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Power Quality Control for A Grid Integrated PV System

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ABSTRACT: This paper presents solution to power quality issues when integratinga 1 MW photovoltaic array (PVA) with a unified power quality conditioner (UPQC) into the power grid. A modified unit vector template control scheme is used to generate a reference load voltage signal, and a synchronous reference frame (SRF) is created using a low-pass filter to control UPQC. Furthermore, the PVA is interfaced with the grid through a common DC link of shunt and series converters. The series converter mitigates power quality problems allied with the grid side, such as 3rd, 5th, and 7th harmonics, voltage sag, and voltage swell, by introducing signals in phase and out of phase voltage, respectively, at the point of common coupling (PCC). The shunt converter mitigates nonlinear load current harmonics and compensates for reactive power using SRF. The suggested methodology is implemented using MATLAB Simulink with both linear and nonlinear loads under different power quality conditions. Total harmonic distortions are maintained below 5% at PCC, as per IEEE-519 standards.

KEYWORDS: Active power filter Dynamic voltage restorer solar photovoltaic array Point of common coupling Total harmonics distortion Unified power quality conditioner

I. INTRODUCTION

Maintaining optimal power quality in distribution systems poses a significant challenge, particularly with the rapid expansion of solar photovoltaic (PV) installations. Recent advancements in both photovoltaic cell manufacturing and converter technology have established solar PV as a leading, renewable energy source capable of generating substantial electricity. However, the widespread deployment of PV systems has the potential to introduce significant changes to power systems, potentially affecting their stability. A key concern related to PV integration is the introduction of harmonics into the grid, leading to distorted voltage waveforms at the Point of Common Coupling (PCC). These distortions, characterized by voltage sag and swells, highlight the need for robust power quality mitigation techniques across distribution networks.

One increasingly popular approach is the adoption of Photovoltaic-Unified Power Quality Conditioners (PV-UPQC). By employing d-q control alongside moving average filters, PV-UPQC effectively manages harmonics. Real and reactive power regulation is achieved through ABC to DQO transformation, enhancing the PCC voltage profile through grid-connected inverters equipped with PI controllers. Furthermore, the implementation of UPQC-DG, which combines synchronous reference frame (SRF) theory with unit vector template generation (UVTG) supplemented by an additional PI controller, facilitates reactive power support to the grid while efficiently managing its flow.

Active power filters (APFs) represent another crucial element in the arsenal of power quality enhancement techniques for PV systems. These filters target harmonics, with particular emphasis on mitigating voltage sag and swells. The utilization of dynamic voltage restorers (DVRs), supported by enhanced differential evolution (DE) algorithms, demonstrates effectiveness in correcting voltage fluctuations, thereby addressing grid-related power quality concerns.

Moreover, integrating PV systems with distributed generation (DG) setups, alongside unified power quality conditioners, presents a promising avenue for improving power quality. Utilizing multi-loop proportional-integral controllers, these systems regulate PV array voltage, thereby enhancing overall power quality within distribution networks.

In conclusion, while the integration of solar PV offers significant potential for meeting growing energy needs sustainably, it requires strict adherence to established standards and the adoption of advanced power quality mitigation techniques to ensure smooth integration and grid stability.

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Table 1. Harmonics voltage distortion limit for non-linear load at PCC (implemented from IEEE 519-1992)

Harmonics voltage distortion in % at PCC	2.3 to 69 kV	69 kV to 161 kV	>161 kV
Maximum for individual harmonics	3.0	1.5	1.0
THD	5.0	2.5	1.5

This study revolves around tackling power quality disruptions within the system while effectively managing the flow of reactive power into the grid. The approach outlined in this paper encompassesseveral key attributes:

- **Suppression of Voltage Sag, Swell, and Harmonic Disturbances:** Achieved through the implementation of a Voltage Source Converter (VSC)-based Unified Power Quality Conditioner(UPQC). The UPQC is preferred for its advantages such as low losses, reduced passive filter requirements, and a high switching frequency, enabling effective mitigation of disturbances arising from both linear and non-linear loads.
- **Utilization of Right-Shunt UPQC:** This configuration offers benefits including low losses, enhanced performance, and simplified control, making it an optimal choice for addressing power quality issues within the system.
- **PV-UPQC Integration:** The PV-UPQC not only provides reactive power support to the grid but also compensates for reactive power requirements of connected loads, thus effectively addressing power quality concerns while integrating a 1 MW large-scale PV system into the grid via a shared DC link.
- **Maintaining Stable DC Link Voltage:** Even under adverse conditions such as voltage sag, swell, and the presence of 3rd and 5th harmonics, the proposed system ensures stable DC link voltage, thereby enhancing overall system stability.
- **Compliance with IEEE-519 Standards:** The achieved Total Harmonic Distortion (THD) level at the Point of Common Coupling (PCC) is less than 5%, meeting the stringent standards set forth by IEEE-519.

II. PROPOSED SYSTEM

Two primary methods are utilized to address power quality concerns such as voltage sag, voltage swell, and harmonics. The first technique, referred to as conditioning, involves strengthening power system components to reduce their susceptibility to power quality disturbances. Through the implementation of conditioning measures, the power system gains resilience, enabling it to continue operating even under significant voltage fluctuations. The second approach involves integrating a line conditioning system into the power network to actively prevent power quality disruptions. This system acts as a protective barrier, intercepting and correcting disturbances before they spread throughout the network, thereby safeguarding the reliability of the power supply. Figure 1 illustrates the basic configuration of a Unified Power Quality Conditioner (UPQC). The UPQC integrates a series Active Power Filter (APF) with a shunt Active Power Filter (APF). This setup involves the useof two voltage-source converters (VSC1): one is responsible for injecting series voltage to mitigate disturbances, while the other (VSC2) is associated with a Distribution Static Compensator (D- STATCOM), which injects shunt current to address power quality issues. Both VSCs operate in synchronization, sharing a common DC link to ensure coordinated and efficient compensation withinthe power system.

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Simulink model

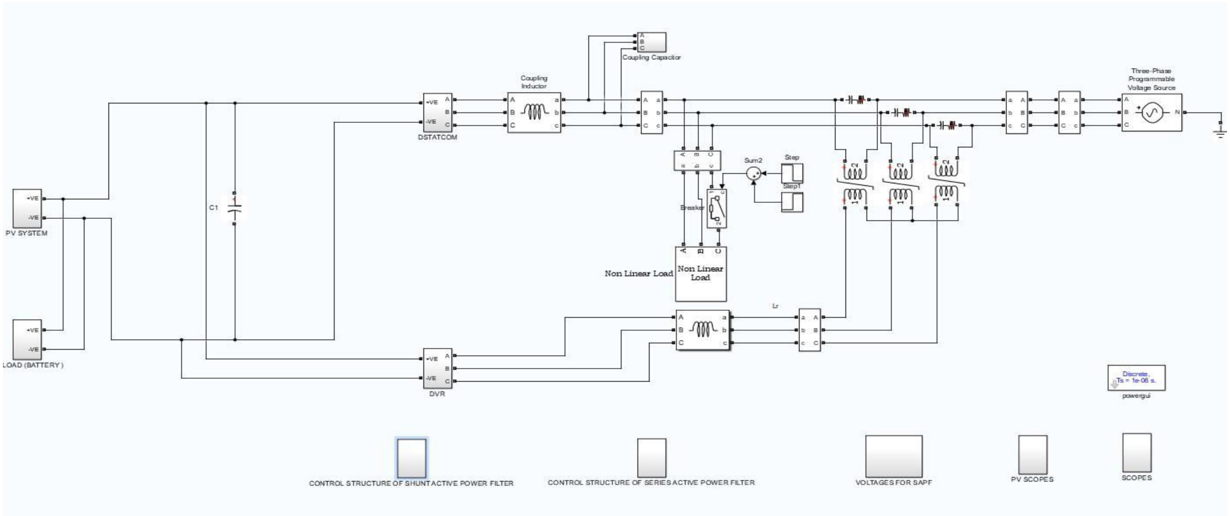

Figure 1.Grid Connected PV System With UPQC

The utilization of Voltage Source Converter (VSC)-based Unified Power Quality Conditioner (UPQC) over Current Source Converter (CSC) in the proposed system offers several advantages that are pivotal for enhancing the overall performance and efficiency of the power system. VSC-based UPQC is preferred due to its ability to effectively mitigate power quality issues while ensuring minimal losses and passive filter requirements. The inherent characteristics of VSC technology facilitate high switching frequencies, which enable precise control and rapid response to grid disturbances, thereby enhancing the system's dynamic performance. Moreover, the decision to opt for a right shunt UPQC configuration further reinforces the strategic design considerations of the system. Right shunt UPQC configuration provides notable advantages such as reduced losses, superior performance, and simplified control algorithms. These benefits are particularly significant in the context of integrating a large-scale photovoltaic (PV) system, like the 1 MW installation mentioned, into the grid. By employing right shunt UPQC, the system can effectively regulate voltage fluctuations, mitigate harmonics, and compensate for reactive power, thereby ensuring optimal operation of the PV system and improving overall gridstability. Additionally, the integration of UPQC into the system architecture signifies a proactive approach towards addressing power quality issues arising from non-linear loads connected to the grid. Non-linear loads, often associated with varying power consumption patterns and harmonic distortions, can adversely impact the grid's stability and efficiency. However, with the implementation of UPQC, these challenges can be effectively mitigated, ensuring reliable and high-quality power supply to both the PV system and other connected loads. In summary, the selection of VSC-based UPQC, particularly in a right shunt configuration, underscores a strategic approach towards enhancing power quality, minimizing losses, and optimizing the performance of the integrated PV system within the grid environment. This proactive stance towards power quality management reflects a commitment to ensuring sustainable and efficient energy distribution while meeting the demands of modern power systems. Fig 1 shows the UPQC configuration with PV system.

2.1 Design of UPQC

Voltage Magnitude of DC-Link:

$$v_{dC} = \frac{2\sqrt{2}v_{LL}}{\sqrt{3}m}$$

Vdc = 677.71 ~ 700

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DC-Bus Capacitor Rating:

$$c_{dc} = \frac{3KaV_{Ph}I_{sh}t}{0.5 * (v_{dc}^2 - v_{dc1}^2)}$$

$$= \frac{3 * 0.1 * 1.5 * 239 * 34.5 * 0.03}{0.5 * (700^2 - 677.8^2)}$$

=9.3mF

Interfacing Inductor for Shunt Compensator:

$$L_f = \frac{\sqrt{3} m v_{dc}}{12 a f_{sh} I_{crPP}}$$

$$= \frac{\sqrt{3} * 1 * 700}{12 * 1.2 * 10000 * 6.9} = 1\text{mH}$$

Series Injection Transformer:

$$k_{SE} = \frac{v_{VSC}}{v_{SE}} = 3$$

SsE =3VsE IsEsag= 3*72*46=10KVA

Interfacing Inductor of Series Compensator:

$$L_r = \frac{\sqrt{3} * m v_{dc} k_{SE}}{12 a f_{se} I_r}$$

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$$\frac{\sqrt{3}*1*700*3}{12*1.2*10000*7.1} = 3.6mH$$

Table 2. Sun Power SPR-415E-WHT-D PV module specification

Parameters	Values
Max. Power output @ STC	P_{max} = 415 W
Open circuit voltage	V_{OC} = 85.3 V
Short circuit current	I_{SC} = 6.09 A
Voltage at maximum power point	V_{mp} =72.9 V
Current at maximum power point	I_{mp} = 5.69 A
Number of cells per module	N_S= 128 Cell

III. CONTROL SCHEME OF UPQC

In the integrated Unified Power Quality Conditioner (UPQC) system, the synergistic operation of its constituent components, namely the Distribution Static Synchronous Compensator (DSTATCOM) and the Dynamic Voltage Restorer (DVR), plays a pivotal role in addressing power quality issues within the grid. The DSTATCOM, functioning as the shunt converter, adeptly injects corrective non-sinusoidal currents to mitigate a spectrum of power quality anomalies, ensuring a stable and reliable power supply. Meanwhile, the DVR, acting as the series converter, precisely injects compensatory voltages to alleviate voltage distortions and maintain grid voltage stability, further enhancing the system's robustness. The proposed UPQC system leverages the sophisticated synchronous reference frame theory, specifically tailored for a three-leg Voltage Source Converter (VSC)-based architecture. This advanced theoretical framework facilitates precise control and coordination of UPQC operations, ensuring seamless integration with the grid and effective mitigation of power quality disturbances. In the context of the proposed right shunt UPQC configuration, meticulous attention is given to maintaining balanced voltage levels at the Point of Common Coupling (PCC), as outlined in the proposed model. This strategic approach underscores a commitment to optimizing system performance and ensuring consistent power quality across the grid infrastructure. In summary, the integration of DSTATCOM and DVR functionalities within the UPQC system, coupled with the adoption of synchronous reference frame theory, exemplifies a holistic approach towards enhancing power quality and grid stability. By effectively addressing voltage and current distortions, the proposed UPQC system is poised to deliver reliable and high-quality power supply, meeting the demands of modern electrical networks while paving the way for sustainable energy integration.

$$(t) = V(t) + VC(t) \qquad (1)$$

Where VL(t) is load side voltage, VS(t) is source/grid side voltage and VC(t) is compensation voltage. The load voltage after compensation becomes as (2) and (3) [4].

$VL = VLSAG - VCOMP$

Where:

$VCOMP = VC(t) = (t)$
$- (t)$

The load voltage after correction becomes as (4) and (5) [4].

$VL = VLSWELL - VCORR$

Where $VCORR = -VC(t) = -(VL(t) - VS(t)$ Similarly, balanced system current is obtained.

A synchronous reference frame control scheme, also known as DQ-control, is used to control UPQC. This transformation is referred to as Park's (DQO) transformation, and it is applied to the distorted supplyin the system as defined.

$$\begin{bmatrix} xd \\ xq \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} cos\theta d & co(\theta d - 2\pi/3) & cos(\theta d + 2\pi/3) \\ -sin\theta d & -si(\theta d - 2\pi/3) & -sin(\theta d + 2\pi/3) \end{bmatrix} \begin{bmatrix} xa \\ xb \end{bmatrix}$$

$\sqrt{2}$

A control signal for the shunt converter, such as for a DSTATCOM, is produced through a method known as hysteresis current control. This technique involves utilizing maximum power point tracking to compare the converter's

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output voltage with a reference voltage. By doing so, it enables adjustments to the converter's duty cycle to maintain the desired output voltage. Additionally, a proportional-integral (PI) controller is incorporated into this process. The transformation of three-phase current signals into a two-phase rotating reference frame is achieved through synchronous reference frame theory. This transformation facilitates the use of a phase-locked loop to detect the grid voltage phase angle. Subsequently, the two-phase rotating signal is converted back into a three-phase signal via inverse park transformation. These transformed signals are then fed into a pulse-width modulation (PWM) generator to produce the necessary gating signal for the shunt converter. To ensure precise control over the shunt converter's operation, a hysteresis controller is employed for the reference current signal. Furthermore, a modified unit vector template control scheme, which operates based on synchronous reference frame theory, is utilized for controlling a series converter like a DVR. This scheme involves transforming the 3- phase voltage and current signals into a two-phase revolving reference frame, allowing for control over the phaseand magnitude of the signals. Fig 2 shows the DSTATCOM control structure.

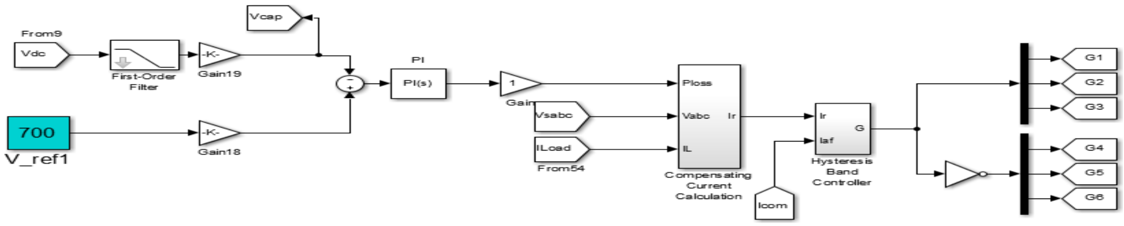

Figure 2. Control structure of Shunt Compensator

The modified unit vector template generates a reference signal based on the required output voltage and current. It transforms the reference grid voltage and current signals into the synchronously revolving frame with the grid vector voltage using park transformation. The error signal between the actual grid voltage signal and the reference voltage signal, along with the current hysteresis controller, is then utilized to generate a control signal for the series converter. In the modified unit vector template control scheme, errorsignals are generated by subtracting the load voltage signals from the reference voltage signal. These controlsignals regulate the compensating voltage, aligning it either in-phase or out-of-phase with the supply voltage,to mitigate voltage distortion. Figure 1 presents the MATLAB/Simulink model for the proposed system, while Figure 4 illustrates the simulation results of a 1 MW photovoltaic array system. This system's specifications and design are depicted Table 2. The photovoltaic array system integrates to the grid througha DC link using a boost converter, with an output DC current of approximately 1467.69A, voltage of around700 V, and DC output power of 1 MW, under constant radiation of 1000 W/m² at 25°C. The control structurefor DVR is shown in Fig 3.

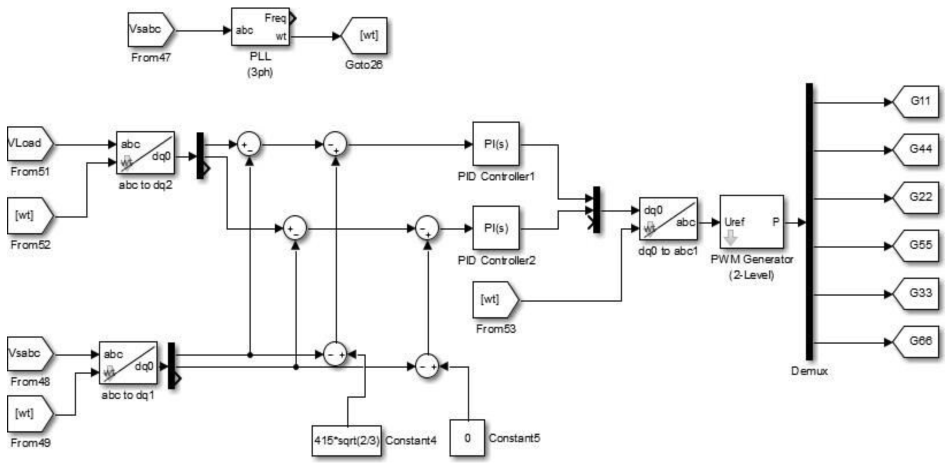

Figure 3. Control structure of Series Compensator

IV. SIMULATION RESULTS AND DISCUSSION

4.1. Voltage characteristics

Voltage sag, also known as voltage dip or voltage drop, refers to a transient decrease in the voltage level of an electrical

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power system. It involves a rapid reduction in voltage magnitude for a short period, usually lasting for a few cycles of the alternating current (AC) waveform. Various factors can cause voltage sags, including the starting of large motors, electrical faults, or sudden changes in load demand. These events can have detrimental effects on sensitive electronic equipment and machinery.

On the other hand, voltage swell, also known as voltage surge or overvoltage, is characterized by a temporary increase in the voltage level of an electrical power system. It entails a sudden and momentary rise in voltage magnitude, typically lasting for a few cycles of the AC waveform. Voltage swells can occur due to factors such as sudden load disconnection, switching operations, or lightning strikes. To address the adverse effects of voltage swells and ensure the safe operation of connected electrical and electronic equipment, a large- scale PV-UPQC system with proportional-integral (PI) control technique is proposed. The system utilizes the modified unit vector template to generate a reference signal for the series controller. This approach aims to alleviate voltage distortion on the grid side resulting from voltage sags and swells. According to IEC standard 61000-2-8, permissible voltage variations in low voltage (LV) distribution include voltage reductions with respect to the reference voltage for durations ranging from 0.5 cycles to 1 minute for sag and swell events. Permissible voltage sag levels are between 0.7 p.u. and 0.9 p.u., while permissible voltage swell levels range from 1.1 to 1.8 p.u. for sensitive loads. In a simulated scenario to measure the impact of sag and swell, a sag is deliberately induced in the grid-side system with a duration set at 0.1 s for both voltage sag and voltage swell. The voltage sag level is defined as 0.7 p.u., while the voltage swell level is set at 1.3 p.u., compliant with IEC standards. Figure 8 illustrates the in-phase and out-of-phase compensating voltages generated by the series converter, aimed at mitigating power quality issues such as sag, swell, and harmonics in all phases. Figure 4 depicts simulation results of the three-phase voltage waveform, indicating grid-side voltage sag occurring between 0.1 s and 0.3 s, with a voltage sag magnitude of 0.3 p.u., and voltage swell taking place between 0.5s and 0.7 s, with a voltage swell of 0.3 p.u., across all three phases. Through the integration of the photovoltaic array (PVA) using UPQC (an active filter), the load voltage is maintained at its rated level, free from sag, swell, and harmonics. Additionally, the system is responsible for keeping the DC link voltage constant under these conditions, achieved through unit vector control signals for the series converter to regulate both the phase and magnitude of the compensating voltage.

4.2 Total harmonics distortion (THD)

Total Harmonic Distortion (THD) holds particular significance in applications where maintaining high-quality power or signal purity is essential, such as in audio equipment, power distribution systems, and sensitive electronic devices. Lower THD values are preferable in these scenarios to ensure that electrical or audio signals closely resemble their pure sinusoidal form. Among the various harmonics, low-frequency harmonics like the 5th and 7th harmonics are particularly problematic, commonly found in electronic loads. These lower-order harmonics possess the potential to induce resonance within the system, amplifying their adverse effects. To assess the impact of the 5th and 7th harmonics, they are intentionally introduced into the system from the grid side for a brief duration of 0.035 s, occurring between 0.3 s and 0.35 s across all three phases. Figure 10 illustrates simulation results of the total harmonic distortion (THD), which reaches 24.95% at the grid side when the 5th and 7th harmonics are injected into the system, in addition to 0.3 p.u. voltage sag and voltage swell distortion. Employing the proposed system with the modified UPQC control technique reduces the load THD to 1.09%, as depicted in Figure 11. Table 3 provides MATLAB simulation parameters for the proposed work, demonstrating that the proposed system achieves a voltage THD of 2.06% at the load side, aligning with IEEE standard 519-1992.

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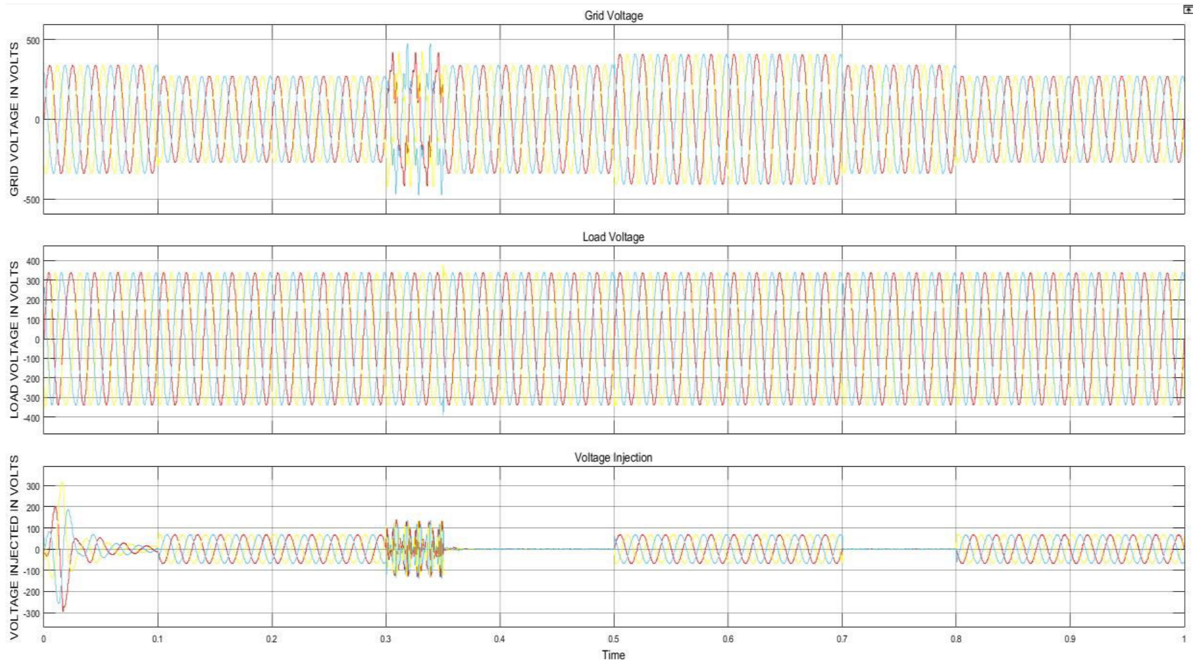

Figure 4. Three phase grid voltage, load voltage and series injected voltage.

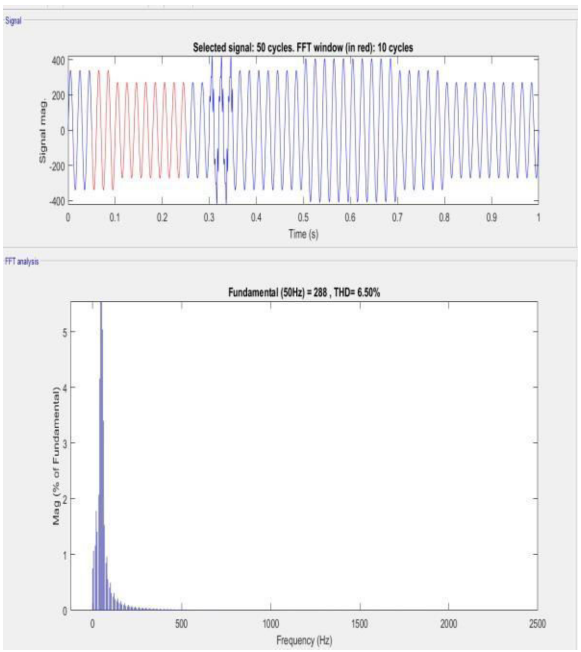

Figure 5.Grid voltage THD during sag.

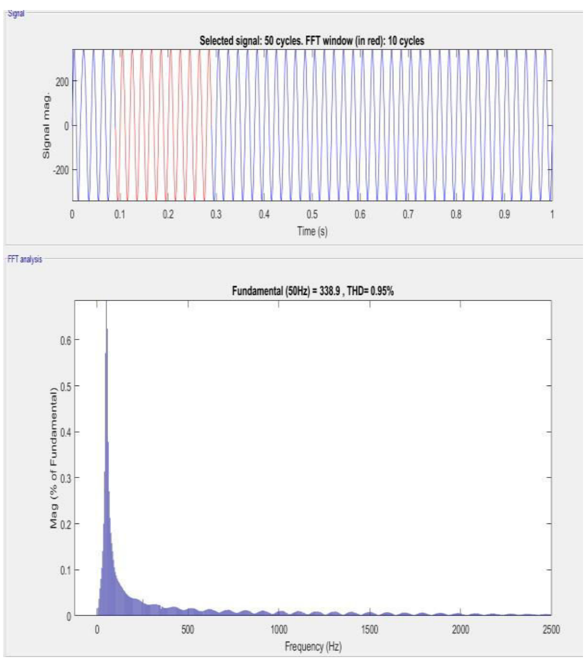

Figure 6.Load Voltage THD during sag.

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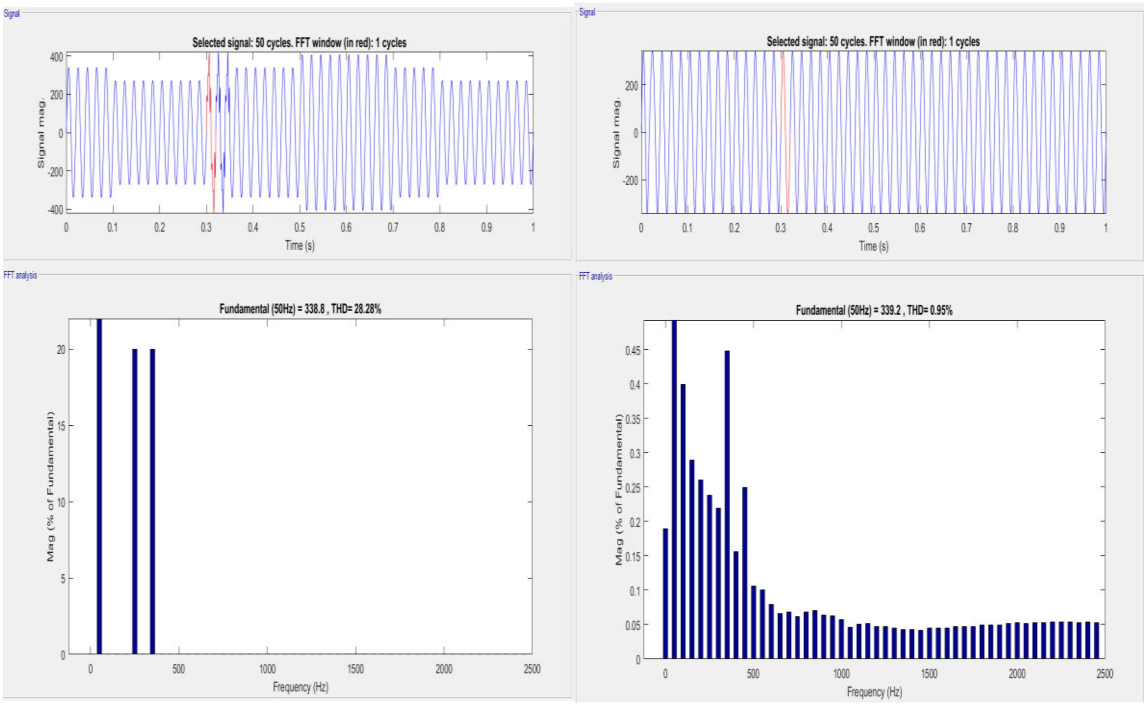

Figure 7. Grid voltage and load voltage THD during harmonics.

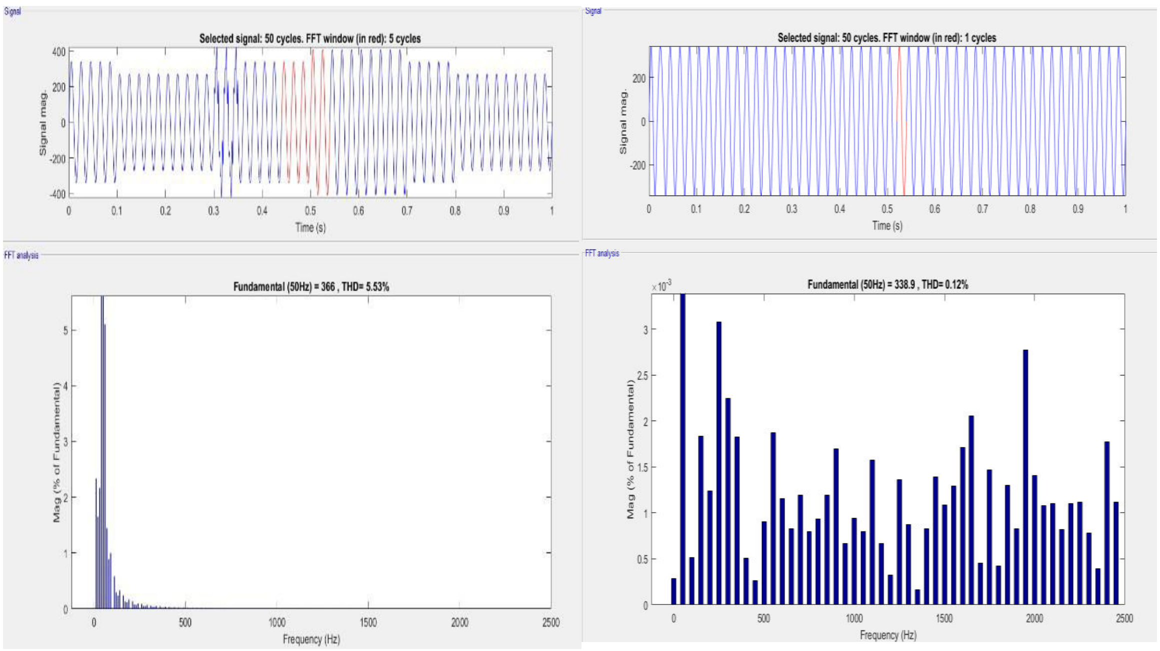

Figure 8. Grid voltage and load voltage THD during voltage swell.

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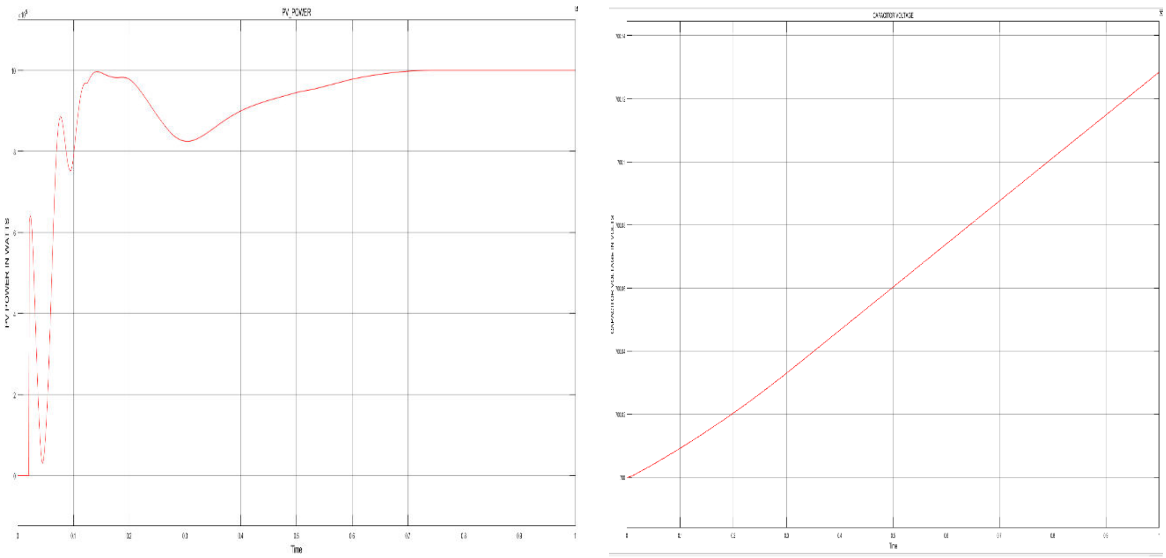

Figure 9. PV output power and capacitor voltage waveform

Table 3. Simulation parameters

Parameters	Values
PV power	P_{PV}=1 MW
PV short circuit current	I_{SC}= 6.09 A
No of series modules in a string	Nseries= 10
PCC line voltage	V_S=415 V
DC link capacitor	C_{DC}= 9300 µf
Series VSC parameters	R_f = 1 Ω & C_f = 10 µf

PV open circuit voltage
No of parallel modules i
DC link voltage
DC-link PI controller ga ... parameters

Load R_L= 60 Ω, L_L= 0.15 mH

Interfacing inductor
Ripple filter

L_f= 3.6 mH
R_f = 1 Ω & C_f = 10 µf

V. CONCLUSION

This study presents a novel power quality enhancement technique tailored to address voltage sag, swell, and harmonic distortions in a grid-connected large-scale solar power system using Unified Power Quality Conditioner (UPQC). The system is modeled and simulated using MATLAB Simulink. Specifically, a 1 MW solar photovoltaic system employing a Perturb and Observe algorithm for Maximum Power Point Tracking (MPPT) is incorporated, with a boost converter integrated into the grid through UPQC. To manage power quality issues, the control scheme for both the series active power filter and the shunt APF of UPQC utilizes a Proportional-Integral (PI) control technique. This is supplemented by a combined control approach, comprising a synchronous reference frame control scheme and a modified unit vector template control scheme. Notably, this proposed control approach is simpler to implement compared to traditional methods, resulting in reduced Total Harmonic Distortion (THD) of voltage (2.06%). Simulation results validate the effectiveness of the system in conforming to IEEE standard 519-1992 regarding power quality issues on the supply side and load- side current harmonics. The system demonstrates stability under varying conditions, including changes in irradiation, voltage sag/swell, and low-frequency harmonics. In conclusion, the integration of large-scale distributed generation with PV-UPQC emerges as a highly effective solution for modern distribution systems,effectively mitigating power quality challenges.

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