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Design and Performance Analysis of a Three-Phase Single Stage Solar Photovoltaic Integrated Unified Power Quality Conditioner (PV-UPQC)

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ABSTRACT

This paper presents the design and performance analysis of a three-phase single stage solar photovoltaic integrated unified power quality conditioner (PV-UPQC). The PV-UPQC comprises shunt and series connected voltage compensators linked back-to-back with a common DC-link. The shunt compensator serves a dual role, extracting power from the PV array and compensating for load current harmonics. An improved synchronous reference frame control, based on a moving average filter, is employed for extracting the load active current component, enhancing the PV-UPQC's performance. The series compensator addresses grid-side power quality issues such as voltage sags and swells by injecting voltage in-phase or out of phase with the point of common coupling (PCC) voltage during sag and swell conditions, respectively. This proposed system harnesses the benefits of clean energy generation while enhancing power quality. The steady-state and dynamic performance of the system are evaluated through simulations in Matlab-Simulink under nonlinear load conditions. Furthermore, the system's performance is validated using a scaled-down laboratory prototype subjected to various disturbances including load unbalancing, PCC voltage sags/swells, and irradiation variations.

Keywords: Power Quality, shunt compensator, series compensator, UPQC, Solar PV, MPPT.

1 Introduction

With the proliferation of power electronic loads in modern distribution systems, there's a pressing need to address voltage distortion issues caused by their nonlinear currents. Concurrently, the rise in rooftop PV systems adds complexity, with intermittent energy sources exacerbating voltage quality problems. This paper proposes a solution in the form of a three-phase single-stage solar photovoltaic integrated unified power quality conditioner (PV-UPQC). The PV-UPQC employs shunt and series connected voltage compensators, leveraging a common DC-link. While shunt compensation addresses load side issues, series compensation tackles grid side problems such as voltage sags and swells.



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An improved synchronous reference frame control, employing a moving average filter (MAF), enhances load active current extraction. This system offers the dual benefits of clean energy generation and power quality improvement, simultaneously addressing voltage and current quality issues. The use of MAF in the d-q control of PV-UPQC ensures stable performance under various dynamic conditions, including voltage variations and load unbalance. Extensive performance analysis, conducted using Matlab-Simulink, verifies the system's efficacy under both steady-state and dynamic conditions. Experimental validation on a scaled-down laboratory prototype further confirms its effectiveness in mitigating voltage sags/swells, load unbalance, and irradiation variations typical of distribution systems.

2 System Configuration and Design

The structure of the PV-UPQC, as depicted in Figure 1, is designed for a three-phase system. It consists of shunt and series compensators connected via a common DC-bus.

The shunt compensator is situated at the load side, while the solar PV array directly integrates with the UPQC's DC-link through a reverse blocking diode. Operating in voltage control mode, the series compensator is responsible for mitigating grid voltage sags/swells. Both compensators interface with the grid through interfacing inductors, with a series injection transformer employed to inject compensating voltage into the grid. Ripple filters are employed to attenuate harmonics generated by converter switching actions. The system is tested using a nonlinear load comprising a bridge rectifier with a voltage-fed load.

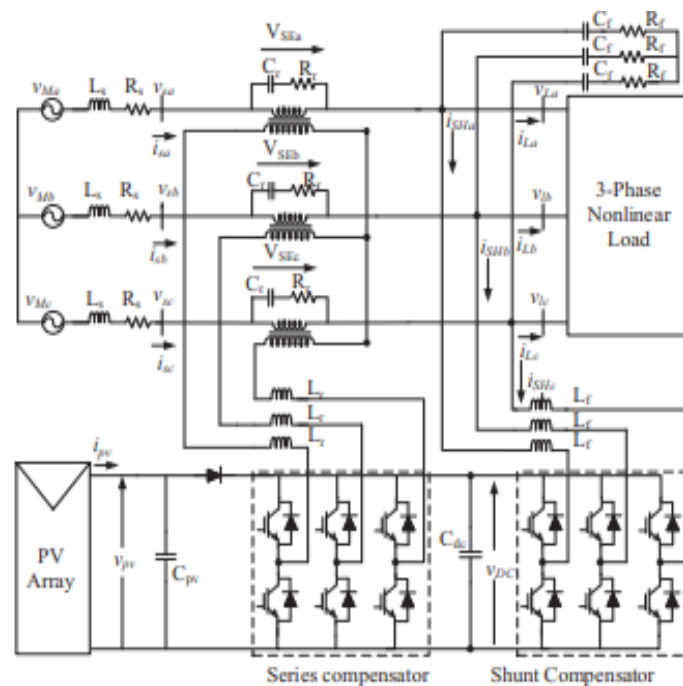


Figure 1: System Configuration PV-UPQC



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The design procedure for the PV-UPQC commences with the appropriate sizing of key components such as the PV array, DC-link capacitor, and DC-link voltage level. The shunt compensator's sizing is determined to accommodate the peak power output from the PV array while also compensating for reactive power and current harmonics from the load. Since the PV array is directly connected to the UPQC's DC-link, its sizing ensures that the maximum power point (MPP) voltage aligns with the desired DC-link voltage. The PV array's rating ensures that, under nominal conditions, it supplies the load's active power while also contributing power to the grid. Detailed specifications for the PV array are provided in Appendix A. Additionally, the design includes sizing the interfacing inductors for both the series and shunt compensators, as well as the series injection transformer for the series compensator. The design of PV-UPQC is elaborated as follows.

1) Voltage Magnitude of DC-Link: The magnitude of DC link voltage V_{dc} depends on the depth of modulation used and per-phase voltage of the system. The DC-link voltage magnitude should more than double the peak of per-phase voltage of the three phase system [8] and is given as, $V_{dc} = 2 \sqrt{2} V_{LL} \sqrt{3} m$ (1) where depth of modulation (m) is taken as 1 and V_{LL} is the grid line voltage. For a line voltage of 415 V, the required minimum value DC-bus voltage is 677.7 V. The DC-bus voltage is set at 700 V (approx), which is same as the MPPT operating voltage of PV array at STC conditions.

2) DC-Bus Capacitor Rating: The DC-link capacitor is sized based upon power requirement as well as DC-bus voltage level. The energy balance equation for the DC-bus capacitor is given as follows [8], $C_{dc} = 3kaV_{ph}I_{sht} 0.5 \times (V_{2dc} - V_{2dc1}) = 3 \times 0.1 \times 1.5 \times 239.6 \times 34.5 \times 0.03 0.5 \times (700 - 677.792) = 9.3mF$ (2) where V_{dc} is the average DC-bus voltage, V_{dc1} is the lowest required value of DC-bus voltage, a is the overloading factor, V_{ph} is per-phase voltage, t is the minimum time required for attaining steady value after a disturbance, I_{sh} is per-phase current of shunt compensator, k factor considers variation in energy during dynamics. The minimum required DC-link voltage is $V_{dc1} = 677.69$ V as obtained from (2), $V_{dc} = 700$ V, $V_{ph} = 239.60$ V, $I_{sh} = 57.5$ A, $t = 30$ ms, $a = 1.2$, and for dynamic energy change = 10%, $k = 0.1$, the value of CDC is obtained as 9.3 mF.

3) Interfacing Inductor for Shunt Compensator: The interfacing inductor rating of the shunt compensator depends upon the ripple current, the switching frequency and DC-link voltage. The expression for the interfacing inductor is as, $L_f = \sqrt{3} m V_{dc} 12 a f_{sh} I_{cr,pp} = \sqrt{3} \times 1 \times 700 12 \times 1.2 \times 10000 \times 6.9 = 800\mu H \approx 1mH$ (3) where m is depth of modulation, a is pu value of maximum overload, f_{sh} is the switching frequency, $I_{cr,pp}$ is the inductor ripple current which is taken as 20% of rms phase current of shunt compensator. Here, $m=1$, $a=1.2$, $f_{sh}=10$ kHz, $V_{dc}=700V$, one gets 800 ph. as value. The value chosen is approximated to 1mH.



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4) Series Injection Transformer: The PV-UPQC is designed to compensate for a sag/swell of 0.3 Pu i.e 71.88 V. Hence, the required voltage to be injection is only 71.88 V which results in low modulation index for the series compensator when the DC-link voltage is 700V. In order to operate the series compensator with minimum harmonics, one keeps modulation index of the series compensator near to unity. Hence a series transformer is used with a turns ratio, $KSE = \frac{V_{SC}}{V_{SE}} = 3.33 \approx 3$ (4) the value obtained for KSE is 3.33. The value selected is 3. The rating of series injection transformer is given as, $SSE = 3V_{SE}I_{SEsag} = 3 \times 72 \times 46 = 10kV A$ (5) the current through series VSC is same as grid current. The supply current under sag condition of 0.3 Pu is 46 A and hence the VA rating of injection transformer achieved is 10 kVA.

5) Interfacing Inductor of Series Compensator: The rating of interfacing inductor of the series compensator depends on ripple current at swell condition, switching frequency and DClink voltage. Its value is expressed as, $L_r = \frac{\sqrt{3} \times mV_{dc}KSE}{12afseI_r} = \frac{\sqrt{3} \times 1 \times 700 \times 3}{12 \times 1.2 \times 10000 \times 7.1} = 3.6mH$ (6) where m is the depth of modulation, a is the pu value of maximum overload, fse is the switching frequency, I_r is the inductor current ripple, which is taken to be 20% of grid current. Here, $m=1$, $a=1.5$, $fse=10$ kHz, $V_{dc}=700$ V and 20% ripple current, one gets 3.6 mH as selected value.

3 Control of PV-UPQC

The PV-UPQC comprises two main subsystems: the shunt compensator and the series compensator. The shunt compensator primarily addresses load power quality issues such as load current harmonics and reactive power. In the case of the PV-UPQC, the shunt compensator additionally serves the function of harnessing power from the solar PV array. This is achieved through the implementation of a maximum power point tracking (MPPT) algorithm, allowing the shunt compensator to extract power efficiently from the PV array.

On the other hand, the series compensator focuses on safeguarding the load from grid-side power quality problems, such as voltage sags and swells. It achieves this by injecting appropriate voltage in phase with the grid voltage, thereby stabilizing the voltage supplied to the load. By compensating for these grid disturbances, the series compensator ensures the reliability and stability of the load operation.

The shunt compensator extracts the maximum power from the solar PV-array by operating it at its maximum power point. The maximum power point tracking (MPPT) algorithm generates the reference voltage for the DC-link of PV-UPQC. Some of the commonly used MPPT algorithms [28] are Perturb and Observe (P& O) algorithm, incremental conductance algorithm (INC). In this work, (P& O) algorithm is used for implementing MPPT. The DC-link voltage is maintained at the generated reference by using a PI-controller.



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The control strategy for the series compensator encompasses three main compensation techniques: pre-sag compensation, in-phase compensation, and energy optimal compensation. These strategies are extensively discussed in [29] and [30]. However, in this study, the series compensator injects voltage in the same phase as the grid voltage, minimizing the injected voltage required by the compensator.

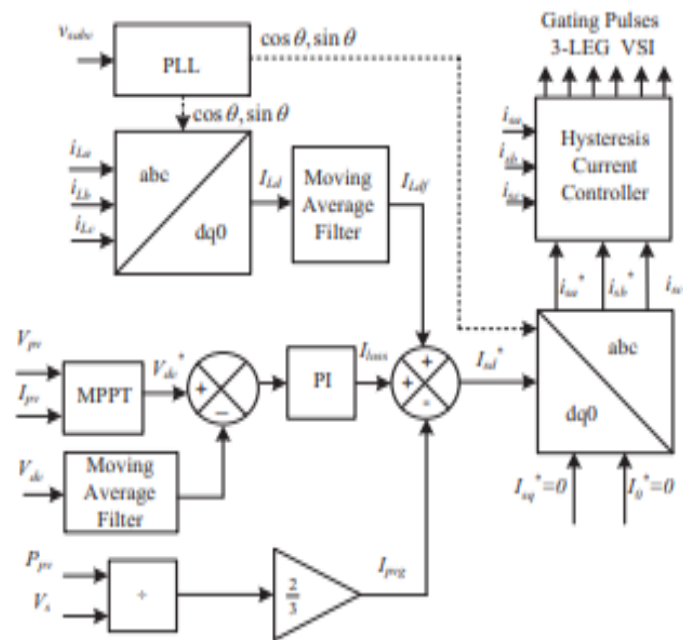


Figure 2: Control Structure of Shunt compensator

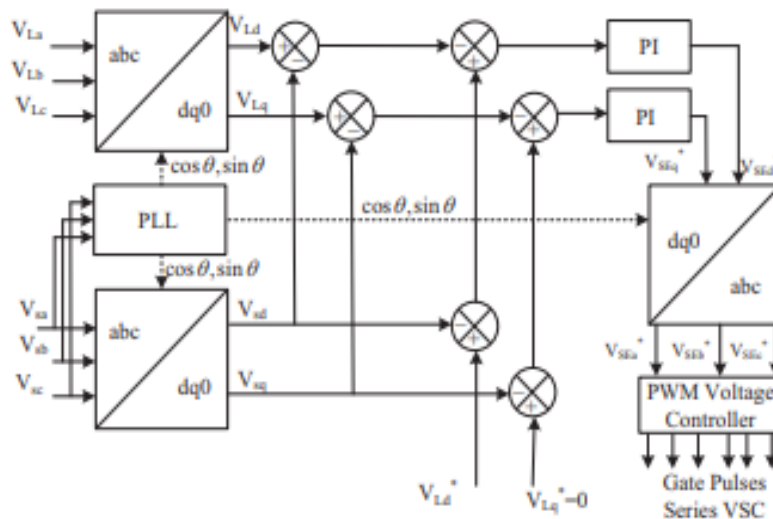


Figure 3: Control Structure of Series Compensator



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The control structure of the series compensator is illustrated in Figure 3. The fundamental component of the point of common coupling (PCC) voltage is extracted using a phase-locked loop (PLL), which serves to generate the reference axis in the d-q-0 domain. Utilizing the phase and frequency information of the PCC voltage obtained via PLL, the reference load voltage is generated. Subsequently, both PCC voltages and load voltages are converted into the d-q-0 domain.

Given that the reference load voltage should be in phase with the PCC voltage, the peak load reference voltage corresponds to the d-axis component value of the load reference voltage, with the q-axis component maintained at zero. The discrepancy between the load reference voltage and the PCC voltage yields the reference voltage required for the series compensator. Similarly, the difference between the load voltage and the PCC voltage determines the actual series compensator voltages.

This disparity between the reference and actual series compensator voltages is fed into proportional-integral (PI) controllers to generate appropriate reference signals. These signals are subsequently converted into the ABC domain and passed through a pulse width modulation (PWM) voltage controller to generate suitable gating signals for the series compensator.

4 Simulation Results

During simulation, a solver step size of $1e-6$ seconds is utilized to ensure accurate representation of system dynamics. The PV-UPQC is subjected to various dynamic conditions, including voltage sags and swells at the point of common coupling (PCC), as well as variations in photovoltaic (PV) irradiation.

By simulating these dynamic scenarios, the performance of the PV-UPQC can be thoroughly assessed, providing insights into its effectiveness in mitigating power quality issues and regulating voltage under changing operating conditions. This simulation-based analysis serves as a crucial step in evaluating the practical viability and robustness of the PV-UPQC design.

The dynamic performance of PV-UPQC under varying solar irradiation is shown in Figure 6. The solar irradiation is varied from $500\text{W}/\text{m}^2$ at 0.8s to $1000\text{W}/\text{m}^2$ at 0.85s . It is observed that as irradiation increases, the PV array output increases and hence grid current rises as the PV array is feeding power into the grid. The shunt compensator tracks MPPT along with compensating for the harmonics due to load current. The harmonic spectra and THD load current and grid current are shown in Figure 7 and Figure 8. It is observed that the load current THD is 26.31% and the grid current THD is 2.00% thus meeting the requirement of IEEE-519 standard.



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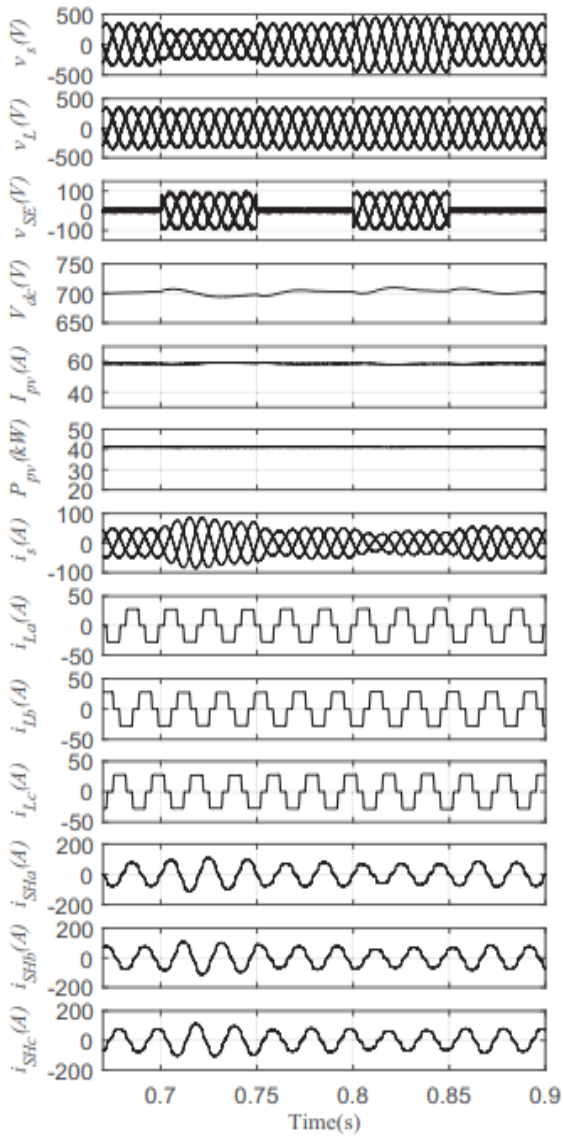


Figure 4: Performance of PV-UPQC under Voltage Sag and Swell Conditions

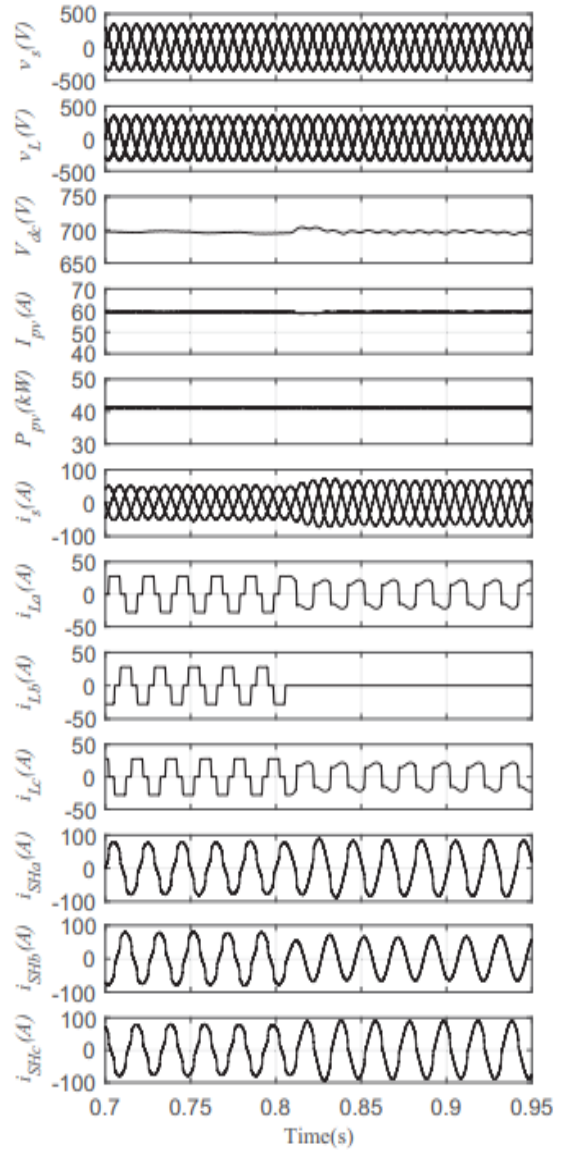


Figure 5: Performance of PV-UPQC during Load Unbalance Condition



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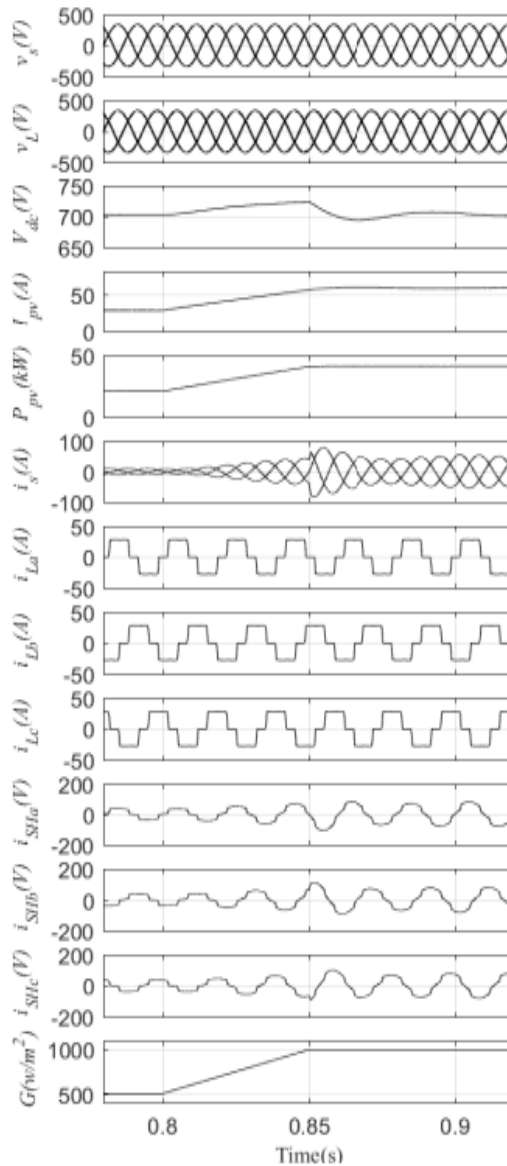


Figure 6: Performance PV-UPQC at Varying Irradiation Condition

5 Experimental Results

The PV-UPQC behaviour under steady state and dynamic conditions are extensively analyzed on scaled down prototype developed in laboratory. A solar array simulator (AMTEK ETS 600*17DPVF) is used to generate power characteristics similar to a PV array. The shunt and series compensators are realized by using two voltage source converters (SEMIKRONMD B6CI 750/415-35F) with a common DC-link. The three phase nonlinear load is realized using a bridge rectifier along with an R-L load. The control is realized using a dSPACE MicrolabBox



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DSP controller. The performance of the prototype under steady state and dynamic conditions are explained in the following sections.

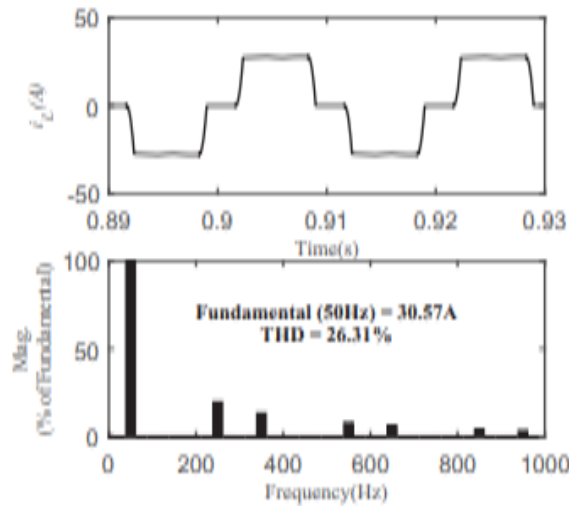


Figure 7: Load Current Harmonic Spectrum and THD

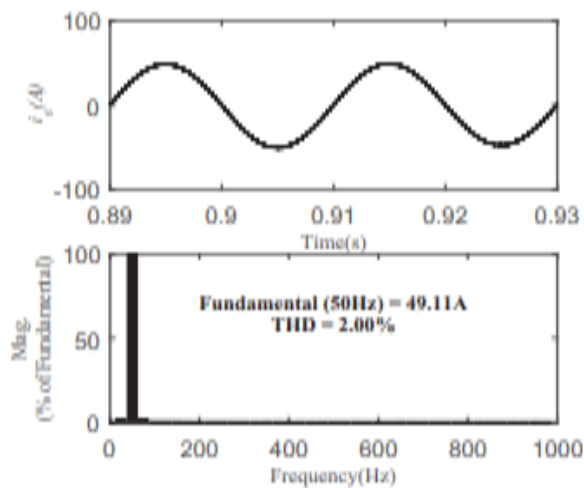


Figure 8: Grid Current Harmonic Spectrum and THD

6 Conclusion

In conclusion, the design and dynamic performance analysis of the three-phase PV-UPQC have been conducted under varying irradiation levels and grid voltage sags/swells. Through experimentation on a scaled-down laboratory prototype, the system's performance has been validated. Key observations include the effective mitigation of harmonics caused by nonlinear loads and the maintenance of total harmonic distortion (THD) of grid current within the limits



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specified by the IEEE-519 standard. Furthermore, the PV-UPQC demonstrates stability under fluctuations in irradiation, voltage sags/swells, and load unbalance. Overall, the PV-UPQC emerges as a promising solution for modern distribution systems, offering the integration of distributed generation with power quality improvement. By effectively addressing power quality issues while harnessing renewable energy sources, the PV-UPQC contributes to enhancing the reliability and efficiency of distribution networks in the transition towards a more sustainable energy future.

Appendix A

Simulation Parameters

PCC Line Voltage: 415 V, 50 Hz; Load: Current Fed Bridge Rectifier Load (14.8kW); DC-link Voltage: 700 V; DC-link Capacitor: 9.3 mF; Shunt compensator interfacing inductor: 1 mH; PWM Switching frequency of VSC: 10 kHz; Ripple Filter: 10 μ F, 10 Ω ; series compensator interfacing inductor: 3.6 mH; DC-link PI controller gains: $K_p = 1.5$, $K_i = 0.1$; Series VSC PI gains for d and q axis : $K_p = 8$, $K_i = 1200$; PV array parameters: $V_{oc} = 864$ V, $I_{sc} = 62.65$ A; $V_{mpp} = 701$ V; $I_{mpp} = 58.94$ A; $P_{pv} = 41.35$ kW.

Appendix B

Experimental Parameters

PCC Line Voltage: 220 V, 50 Hz; Load: Current Fed Bridge Rectifier Load 750 W; DC-link Voltage: 700 V; DC-link Capacitor: 3.3 mF; Shunt compensator interfacing inductor: 4 mH; PWM Switching frequency of VSC: 10 kHz; Ripple Filter: 20 μ F, 5 Ω ; series compensator interfacing inductor: 0.5 mH; DC-link PI controller gains: $K_p = 2.5$, $K_i = 1.1$; Series VSC PI gains for d and q axis : $K_p = 5$, $K_i = 800$; PV array parameters: $V_{oc} = 415$ V, $I_{sc} = 13$ A; $V_{mpp} = 371$ V; $I_{mpp} = 12.57$ A; $P_{pv} = 4.62$ kW.

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