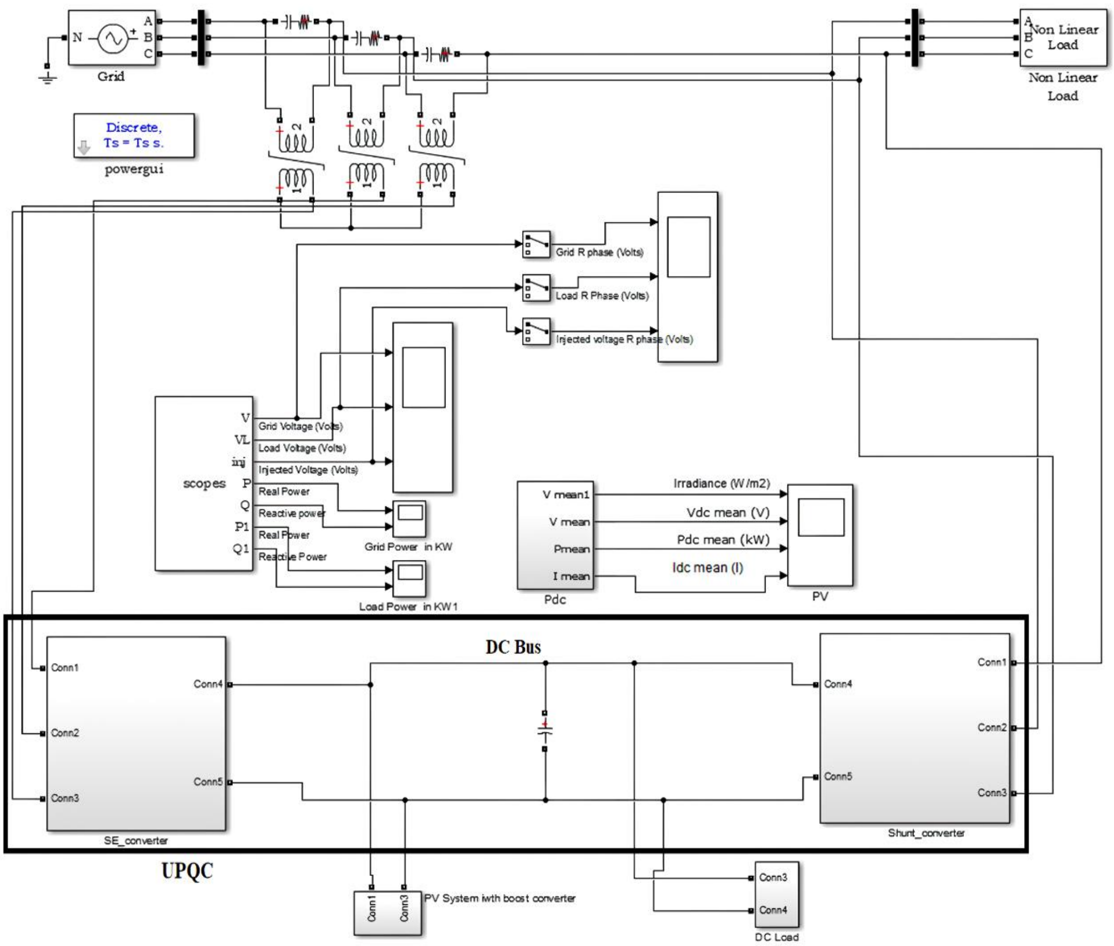

Figure 1. Simulation model of the proposed system

3.3. Modified unit vector template generation (MUVTG)

MUVTG is a technique employed in UPQC, aimed at refining the control of electrical parameters such as voltage and current. Figure 3 illustrates a basic control scheme for MUVTG in a series active power filter (APF) [24]. This method is used to generate the required pulse-width modulation (PWM) pulses for APF control.

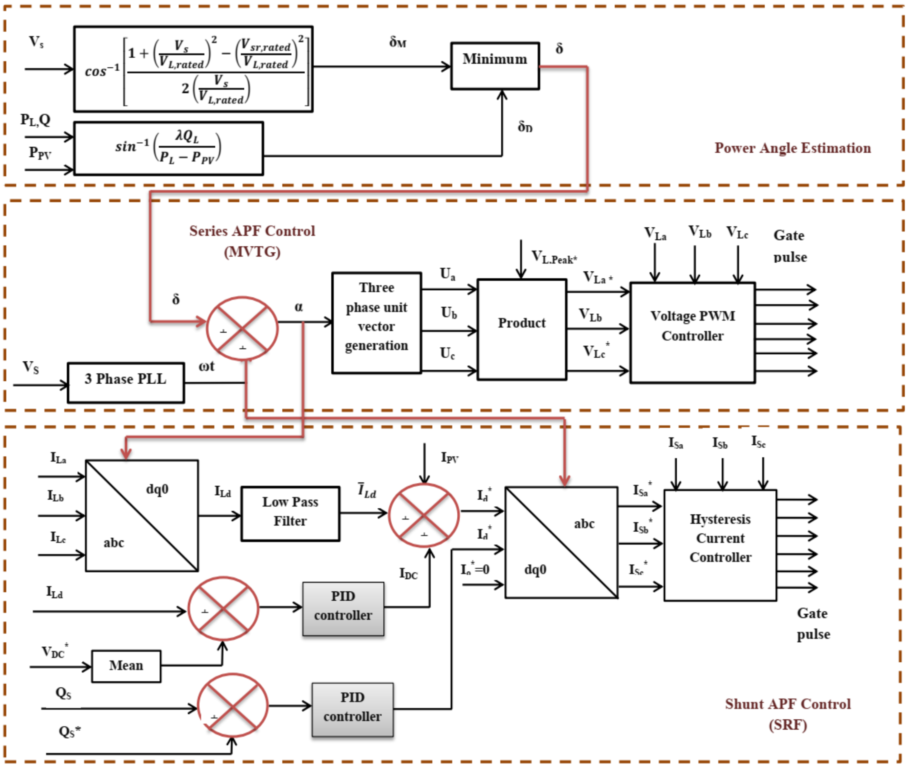

Figure 2. Enhanced grid support via UPQC-DG controller

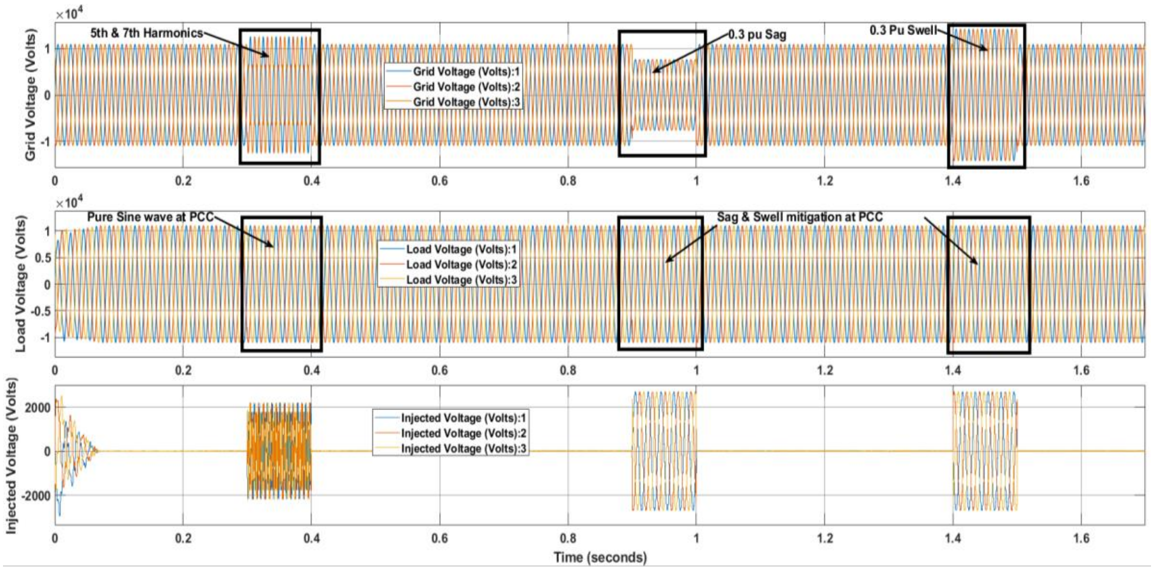

Figure 3. Performance of a UPQC during 0.3 p.u. voltage sag and swell conditions

The reference voltage waveform is represented as Vref (t) and the actual grid voltage waveform as Vgrid (t). Similarly, the reference current waveform is denoted as Iref (t) and the actual grid current waveform as Igrid (t). MUVTG can be expressed by (8) and (9).

$$V_{ref}(t) = V_{template}(t) + \Delta V \quad (8)$$

$$I_{ref}(t) = I_{template}(t) + \Delta I \quad (9)$$

Where, V_template (t) and I_template (t) are the ideal reference templates for voltage and current, respectively. ΔV and ΔI are adjustments made to the reference templates based on the specific conditions of the power system. V_ref (t) and I_ref (t) are the modified reference signals used by the control system.

3.4. Reactive power control

The integration of a PID controller into a UPQC system significantly enhances its capability to regulate reactive power, respond dynamically to grid changes, and maintain overall system stability. Its simplicity and effectiveness make it a critical component in the pursuit of high-performance power quality management. The output of a PID controller, u(t), can be expressed as (10).

$$u(t) = Kp * e(t) + Ki * \int[0\ to\ t]\, e(\tau)d\tau + Kd\ \left({}^{de(t)}/_{dt} \right) \tag{10}$$

Here, u(t) stands for the control output, K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively, and e(t) is the error signal, which is the difference between the desired setpoint and the actual measured process variable.

- Error signal: The error signal e(t) is expressed as (11).

$$e(t) = r(t) - y(t) \tag{11}$$

  Where r(t) is the reference value (set point); y(t) is the measured process variable.
- Proportional term: The proportional term provides an output that is proportional to the current error value:

$$P(t) = Kp * e(t) \tag{12}$$

- Integral term: The integral term provides an output that is proportional to the cumulative sum of past errors, thus addressing the accumulated offset:

$$I(t) = Ki * \int[0tot]\, e(\tau)d\tau \tag{13}$$

- Derivative term: The derivative term provides an output that is proportional to the rate of change of the error, predicting future error based on its current rate of change:

$$D(t) = Kd * \left(\left(de(t) \right)/dt \right) \tag{14}$$

- Combined PID output: Combining these three terms gives the total output of the PID controller:

$$u(t) = P(t) + I(t) + D(t) \tag{15}$$

These equations collectively describe how the PID controller calculates its control output based on the error signal, aiming to minimize the error and thus maintain the stability and performance of the UPQC system. Combining SRF theory and MUVTG, supplemented by a PID controller, enhances reactive power flow control in large-scale solar photovoltaic systems.

4. RESULTS AND DISCUSSION

Simulation results from the MATLAB/Simulink environment shows the effectiveness of the proposed UPQC-DG controller. This system provides reactive power support to the grid. It involves modeling and testing a three-phase, single-stage UPQC-DG system under various dynamic conditions, such as grid voltage sag, voltage swell, load unbalancing, and changes in solar irradiation.

4.1. Case-1

Figure 3 demonstrates the capabilities of a UPQC in managing grid voltage fluctuations. It shows how the UPQC stabilizes the load voltage by rapidly adjusting its injected voltage in response to a 0.3 p.u. voltage sag and swell. Specifically, the UPQC quickly increases its voltage output to counteract sags, and decreases it to mitigate swells.

4.2. Case-2

Figure 4 illustrates the performance of a UPQC in addressing a 0.5 p.u. voltage sag and swell on the power grid. The UPQC exhibits robust control. Specifically, it injects additional voltage at around 1.2 seconds to counteract the sag, and reduces the injected voltage at approximately 1.6 seconds to mitigate the swell.

4.3. Case-3

Figure 5 showcases the capabilities of a UPQC in managing a 0.6 p.u. voltage sag and swell across three phases of a power grid. At around 1.2 seconds, it increases the voltage to counteract the sag, maintaining the load voltage almost constant. Conversely, at about 1.6 seconds, it reduces the injected voltage to mitigate the swell, minimizing disruption to the load.

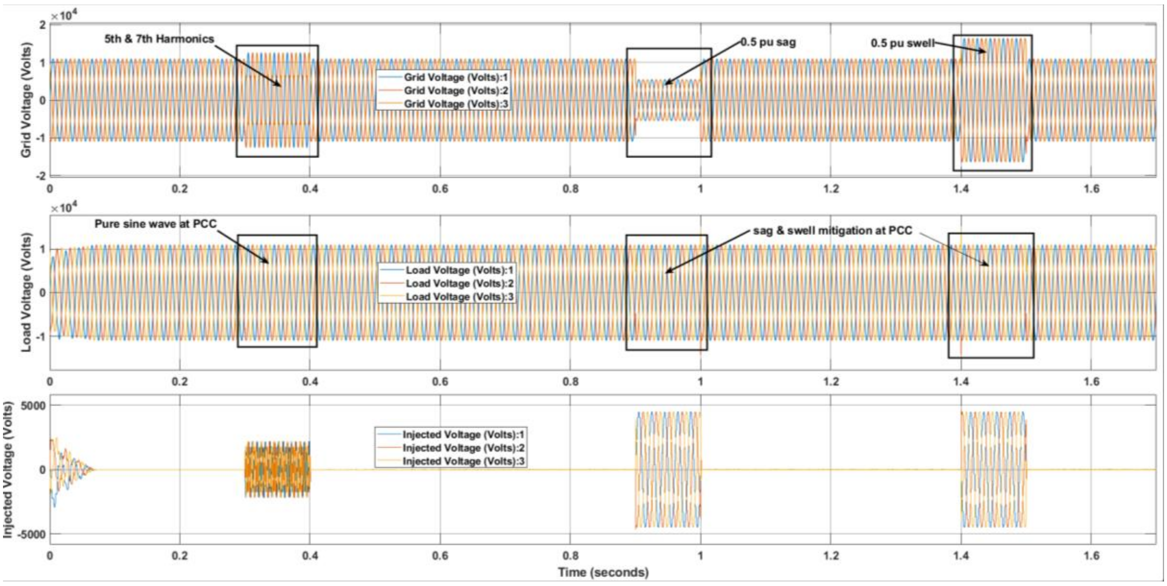

Figure 4. Performance of a UPQC during 0.5 p.u. voltage sag and swell conditions

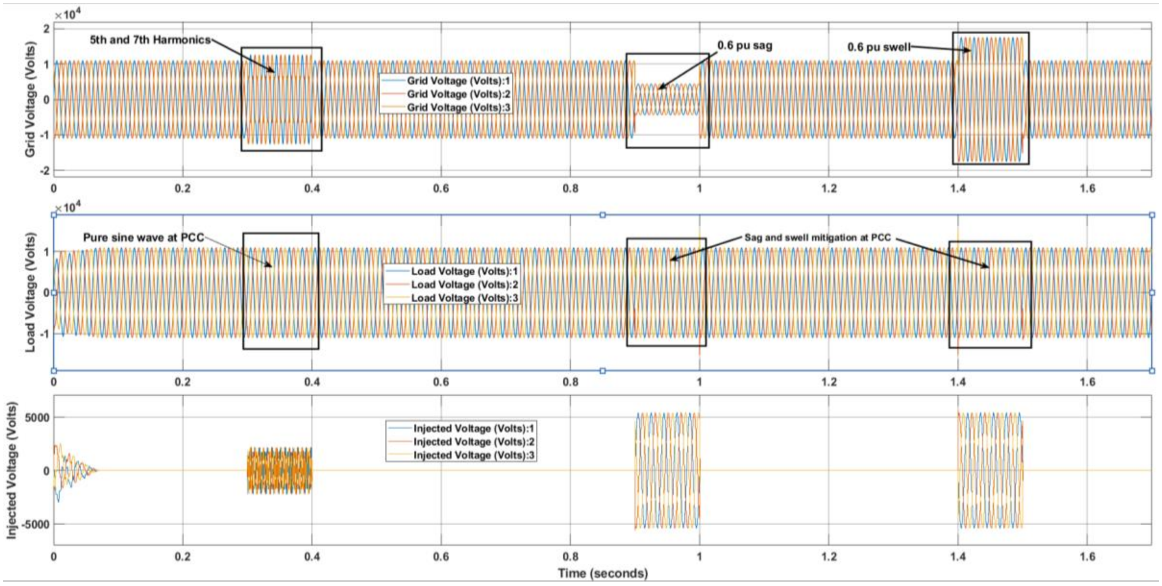

Figure 5. Performance of a UPQC during 0.6 p.u. voltage sag and swell conditions

4.4. Case 4

Figure 6 highlights the performance of a UPQC in managing a 0.7 p.u. voltage sag and swell across three phases of an electrical grid. The UPQC precisely counters these severe disturbances, maintaining a near-constant voltage at the load. At around 1.2 seconds, it quickly injects additional voltage to stabilize the grid during the sag. Then, at about 1.6 seconds, it reduces the injected voltage to mitigate the swell, ensuring the load voltage stays within safe operational limits.

4.5. Case 5

Figure 7 illustrates the effectiveness of a UPQC in managing severe voltage disturbances, specifically a 0.8 p.u. sag and swell across three phases of a power grid. Facing its most challenging scenario yet, the UPQC responds with substantial voltage injections and reductions to counteract extreme grid voltage fluctuations. Across all tested scenarios, from 0.3 p.u. to 0.8 p.u. voltage sags and swells, the proposed UPQC system has proven highly effective in maintaining stability of the system by stable load voltages, ensuring that fluctuations in the grid voltage have minimal impact on the load.

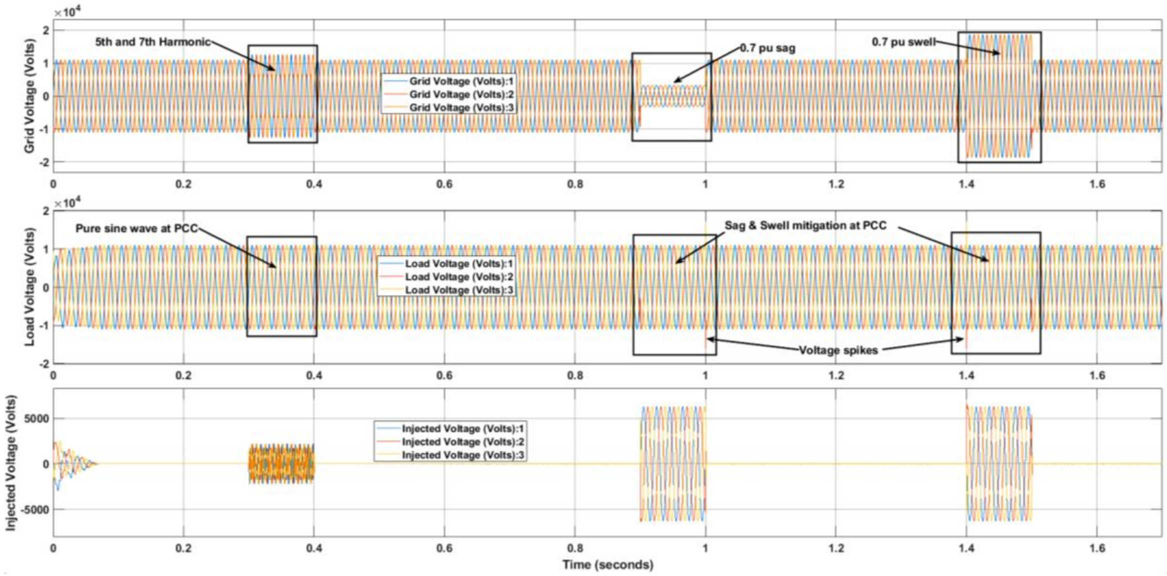

Figure 6. Performance of a UPQC during 0.7 p.u. voltage sag and swell conditions

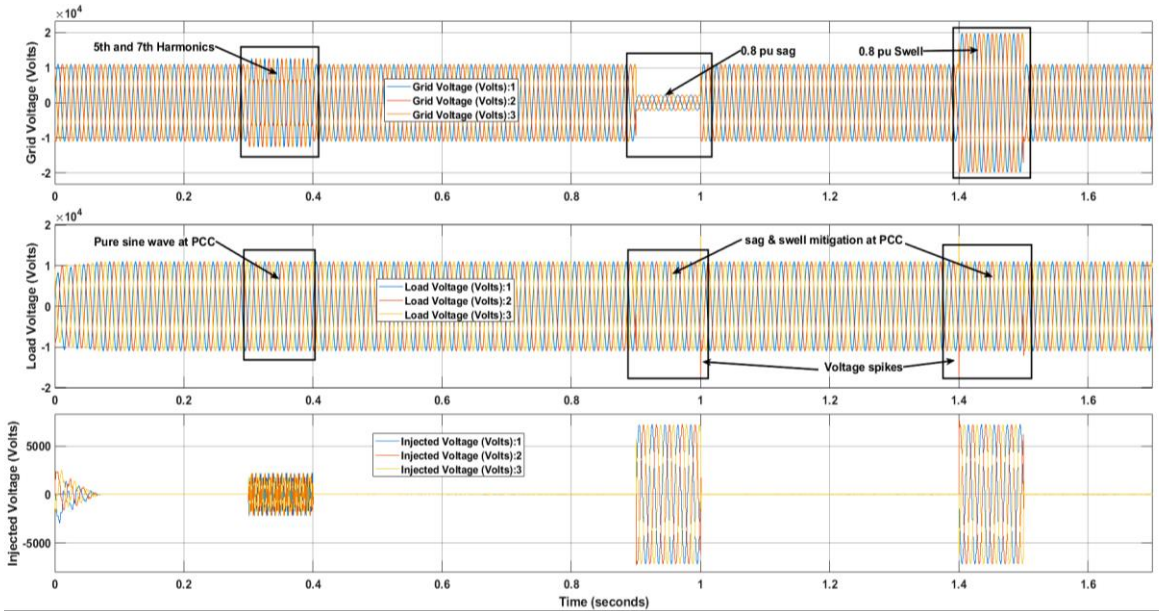

Figure 7. Performance of a UPQC during 0.8 p.u. voltage sag and swell conditions

4.6. Analysis of grid voltage harmonic distortion

Figure 8 displays a time-domain signal of grid voltage across 125 cycles, showing a sinusoidal shape with visible harmonic distortions. The FFT analysis of this voltage, highlighting a strong fundamental frequency at 50 Hz with a magnitude of approximately 413.4. It identifies harmonics up to the 50^{th} order, with a THD of 20.62%.

4.7. Load voltage response to power quality issues

Figure 9 illustrates the load voltage over a span of 125 cycles, clearly showing fluctuations indicative of voltage sags and swells. The FFT analysis of the load voltage, with a fundamental frequency at 50 Hz, around 413.9. Unlike Figure 9, the harmonic spectrum here is broader, yet the THD is significantly lower at 0.30%. This enhanced THD level after compensation indicates that measures such as using unified power quality conditioners (UPQCs) or other power conditioning equipment are effectively maintaining voltage quality.

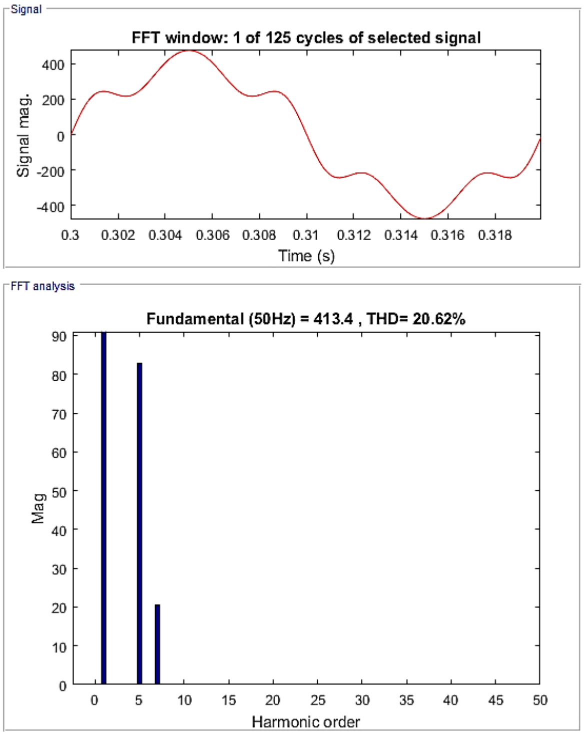

Figure 8. FFT analysis of grid voltage harmonic distortion

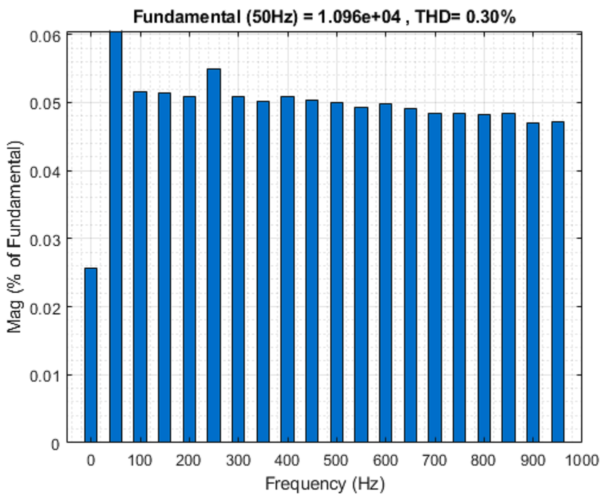

Figure 9. FFT analysis of load voltage during showing voltage sags and swells

Table 1 showcases the effectiveness of various techniques in reducing THD at the PCC. For instance, the inductive hybrid UPQC method exhibits a substantial decrease in THD from 20.52% to 2.53%, indicating its effectiveness in mitigating voltage distortion. Similarly, the UPQC system control method, integrating SRF theory, MUVTG, and a PID controller, achieves a remarkable reduction in THD from 20.62% to 0.30%, underscoring its efficiency in enhancing power quality. These results highlight the importance of employing advanced control techniques, such as those based on SRF theory and MUVTG, supplemented by PID controllers.

Table 1. Effectiveness of power quality enhancement techniques: pre and post compensation THD analysis

Techniques	PCC voltage THD in %	
	Before compensation	After compensation
Inductive hybrid UPQC [15]	20.52	2.53
UPQC with MUVTC and SRF [26]	20.62	2.06
Recent advances in synchronization techniques [27]	55.27	4.66
A systematic design methodology for DC-link voltage control [28]	12.5	4.5
Proposed system	20.62	0.30

4.8. Analyzing power system stability against asymmetrical voltage disturbances

Figure 10 illustrates a power system's response to asymmetrical voltage sags and swells across three phases, despite these fluctuations, the load voltage remains relatively constant, emphasizing the effectiveness of the voltage regulation strategies in place. The voltage injected by a UPQC, which correlates with the disturbances showcasing its role in actively compensating for the asymmetrical conditions to maintain stability at the load.

Figures 11 and 12 display the real and reactive power at the PCC on both the grid and load sides, measured in kilowatts (kW) and kilovolt-amperes reactive (kVAR) respectively. In Figure 11, both real and reactive power on the grid side exhibit distinct fluctuations around specific times (around 1 second and 1.5 seconds), potentially indicating load changes or power control actions, with real power showing dips and peaks, and reactive power displaying a significant dip before returning to baseline. This suggests the activation of mechanisms like reactive power compensation to maintain stability.

Figure 12 presents a more stable scenario on the load side where both real and reactive power levels remain nearly constant throughout the observed period, indicating stable demand or generation and possibly effective power management strategies. This stability might reflect well-managed reactive characteristics of the load, implying that any reactive components are efficiently controlled, contributing to the reliability and efficiency of power delivery to end-users.

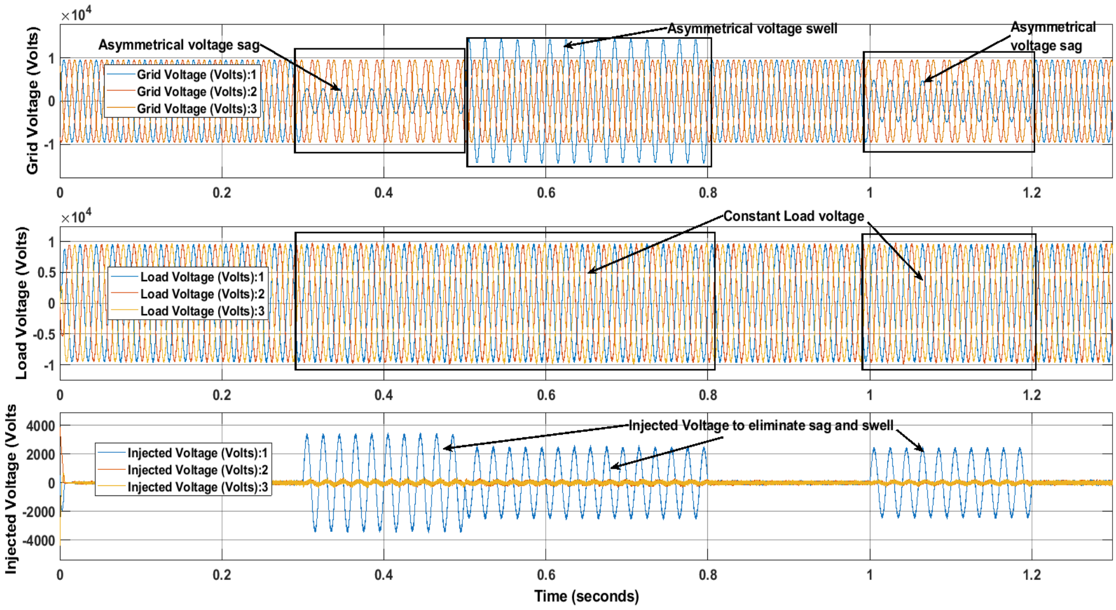

Figure 10. Dynamic response of a power system to asymmetrical voltage sags and swells

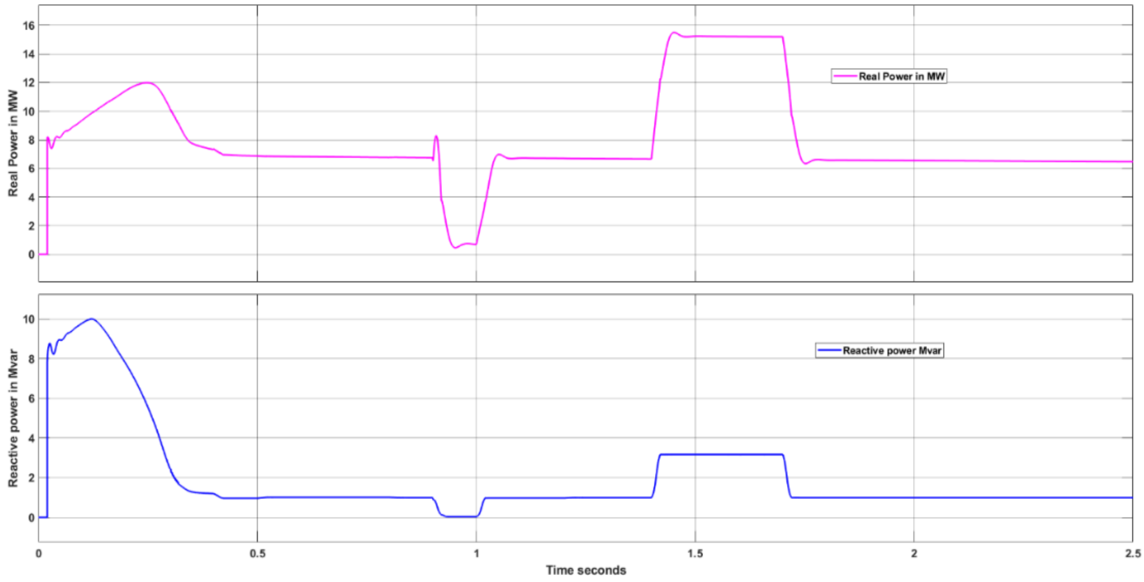

Figure 11. Dynamic variations of real and reactive power at the grid side

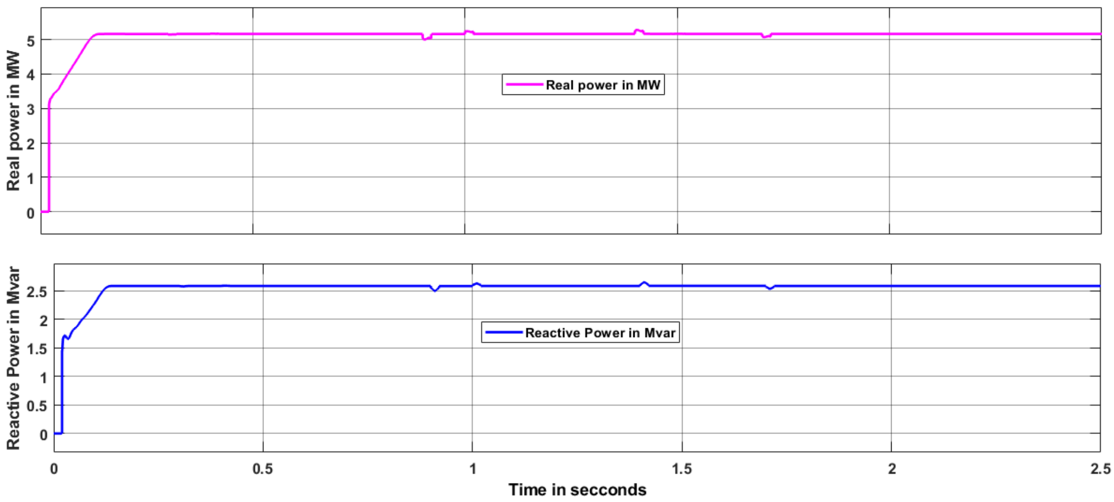

Figure 12. Stability of real and reactive power at the load side

5. CONCLUSION

This research has successfully demonstrated the enhancement of large PV integrated grid stability using an improved UPQC system by incorporating a PID controller in the control loop, the system efficiently regulates the reactive power supplied. The UPQC-PV system employs the SRF theory for shunt APF and a MUVTG for series APFs, supplemented by power angle control to efficiently distribute the reactive power load between both shunt and series APFs. This configuration guarantees a stable power supply to the grid despite PV generation and voltage fluctuations, enhancing the distribution network's overall stability. The effectiveness of the system has been validated through MATLAB simulations under steady-state conditions and in dynamic scenarios during voltage sags, swells, and achieves a THD of 0.30, meeting the IEEE-519 standards.

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AUTHOR CONTRIBUTIONS STATEMENT

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

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Shankaralingappa Channappa Byalihal	✓		✓	✓		✓	✓	✓		✓	✓	✓	✓	

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

Authors state no conflict of interest.

DATA AVAILABILITY

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

REFERENCES

[1] K. N. Nwaigwe, P. Mutabilwa, and E. Dintwa, "An overview of solar power (PV systems) integration into electricity grids," *Materials Science for Energy Technologies*, vol. 2, no. 3, pp. 629–633, Dec. 2019, doi: 10.1016/j.mset.2019.07.002.

[2] 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.

[3] A. A. Alkahtani *et al.*, "Power quality in microgrids including supraharmonics: Issues, standards, and mitigations," *IEEE Access*, vol. 8, pp. 127104–127122, 2020, doi: 10.1109/ACCESS.2020.3008042.

[4] A. Alshahrani, S. Omer, Y. Su, E. Mohamed, and S. Alotaibi, "The technical challenges facing the integration of small-scale and large-scale PV systems into the grid: A critical review," *Electronics*, vol. 8, no. 12, p. 1443, Dec. 2019, doi: 10.3390/electronics8121443.

[5] O. E. Okwako, Z.-H. Lin, M. Xin, K. Premkumar, and A. J. Rodgers, "Neural network controlled solar PV battery powered unified power quality conditioner for grid connected operation," *Energies*, vol. 15, no. 18, p. 6825, Sep. 2022, doi: 10.3390/en15186825.

[6] S. Devassy and B. Singh, "Performance analysis of solar PV array and battery integrated unified power quality conditioner for microgrid systems," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 5, pp. 4027–4035, May 2021, doi: 10.1109/TIE.2020.2984439.

[7] M. Ourahou, W. Ayrir, B. EL Hassouni, and A. Haddi, "Review on smart grid control and reliability in presence of renewable energies: Challenges and prospects," *Mathematics and Computers in Simulation*, vol. 167, pp. 19–31, Jan. 2020, doi: 10.1016/j.matcom.2018.11.009.

[8] N. Zanib, M. Batool, S. Riaz, and F. Nawaz, "Performance analysis of renewable energy based distributed generation system using ANN Tuned UPQC," *IEEE Access*, vol. 10, pp. 110034–110049, 2022, doi: 10.1109/ACCESS.2022.3213948.

[9] J. Wang, S. Mu, Q. Zhou, Y. J. Li, and T. L. Zhang, "Design and performance analysis of PV-SMES-based microgrid integrated with power fluctuation suppression and active filtering control," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 8, pp. 1–5, Nov. 2021, doi: 10.1109/TASC.2021.3103732.

[10] A. A. Smadi, M. F. Allehyani, B. K. Johnson, and H. Lei, "Power quality improvement utilizing PV-UPQC based on PI-SRF and PAC controllers," in *2022 IEEE Power & Energy Society General Meeting (PESGM)*, IEEE, Jul. 2022, pp. 1–5, doi: 10.1109/PESGM48719.2022.9916826.

[11] J. Zhang, D. G. Dorrell, L. Li, and Y. Guo, "Decoupling controller design and controllable regions analysis for the space vector modulated matrix converter-unified power flow controller in transmission systems," *Electric Power Components and Systems*, vol. 46, no. 1, pp. 1–14, Jan. 2018, doi: 10.1080/15325008.2018.1431818.

[12] Z. Alqarni, "Maximum power point tracking for solar photovoltaic system using synchronous reference frame theory," in *2021 IEEE 12th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, IEEE, Oct. 2021, pp. 0811–0819, doi: 10.1109/IEMCON53756.2021.9623114.

[13] A. Govind, V. K. Tayal, P. Kumar, and R. K. Kumawat, "Phase synchronization control techniques under adverse grid conditions using shunt active power filter," in *2021 6th IEEE International Conference on Recent Advances and Innovations in Engineering (ICRAIE)*, IEEE, Dec. 2021, pp. 1–5, doi: 10.1109/ICRAIE52900.2021.9704027.

[14] S. S. Bhosale, Y. N. Bhosale, U. M. Chavan, and S. A. Malvekar, "Power quality improvement by using UPQC: A review," in *2018 International Conference on Control, Power, Communication and Computing Technologies (ICCPCCT)*, IEEE, Mar. 2018, pp. 375–380, doi: 10.1109/ICCPCCT.2018.8574264.

[15] J. Yu, Y. Xu, Y. Li, and Q. Liu, "An inductive hybrid UPQC for power quality management in premium-power-supply-required applications," *IEEE Access*, vol. 8, pp. 113342–113354, 2020, doi: 10.1109/ACCESS.2020.2999355.

[16] 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," *IEEE Transactions on Industry Applications*, vol. 58, no. 1, pp. 201–211, Jan. 2022, doi: 10.1109/TIA.2021.3131404.

[17] D. Stanelytė and V. Radziukynas, "Analysis of voltage and reactive power algorithms in low voltage networks," *Energies*, vol. 15, no. 5, p. 1843, Mar. 2022, doi: 10.3390/en15051843.

[18] C. S. Kumar and G. Mallesham, "Performance of three phase AI controller based UPQC to enhance power quality of hybrid RES," *Microsystem Technologies*, vol. 26, no. 8, pp. 2673–2682, Aug. 2020, doi: 10.1007/s00542-020-04810-z.

[19] P. R. Sonawane, S. Bhandari, R. B. Patil, and S. Al-Dahidi, "Reliability and criticality analysis of a large-scale solar photovoltaic system using fault tree analysis approach," *Sustainability*, vol. 15, no. 5, p. 4609, Mar. 2023, doi: 10.3390/su15054609.

[20] X. P. Yokwana, A. A. Yusuff, M. Ntombela, and T. C. Mosetlhe, "Fault detection scheme for a large-scale photovoltaic installation based on frequency response analysis," in *2021 IEEE 6th International Forum on Research and Technology for Society and Industry (RTSI)*, IEEE, Sep. 2021, pp. 24–29, doi: 10.1109/RTSI50628.2021.9597310.

[21] R. Rudraram, S. Chinnathambi, and M. Mani, "PV integrated UPQC with intelligent control techniques for power quality enhancement," *International Journal of Electrical and Electronics Research*, vol. 11, no. 1, pp. 202–212, Mar. 2023, doi: 10.37391/ijeer.110128.

[22] K. Srilakshmi *et al.*, "Optimization of ANFIS controller for solar/battery sources fed UPQC using an hybrid algorithm," *Electrical Engineering*, vol. 106, no. 4, pp. 3743–3770, Aug. 2024, doi: 10.1007/s00202-023-02185-8.

[23] 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.

[24] A. Patel, S. K. Yadav, and H. D. Mathur, "Utilizing UPQC-DG to export reactive power to grid with power angle control method," *Electric Power Systems Research*, vol. 209, p. 107944, Aug. 2022, doi: 10.1016/j.epsr.2022.107944.

[25] Y. A. G. Gómez, N. T. García, and F. E. Hoyos, "Unit vector template generator applied to a new control algorithm for an UPQC with instantaneous power tensor formulation, a simulation case study," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 4, p. 3889, Aug. 2020, doi: 10.11591/ijece.v10i4.pp3889-3897.

[26] V. K. Kalal and S. C. Byalihal, "Power quality stabilization system for grid connected large-scale solar power system," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 1, p. 518, Mar. 2024, doi: 10.11591/ijpeds.v15.i1.pp518-529.

[27] P. Gawhade and A. Ojha, "Recent advances in synchronization techniques for grid-tied PV system: A review," *Energy Reports*, vol. 7, pp. 6581–6599, Nov. 2021, doi: 10.1016/j.egyr.2021.09.006.

[28] M. Merai, M. W. Naouar, I. Slama-Belkhodja, and E. Monmasson, "A systematic design methodology for DC-link voltage control of single phase grid-tied PV systems," *Mathematics and Computers in Simulation*, vol. 183, pp. 158–170, May 2021, doi: 10.1016/j.matcom.2020.05.007.

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