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# Power quality stabilization system for grid connected large-scale solar power system

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**ABSTRACT**

This paper presents solution to power quality issues when integrating a 1.5 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 3$^{rd}$, 5$^{th}$, and 7$^{th}$ 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.



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## 1. INTRODUCTION

In a distribution system, maintaining power quality is a challenge. Recent advancements in photovoltaic cell manufacturing and converter technology, solar photovoltaic has been identified as one of the most attractive inexhaustible sources for generating large amount of electricity. If the present installation rate persists, photovoltaic power will result in many aspects of the power system being changed and may affect system stability. Also, photovoltaic (PV) energy source inject harmonics in to the grid and causing distorted voltage waveforms at PCC leads to power quality issues like voltage sag and swells, hence power quality mitigation techniques are required for distribution network. Photovoltaic-unified power quality conditioner (PV-UPQC) is applied to control the harmonics, PV-UPQC is controlled using d-q control under unbalanced load condition along with moving average filter. Real and reactive power is regulated using ABC to DQO transformation to boost the PCC voltage profile in a grid-connected inverter with a PI controller [1]. The UPQC-DG employs a blend of synchronous reference frame (SRF) theory and unit vector template generation (UVTG), along with an extra PI controller, to supply reactive power support to the grid while managing the flow of reactive power [2]. Active power filters (APF) are employed to address harmonics in PV systems. To mitigate issues associated with voltage fluctuations in the source voltage that affect load voltage regulation when using UPQC, it becomes imperative to tackle power quality constraints related to load current. These constraints encompass factors such as a diminished power factor, elevated total harmonic distortion levels, and power imbalance. A proportional-integral controller, enhanced by the adaptive updating-sparrow search algorithm (AU-SSA) and synthesized alongside clean energy sources, is utilized to accurately rectify current imperfections and harmonics [3].

A series active power filters require an energy source to compensate for voltage sag/swell. The control approach is built on dual formulation principles compensation method with an adaptive fuzzy logic controller. Multi-objective parallel operation for an improved differential evolution (DE), the dynamic voltage restorer (DVR) is used because of its efficient mitigation of voltage sag and swells, to address power quality concerns in the grid [4]. A revised generalized integrator with the potential to remove DC offset for managing a unified power quality conditioner in conjunction with a solar photovoltaic array. The control algorithm enhances power quality (PQ) by addressing issues such as balancing grid currents, eliminating harmonics, compensating for reactive power, and mitigating grid voltage sags and swells [5]. Incorporating a photovoltaic (PV) system into a distributed generation (DG) setup alongside a single-phase to three-phase unified power quality conditioner enables an injection of PV-generated power into the grid. This system employs a multi-loop proportional-integral controller to regulate the photovoltaic array voltage and subsequently enhances power quality [6].

An inductive hybrid unified power quality conditioner is employed alongside an inductive filtering transformer (IFT) to enhance power quality. This is achieved through a control strategy that combines series and shunt hybrid active power filters and the synchronous method, which involves sliding Goertzel discrete Fourier transformation-based pre-filtering phase-locked loop techniques. This setup operates at medium voltage grids and addresses reactive power compensation at the point of common coupling (PCC). For the series active filter, a reference current is generated from the load current, and a PI-controlled constant DC link voltage is used to regulate the shunt active filter [7]. A flexible control strategy that empowers the system with the ability to achieve maximum power point tracking through the stepped perturbation and observation (P&O) algorithm while ensuring that the grid current remains at a unity power factor. Two- level, 3-ϕ distribution static compensator (DSTATCOM) is applied to improve power quality, modified synchronous reference frame (MSRF) based current control method is used to maintain DC-link voltage [8]. The generalized unified power flow controller (GUPFC) serves the purpose of ensuring system voltage, power stability, and quality are consistently maintained, even in the presence of both normal and fault conditions, yielding improved outcomes. Employing a fuzzy logic controller for the GUPFC converter, the system effectively preserves its stability and sustains voltage levels at approximately 95% of the reference value [9].

As of December 31, 2021, the National Solar Mission in India has successfully installed a combined solar power capacity of 48.087 GW. According to the ministry of new and renewable energy, there is a projection that this capacity will surpass 500 GW by the year 2030. In Karnataka State, India, a total solar power commissioned is 7472.46 MW as on 31/12/2022 as per Karnataka Renewable Energy Development Limited (KREDL) data, among that, in Tumkur district, Pavagada taluk a mega solar park of 2000 MW is spread over a total area of 13,000 acres.

Because of the intermittent existence of solar energy, the integration with conventional electric network leads to stability issues. Therefore, integration of photovoltaic system into the grid must adhere to the specified standards such as IEEE-1547, IEC-61727, ENC 61000-3-2, IEEE-519, and IEEE-1159 set by the service provider and is given in Table 1 [10]. Proportional-integral-centered controller for the DC-link voltage to mitigate fluctuations and limit grid current total harmonic distortion (THD) to acceptable levels [11].

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 paper is centered on addressing power quality disruptions within the system and managing the flow of reactive power into the grid. The key attributes of the presented approach can be outlined as:

- Suppression of voltage sag, swell, and harmonic disturbances within the system arising from both linear and non-linear loads. This is achieved through the application of a voltage source converter (VSC)-based unified power quality conditioner (UPQC), known for its advantages including low losses, reduced passive filter requirements, and a high switching frequency;
- Utilization of a right-shunt UPQC due to its benefits, which encompass low losses, enhanced performance, and simplified control;

- The PV-UPQC has the capability to provide reactive power support to the grid while simultaneously compensating for reactive power requirements of connected loads, addressing power quality issues effectively;
- Integration of a 1.5 MW large-scale PV system into the grid via a shared DC link, maintaining a stable DC link voltage even under quality problems like voltage sag, swell, and the presence of $3^{rd}$ and $5^{th}$ harmonics within the system; and
- Achievement of a THD level less than 5% at the PCC, adhering to IEEE-519 standards.

Figures 1 and 2 provides a visual representation of the proposed project, highlighting the incorporation of a substantial PV system into the power grid. Typically, in conventional UPQC and DG-based systems, the emphasis has been on integrating smaller PV systems with the grid. The control methodologies examined in the literature for mitigating power quality concerns were successful in limiting voltage total harmonic distortions to approximately 4%. However, in the proposed system, the voltage THD is reduced to nearly 2%.

## 2. PROPOSED SYSTEM

Two techniques are used to minimize power quality obstacle such as voltage sag, voltage swell, and harmonics [12]. The first method, known as conditioning, involves making power system components less sensitive to power quality disturbances, allowing the system to operate even under critical voltage disturbances. In the second method, a line conditioning system is deployed in the power system to prevent power quality disturbances. Figure 1 shows the basic UPQC configuration. UPQC combines a series active power filter alongside a shunt APF. The configuration consists of two voltage-source converters (VSC1) of a dynamic voltage restorer injecting series voltage, alongside VSC2 of a distribution static compensator (D-STATCOM) injecting shunt current with a common DC link.

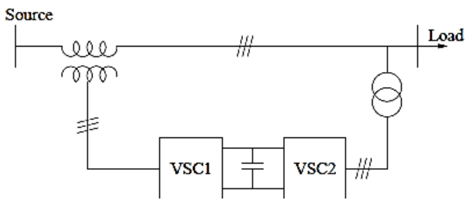



Figure 1. Basic UPQC configuration

Out of voltage source converter (VSC) and current source converter (CSC) based UPQC, VSC-based UPQC is used due to the following benefits: low losses, low passive filter demand, and a high switching frequency. Similarly, out of right and left shunt UPQC options, right shunt UPQC is chosen for its advantages, including low losses, better performance, and simple control. In the proposed system, UPQC is utilized to interface a large-scale photovoltaic system of 1.5 MW, which is integrated into the grid [10]. The grid is connected to non-linear loads, as shown in Figure 2.

### 2.1. Design of UPQC

The design of UPQC is crucial because the PV system needs to be interfaced with a common DC link by selecting the appropriate rating for the DC link capacitor and DC bus voltage. The sun power PV module, with a rating of 1.5 MW, is provided in Table 2. Figure 3 shows the series and parallel configuration of a 1.5 MW photovoltaic array (PVA) system. Maximum power is extracted from PV panels using the perturb and observe algorithm for MPPT implementation. The number of modules required is calculated as $1.5 * 10^6/415 = 3{,}618$ [13]–[15]. The DC link is rated at 700 Volts, and the number of series-connected modules per string is determined as $(V_{nom}/V_{mpp}) = (700/72.9) = 10$ modules. The number of parallel strings is calculated as (3,618/10) = 362 [16].

DC-link voltage, DC bus capacitor, interfacing inductor for the shunt and series converter, and series injection transformer ratings are selected and considered in the proposed system [1]. The line voltage of the grid is taken as 415 V, and the minimum DC voltage is $V_{dc1} = 677.7$ V, with $V_{dc}$ assumed to be 700 V. Additionally, $V_{ph} = 415/1.73 = 239.6$ V, $I_{sh} = 51.2$ A, and the DC link capacitor is $C_{dc} = 8.366$ mF. The shunt converter interfacing inductor is $L_f = 0.8$ mH. UPQC is designed to compensate for a 0.3 p.u. sag/swell, which amounts to $0.3(239.6) = 71.88 \approx 72$ V. Therefore, the system requires compensation using a series injection transformer with a turns ratio of 3, and the rating of each series transformer is 4.76 kVA. The series converter interfacing inductor is $L_f = 6$ mH.

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 |

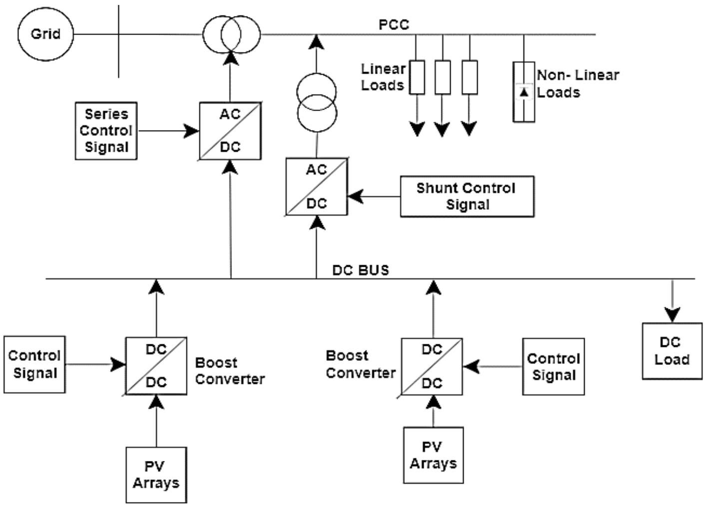



Figure 2. Proposed system

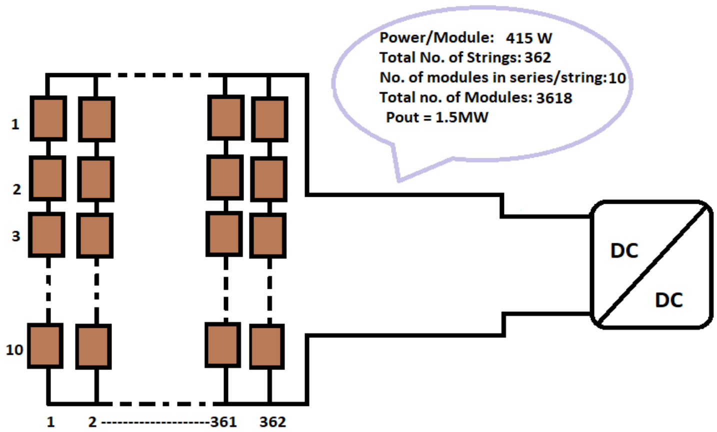



Figure 3. 1.5 MW PV system configuration

## 3. CONTROL SCHEME OF UPQC

UPQC consists of a DSTATCOM and a DVR. The shunt converter, i.e., DSTATCOM, injects shunt corrective non-sinusoidal current to mitigate power quality issues, while the series converter, DVR, injects compensation voltage to mitigate voltage distortions in the system. The proposed system utilizes a synchronous reference frame theory for a three-leg VSC-based UPQC. In the proposed right shunt UPQC, the balanced voltage at PCC is as (1) [4].

$$V_L(\mathrm{t}) = V_S(\mathrm{t}) + V_C(\mathrm{t}) \quad (1)$$

Where $V_L$(t) is load side voltage, $V_S$(t) is source/grid side voltage and $V_C$(t) is compensation voltage. The load voltage after compensation becomes as (2) and (3) [4].

$$V_L = V_{LSAG} - V_{COMP} \quad (2)$$

Where:

$$V_{COMP} = V_C(\mathrm{t}) = V_L(\mathrm{t}) - V_S(\mathrm{t}) \tag{3}$$

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

$$V_L = V_{LSWELL} - V_{CORR} \tag{4}$$

Where $V_{CORR} = -V_C(\mathrm{t}) = -(V_L(\mathrm{t}) - V_S(\mathrm{t})$ (5)

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 supply in the system as defined.

$$\begin{bmatrix} x_d \\ x_q \\ x_O \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} cos\theta_d & cos(\theta_d - 2\pi/3) & cos(\theta_d + 2\pi/3) \\ -sin\theta_d & -sin(\theta_d - 2\pi/3) & -sin(\theta_d + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{6}$$

A control signal for the shunt converter, i.e., for DSTATCOM, is generated using a technique called hysteresis current control [17], [18]. In this method, maximum power point tracking is used to compare the output voltage of the converter with a reference voltage, thereby allowing for the adjustment of the converter's duty cycle and maintain the desired output voltage, along with a PI controller.

A synchronous reference frame theory [19] is used to transform the three-phase current signals into a two-phase rotating reference frame [1], along with a phase-locked loop is used to detect the grid voltage phase angle. This two-phase rotating signal is then transformed back into a three-phase signal using inverse park transformation and these signals are provided to the PWM generator to yield the required gating signal for the shunt converter [20].

To ensure that the shunt converter operates in a controlled manner, a hysteresis controller is used for the reference current signal, as shown in Figure 4. A modified unit vector template control scheme, as shown in Figure 5, is used to control a series converter (DVR) based on the synchronous reference frame (SRF) theory. In this theory, the 3-phase voltage and current signals are altered into a two-phase revolving reference frame, where the phase and magnitude of the signals can be controlled.

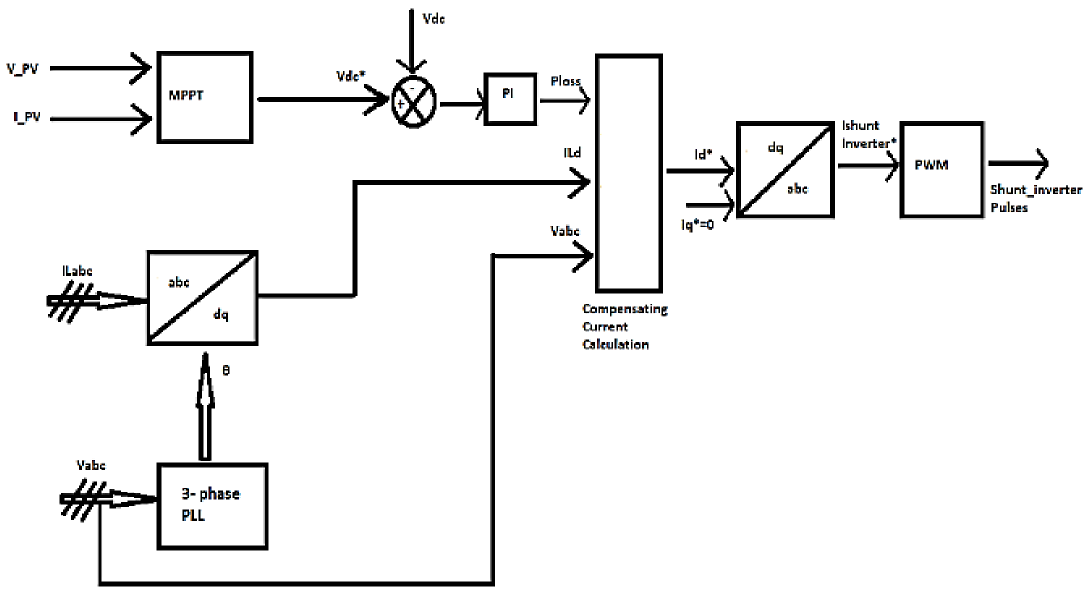



Figure 4. Block diagram of shunt control of UPQC

The modified unit vector template generates a reference signal based on the required output voltage and current. The reference grid voltage and current signal are modified into the synchronously revolving frame with the grid vector voltage with the help of park transformation. The error signal between the actual grid voltage signal and the reference voltage signal is then used, along with the current hysteresis controller, to generate a control signal for the series converter. The error signals are generated in the modified unit vector template control by subtracting the load voltage signals from the reference voltage signal [21]. These control signals regulate the compensating voltage, which is either in-phase or out-of-phase with the supply voltage, to mitigate the voltage distortion.

Figure 6 shows the MATLAB/Simulink model for a proposed system, Figure 7 depicts the simulation results of 1.5 MW photovoltaic array system with the specification and design as shown in Figure 3 and Table 2, with a constant radiation of 1000 W/m$^2$ at 25 ℃ integrated to grid through DC link using boost converter with an output DC current of approx. 2200 A, voltage of approx. 700 V and DC output power of 1.5 MW.

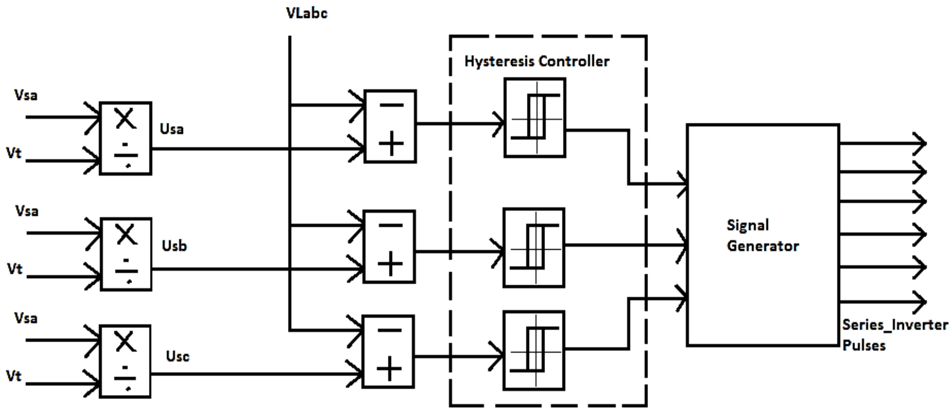



Figure 5. Block diagram of series control of UPQC

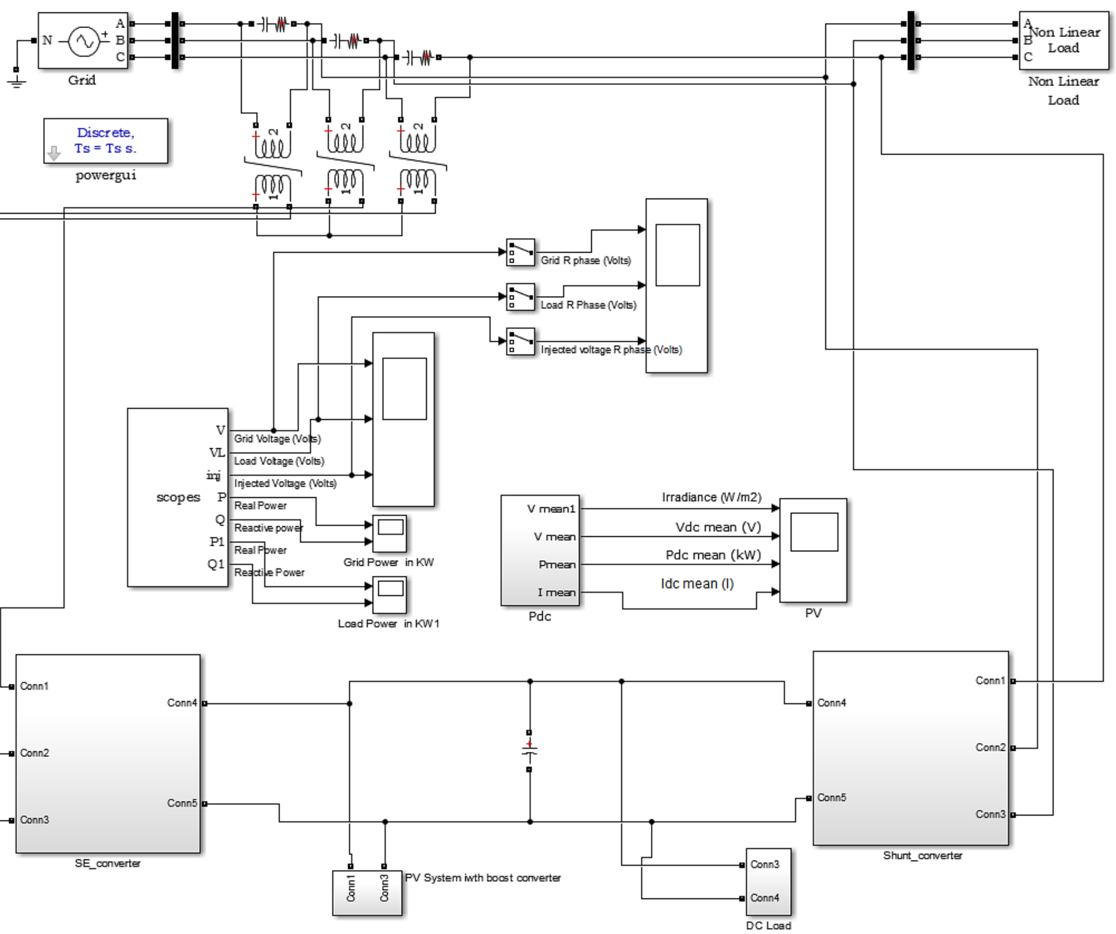



Figure 6. MATLAB Simulink model of proposed system

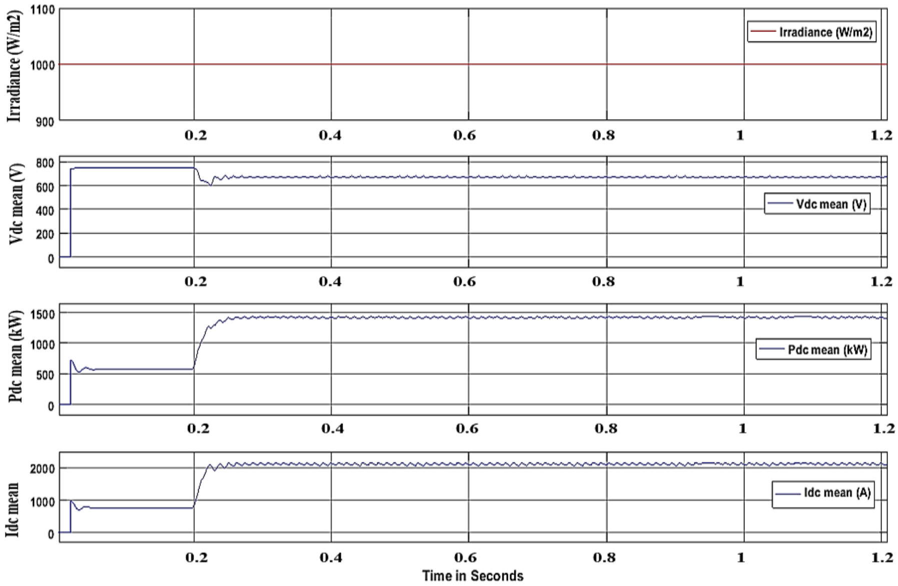



Figure 7. PV system output with constant irradiance

## 4. SIMULATION RESULTS AND DISCUSSION

### 4.1. Voltage characteristics

Voltage sag, also known as voltage dip or voltage drop, refers to a temporary reduction in the voltage level of an electrical power system. It is characterized by a rapid decrease in voltage magnitude for a short duration, typically lasting for a few cycles of the alternating current (AC) waveform. Voltage sags can be caused by various factors, such as the starting of large motors, electrical faults, or sudden changes in load demand, and they can have adverse effects on sensitive electronic equipment and machinery.

Voltage swell, also known as voltage surge or overvoltage, refers to a temporary increase in the voltage level of an electrical power system. It is characterized by a rapid and momentary rise in voltage magnitude, typically lasting for a few cycles of the alternating current (AC) waveform. Voltage swells can occur due to various factors, such as sudden load disconnection, switching operations, or lightning strikes. To mitigate the effects of voltage swells and ensure the safe operation of connected electrical and electronic equipment, we employ the proposed large-scale PV-UPQC system with a proportional-integral (PI) control technique and utilize the modified unit vector template to create a reference signal for the series controller. This approach is adopted to alleviate voltage distortion on the grid side resulting from voltage sags and swells. As per IEC standard 61000-2-8, permissible voltage variations in LV distribution include a reduction in voltage with respect to reference voltage for a duration of 0.5 cycle to 1 minute for sag and swell. The permissible voltage sag levels are between 0.7 p.u. and 0.9 p.u., and the permissible voltage swell levels are between 1.1 and 1.8 p.u. for sensitive loads.

To measure the effect of sag and swell, a sag is deliberately induced in the grid-side system, with a duration for both voltage sag and voltage swell set at 0.1 s. The voltage sag level is considered to be 0.7 p.u., while the voltage swell level is set at 1.3 p.u., well within the IEC standards. Figure 8 illustrates the in-phase and out-of-phase compensating voltages generated by the series converter, which is utilized to mitigate power quality issues such as sag, swell, and harmonics in R phases. Figure 9 displays simulation results of the three-phase voltage waveform, showing grid-side voltage sag occurring between 0.9 s and 1 s, with a voltage sag magnitude of 0.3 p.u., and voltage swell taking place between 1.6 s and 1.7 s, with a voltage swell of 0.3 p.u., for all three phases. Through the integration of the PVA using UPQC (an active filter), the load voltage is maintained at its rated level, free from sag, swell, and harmonics. Additionally, it is responsible for maintaining the DC link voltage constant under these conditions. This is achieved using 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)

THD is particularly important in applications where high-quality power or signal purity is critical, such as in audio equipment, power distribution systems, and sensitive electronic devices. Lower THD values are desirable in these applications to ensure that the electrical or audio signals closely resemble their pure, sinusoidal form. Low-frequency harmonics, especially the 5th and 7th harmonics, are considered particularly problematic and are commonly found in electronic loads. These lower-order harmonics have the potential to induce resonance within the system, magnifying their consequences. To investigate the influence of the 5th and 7th harmonics, they are introduced into the system from the grid side for a brief period of 0.1 s, occurring between 0.3 s, and 0.4 s across all three phases. Figure 10 displays the simulation results of total harmonic distortion (THD), which is 20.62% at the grid side when the 5th and 7th harmonics are injected into the system, along with 0.3 p.u. voltage sag and voltage swell distortion. By using the proposed system with the modified UPQC control technique, the load THD is reduced to 2.06%, as shown in Figure 11. Table 3 provides a comparison of voltage THD at PCC before and after compensation, demonstrating that the proposed system achieves a voltage THD of 2.06% at the load side, in accordance with IEEE standard 519-1992.

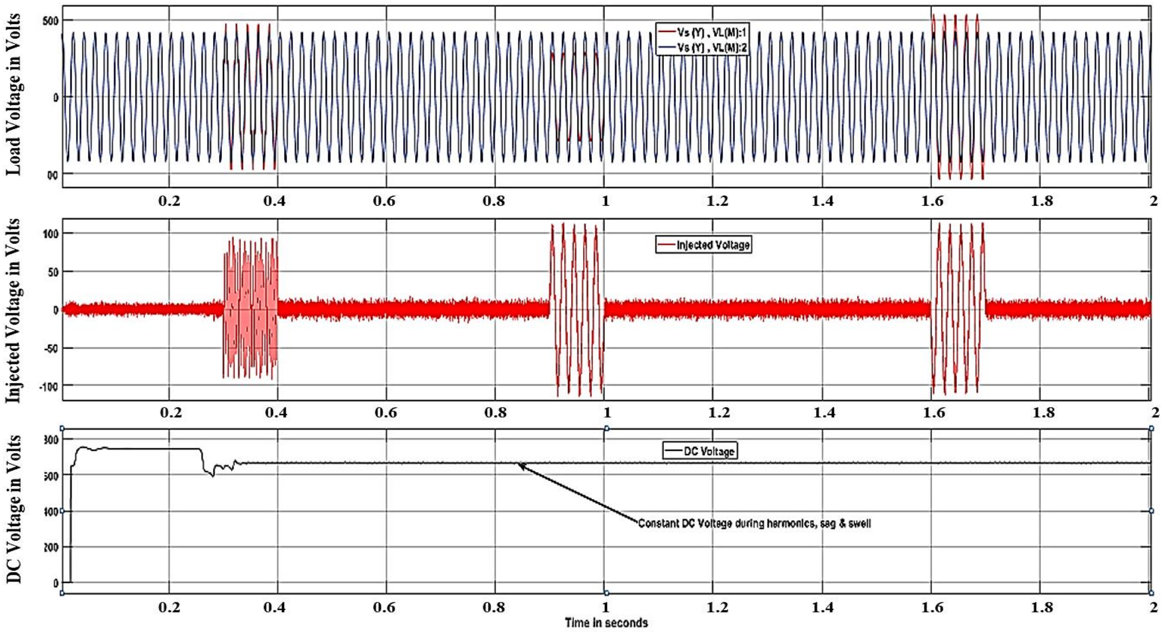



Figure 8. R phase grid voltage and load voltage, series injected voltage, and DC link voltage

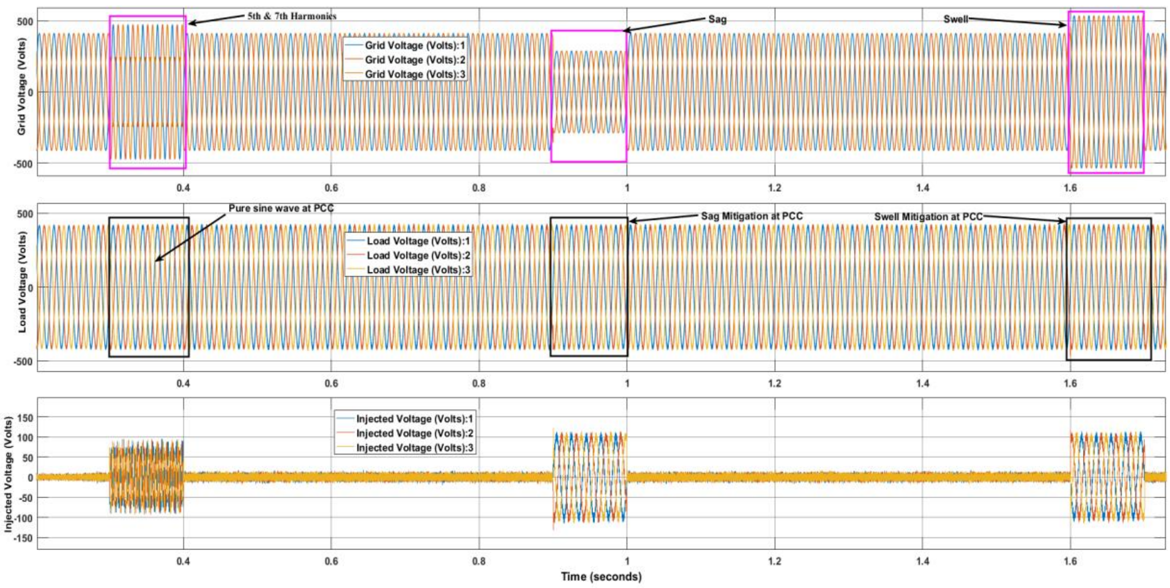



Figure 9. Three-phase grid voltage, load voltage, and series injected voltage

Table 3. Results comparison

| Source | PCC voltage THD % before compensation | PCC voltage THD % after compensation |
|---|---|---|
| Designing and analyzing the performance of a UPQC integrated with three-phase solar PV system [1] | - | 4.38 |
| Solar PV array integrated UPQC to enhance power quality, relying on modified GI [10] | - | 2.4 |
| Inductive hybrid unified power quality conditioner (IH-UPQC) [7] | 20.52 | 2.53 |
| Enhancing power quality in grid-connected solar power systems utilizing UPQC [22] | 55.27 | 4.66 |
| A methodical approach for controlling DC-link voltage in single-phase grid-tied PV systems [11] | 12.5 | 4.5 |
| An adaptive neuro-fuzzy control approach to enhance power quality within multi-microgrid clusters [23] | - | 2.92 |
| Utilizing a fuzzy hysteresis current controller to improve power quality in clusters incorporating renewable energy [24] | - | 2.59 |
| Proposed system | 20.62 | 2.06 |

## 4.3. Power characteristics

To analyze the real and reactive power behavior of the suggested system, a reactive load is linked to the PCC. Figure 12 illustrated the simulated outcomes for real and reactive power concerning both the grid and the load at the PCC. Negative real power signifies that the PV system is providing power to the load, while the reactive power consumption remains at zero. In this scenario, the grid is not delivering power to the load, primarily due to power quality issues within the system.

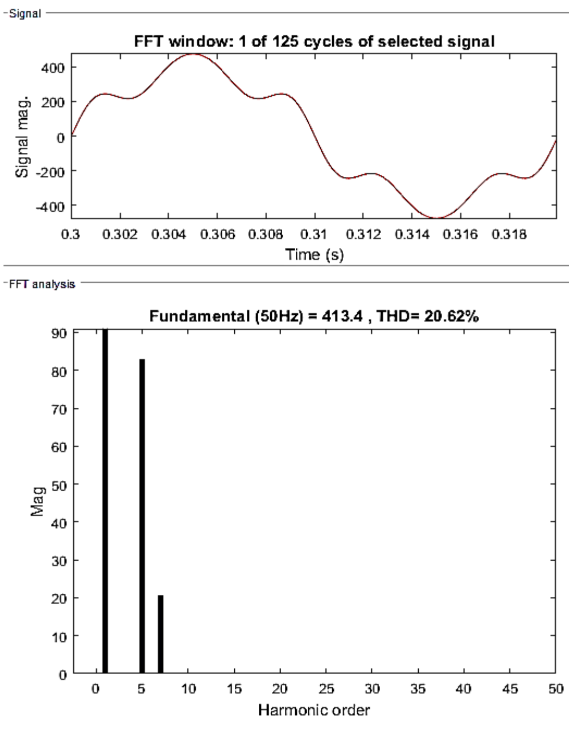



Figure 10. Grid voltage THD during harmonics, sag and swell

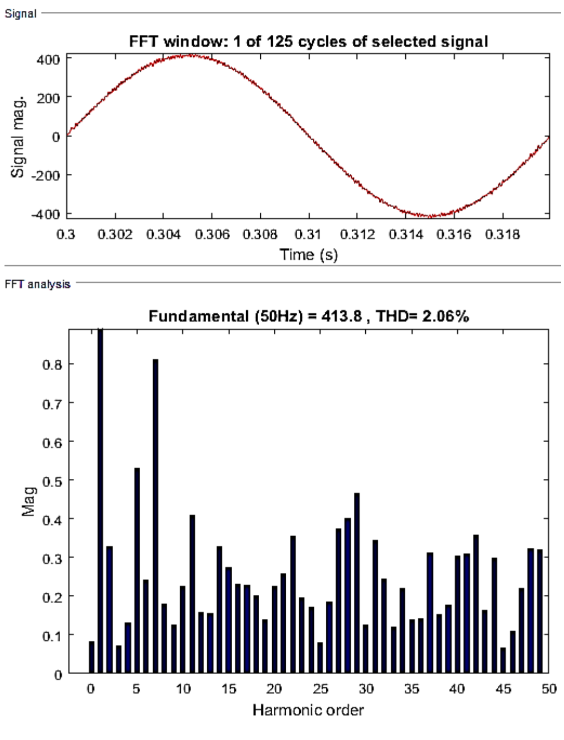
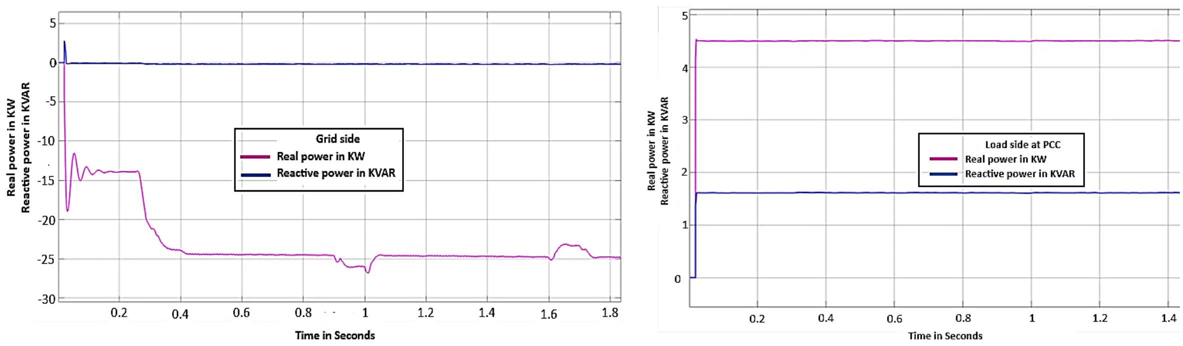



Figure 11. Load voltage THD with proposed compensation

## 4.4. System performances at insolation variation

Figure 13 shows the simulation results of 1.5 MW photovoltaic array systems output DC current, voltage and power under variation of irradiance from 800 W/m$^2$ to 1000 W/m$^2$ between the duration of 0 s to 0.3 s and from 1000 W/m$^2$ to 800 W/m$^2$ between the duration of 0.7 to 1.2 s [25]. Figure 14 shows simulation results of the 3- $\phi$ grid voltage, load voltage and series compensation voltage injected with variation in PV irradiance. Waveforms are free from power quality problems and DC link voltage is maintained almost constant during isolation variation. MATLAB simulation parameters of the proposed work is given in the Table 4.




(a) (b)

Figure 12. Real and reactive power at PCC in kW and kVAR (a) grid and (b) load side

Table 4. Simulation parameters

| Parameters | Values |
|---|---|
| PV power | $P_{PV}$=1.5 MW |
| PV open circuit voltage | $V_{OC}$ = 85.3 V |
| PV short circuit current | $I_{SC}$= 6.09 A |
| No of parallel modules in a string | Nparallel= 362 |
| No of series modules in a string | Nseries= 10 |
| DC link voltage | $V_{DC}$= 700 V |
| PCC line voltage | $V_S$=415 V |
| DC-link PI controller gains | $K_p$= 0.01 & $k_i$=0.001 |
| DC link capacitor | $C_{DC}$= 3000 µf |
| Shunt VSC parameters | |
| Interfacing inductor | $L_f$= 0.8 mh |
| Ripple filter | $R_f$ = 10 Ω & $C_f$= 5.5 µf |
| Load | $R_L$= 60 Ω, $L_L$= 0.15 mh |
| Series VSC parameters | |
| Interfacing inductor | $L_f$= 0.6 mh |
| Ripple filter | $R_f$= 5 Ω & $C_f$ = 6.37 µf |

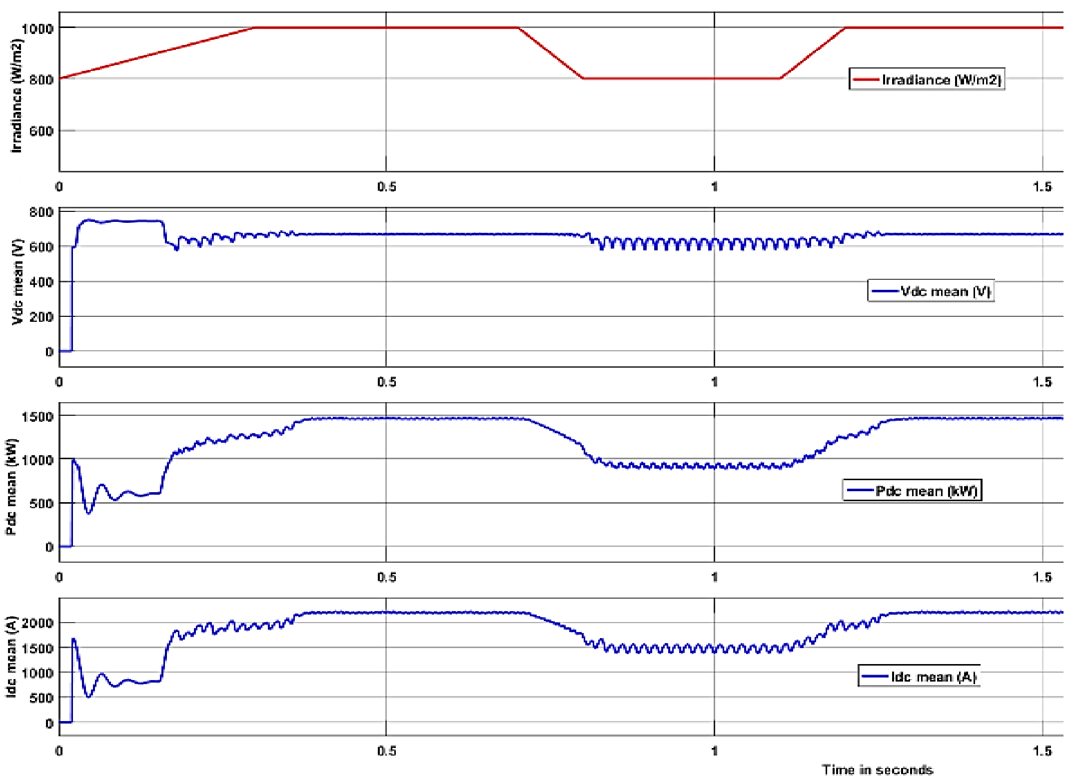



Figure 13. PV system output with variation in PV irradiance

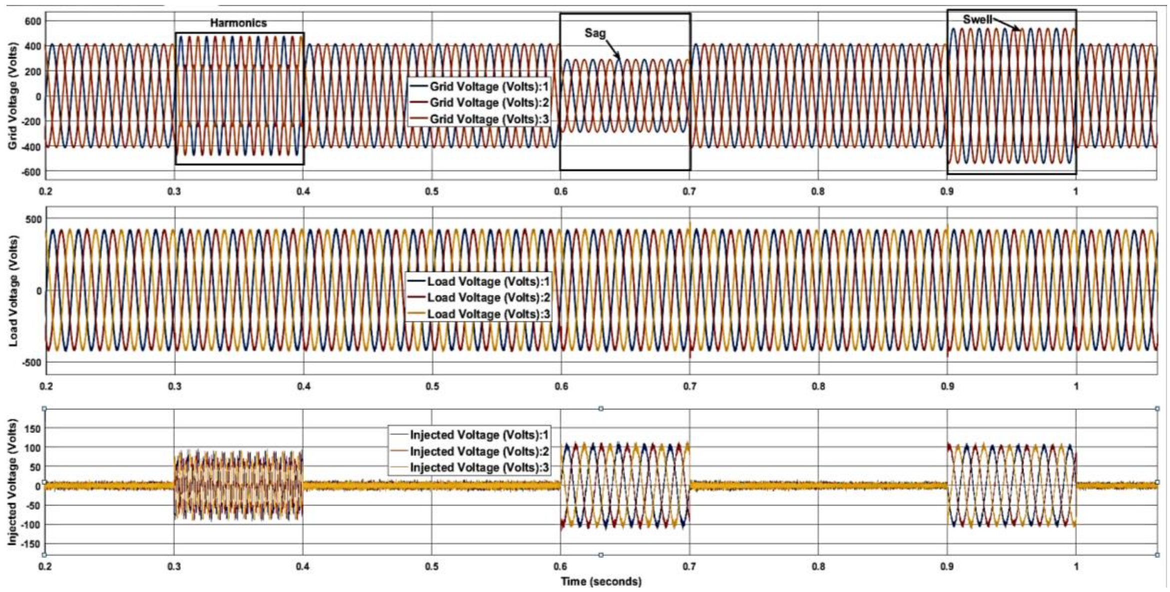



Figure 14. 3- ϕ Grid voltage, load voltage, and series injected voltage with variation in PV irradiance

## 5. CONCLUSION

This paper introduced a power quality enhancement technique designed to address issues such as voltage sag and swell at 0.3 per unit (p.u.), as well as the presence of 5$^{th}$ and 7$^{th}$ harmonics in a grid-connected large-scale solar power system using UPQC. The system is constructed and simulated using a MATLAB Simulink model. Furthermore, a 1.5 MW (large-scale) solar photovoltaic system employing a perturb and observe algorithm for maximum power point tracking (MPPT) is implemented. This algorithm is utilized for a boost converter integrated into the grid through UPQC. To tackle power quality challenges in the system, the control scheme for both the series active power filter and the shunt APF of UPQC is governed by the proportional-integral (PI) control technique. This is complemented by a combined control approach, which includes a synchronous reference frame control scheme and the proposed modified unit vector template control scheme. Notably, the proposed control approach is more straightforward to implement compared to traditional control methods, resulting in a reduced voltage total harmonic distortion (THD) of 2.06%. Simulation results demonstrate that power quality issues on the supply side, encompassing voltage sag/swell and harmonics, as well as load-side current harmonics, conform to IEEE standard 519-1992. The system exhibits stability under varying conditions, including changes in irradiation, voltage sag/swell, and low-frequency harmonics. In conclusion, it is determined that the integration of large-scale distributed generation with PV-UPQC is the most effective solution for modern distribution systems, effectively mitigating power quality challenges.

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