Optimal Design and Performance Analysis of Solar PV Integrated UPQC for Distribution Network

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Abstract — The increasing number of electricity consumers results in power quality problems in the distribution system. Solar photovoltaic integrated unified power quality conditioner (UPQC-PV) is a widely adopted device that can improve a distribution system's voltage and current quality. This paper presents an optimal design and performance analysis of a unified power quality conditioner integrated with a double-stage solar photovoltaic system (UPQC-PV). A technique based on sequence component detection (SCD) and unit vector template generation (UVTG) is proposed for the UPQC-PV control. Using a SCD technique, the fundamental active component of the distorted load current is estimated, which is used to generate a reference signal for shunt compensator control. The UPQC-PV consists of shunt and series compensators; the shunt compensator eliminates the harmonic currents produced by nonlinear loads and extracts the active power generated by the solar PV array. In addition, the series compensator compensates for the grid side power quality problems such as voltage sags/swells. Hence, the proposed system can simultaneously perform clean energy generation and power quality improvement. The UPQC-PV system performance is evaluated in MATLAB-Simulink software under different grid conditions.

Keywords — Distribution system, Power quality (PQ), Solar photovoltaic system, Sequence component detection (SCD), Unit vector template generation (UVTG), Unified power quality conditioner (UPQC).

I. INTRODUCTION

The integration of wind and solar distributed energy resources into the grid has become increasingly common due to the invention of reliable and adequate power electronic converters and increased PV panel performance [1]. Consequently, as solar and wind energy systems, which are variable sources of energy, become more widely adopted, the occurrence of voltage variations at the point of common coupling (PCC) has increased significantly in distribution networks. Therefore, modern distribution systems are expected to withstand high penetration of distributed energy resources and maintain high power quality standards [2], [3].

Furthermore, the widespread use of nonlinear power electronic loads, which draw highly distorted currents, is

another significant problem in modern distribution systems. Depending on the current level and impedance of the grid, these distorted currents cause PCC voltage distortion. As a result, feeders and distribution transformers experience

substantial power loss because of these nonlinear power electronic loads [4]. Furthermore, these loads are vulnerable to PCC voltage sags and swells, resulting in irregular tripping and increased cost of maintenance.

Numerous power quality devices focusing on power factor correction have been employed for power quality improvement. These power quality devices are best suited for medium and low-power applications [5], [6]. In large-scale industrial systems, custom control devices, including the dynamic voltage restorer (DVR), distribution static compensator (DSTATCOM), and unified power quality conditioner (UPQC), are used as additional solutions for power quality improvement.

The combination of solar PV systems and custom power devices offers multiple solutions of power quality enhancement and clean energy generation. A solar system integrated with DSTATCOM has been proposed in [7], [8]. The proposed systems serve a dual function of generating power from a solar system and grid current harmonic elimination. A three-phase supply system with a grid-interfacing converter and adjustable dc-link voltage has been introduced in [9]. This system performs an active filtering function while generating and integrating clean energy into the distribution network. A DSTATCOM can perform both active filtering and load voltage control; however, it controls only the load bus voltage through reactive power injection. Consequently, DSTATCOMs are unable to manage the load bus voltage and maintain grid current at unity power factor at the same time.

The unified power quality conditioners (UPQC) have recently attracted much interest due to the increasing attention on distributed generation and microgrids [10]-[13]. The integration of a UPQC with a solar PV system was proposed in [14]-[16]. The UPQC integrated PV system is more beneficial than traditional grid-connected voltage source converters (VSC). Some of its benefits include power quality improvement of the grid, protection of sensitive loads against grid side disturbances, and increased converter fault ride-through competency during transients. However, the UPQC integrated PV system is suitable for three-phase three-wire distribution systems. The neutral phase was not provided for single-phase loads, which are the most common type of loads in a distribution system.

The generation of a reference signal is the main challenge in UPQC-PV control. Methods used for generating the reference signal for series and shunt compensators of the

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UPQC-PV are grouped into time-domain and frequency-domain methods [3]. Time domain-based methods are generally adopted due to lower computational demand in real-time applications. The synchronous reference frame theory (d-q theory), instantaneous reactive power theory (p-q theory), and instantaneous symmetrical component theory are the frequently used methods [17]. The downside in using the synchronous reference frame theory-based method is the existence of a double harmonic component in the d -axis current during load unbalance situations. Therefore, to eliminate the double harmonic component, low-pass filters with low cut-off frequency are used, leading to the poor dynamic performance of the system [18].

According to [19], the instantaneous reactive power theory-based method's identified shortcoming includes poor performance in unbalanced and distorted voltage. A new voltage sensorless control technique for the control of shunt active power filter for the case of unstable grid conditions has been proposed in [20]. The voltage of the grid was not detected in this method. An improved sensorless voltage technique for shunt active power filter control has been proposed in [21]. This technique was aimed to achieve the use of only current sensors to generate reference signals for the shunt active power filter control. This technique used a constant dc power supply at the shunt active power filter dc-link instead of a capacitor. Therefore, it is impossible to realize the integration of a solar PV system at the dc-link of the shunt active power filter from the proposed technique.

The review shows that a three-phase four-wire UPQC-PV system for distribution application is not common in literature. Therefore, this work presents an optimal design of a UPQC-PV suitable for a three-phase four-wire distribution system. Furthermore, a control technique for the UPQC-PV system is also proposed. This technique is based on the sequence component detection (SCD) method for shunt compensator control and the unit vector template generation (UVTG) method for series compensator control. A sequence component detection (SCD) method based on [21] is used to separate the load current's positive and negative sequence components. The negative sequence component is passed through a harmonic filter at the system fundamental frequency. The output current components of the filter are subtracted from the distorted load current to produce the fundamental positive sequence components (FPSCs). The FPSCs are transformed at suitable instances to estimate the magnitude of load current fundamental active components. These are used to produce the reference signals for the shunt compensator control. The proposed SCD technique has good dynamics with better accuracy in extracting distorted load current active components. The significant benefits of the proposed system are:

- 1) It provides a neutral phase for the single-phase loads.
- 2) It is a multifunctional configuration that combines the function of clean energy generation with power quality improvement.
- 3) It ensures that sensitive loads are protected from PCC voltage sags/swells and distortion while mitigating harmonic currents produced by nonlinear loads.
- 4) It can withstand severe load current unbalancing and single-phasing conditions.

- 5) It requires fewer sensing devices and does not require complex transformations.

II. UPQC-PV SYSTEM CONFIGURATION AND CONTROL

Fig.1 shows the configuration of the UPQC-PV system designed for a three-phase four-wire distribution system. A dc boost converter is used to connect the PV array to the dc-link of the UPQC. Filter inductors are used to connect the series and shunt compensators to the distribution system's point of common coupling (PCC). The series compensator uses series transformers to inject missing voltages into the PCC. Some loads connected to the distribution system consist of three-phase nonlinear load, balanced linear load, unbalanced linear load, and single-phase linear and nonlinear loads. Ripple filters comprised of resistors and capacitors connected in series are used to eliminate the harmonics produced by the switching actions of the series and shunt compensators. The primary function of a UPQC-PV system is to mitigate current harmonics produced by nonlinear loads and protect sensitive loads from PCC voltage disruptions such as voltage sags/swells and distortion. In addition to power quality improvement, the UPQC-PV system also generates active power through the PV arrays. The control and the design process of the shunt and series compensators are explained as follows.

Fig.1. UPQC-PV system configuration.

A. Control Configuration of Shunt Compensator

The diagram of the shunt compensator control is shown in Fig. 2(b). The first step in the shunt compensator control design is separating the positive and negative sequence components of the distorted load current. The method used to separate these components is based on the correlation between time delay and phase difference. The time delay due to the phase difference between two consecutive phases is determined using (1). Therefore, the positive and the negative sequence components are separated using the symmetrical component transformation given in (2).

$$\Delta t = \frac{\text{Phase shift between two phases in degrees}}{360} \times \frac{1}{f} \quad (1)$$

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \text{ and } A^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \quad (2)$$

where f is the frequency, Δt is the time delay, and "A" is the symmetrical component transformation matrix. In the standard symmetrical component transformation, the operator $\alpha = 1\angle 120^\circ = 1\angle -240^\circ$. Using (1), a -240° phase shift is equal to a time delay of 13.33 ms or $[(-240/360)/50]$ for a 50 Hz system. Also, the operator $\alpha^2 = 1\angle 240^\circ = 1\angle -120^\circ$ is equivalent to a time delay of 6.67 ms or $[(-120/360)/50]$ for a 50 Hz system. The proposed sequence component detection (SCD) method uses symmetrical time-domain components given in (3). This equation utilizes α and α^2 variables with time intervals of 13.33 ms for α and 6.67 ms for α^2 . The schematic diagram of the sequence component detection method is shown in Fig. 2(a).

Fig. 2. Shunt compensator control based on sequence component detection.
(a) Load active component extraction using sequence component detection.
(b) Shunt compensator control configuration.

$$\begin{bmatrix} I^{(1)} \\ I^{(2)} \\ I^{(3)} \end{bmatrix} = A^{-1} I_{abc}(t) = \frac{1}{3} \begin{bmatrix} (I_a + I_b + I_c) \\ (I_a + \alpha I_b + \alpha^2 I_c) \\ (I_a + \alpha^2 I_b + \alpha I_c) \end{bmatrix} \quad (3)$$

The positive and negative sequence components are derived from a set of 3-phase quantities $I_a(t)$, $I_b(t)$, and $I_c(t)$ using a formulated symmetrical time-domain components transformation. The three-phase quantities a, b, and c of the load current is derived from time-domain symmetrical components as shown in (4). From (4), the positive and negative sequence quantities are determined as shown in (5) and (6).

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = A I_{012}(t) = \begin{bmatrix} I^{(0)} \\ I^{(1)} \\ I^{(2)} \end{bmatrix} + \begin{bmatrix} I^{(1)} \\ \alpha^2 I^{(1)} \\ \alpha I^{(1)} \end{bmatrix} + \begin{bmatrix} I^{(2)} \\ \alpha I^{(2)} \\ \alpha^2 I^{(2)} \end{bmatrix} = \begin{bmatrix} I_a^{(0)} \\ I_b^{(0)} \\ I_c^{(0)} \end{bmatrix} + \begin{bmatrix} I_a^{(1)} \\ I_b^{(1)} \\ I_c^{(1)} \end{bmatrix} + \begin{bmatrix} I_a^{(2)} \\ I_b^{(2)} \\ I_c^{(2)} \end{bmatrix} \quad (4)$$

$$\begin{aligned} I_a^{(1)}(t) &= I^{(1)}(t) \\ I_b^{(1)}(t) &= \alpha^2 I^{(1)}(t) \\ I_c^{(1)}(t) &= \alpha I^{(1)}(t) \end{aligned} \quad (5)$$

$$\begin{aligned} I_a^{(2)}(t) &= I^{(2)}(t) \\ I_b^{(2)}(t) &= \alpha I^{(2)}(t) \\ I_c^{(2)}(t) &= \alpha^2 I^{(2)}(t) \end{aligned} \quad (6)$$

Once the negative sequence component of the load current is estimated, it is passed through a harmonic filter to produce the current components at the system fundamental frequency of 50 Hz in this case. Next, the filtered negative sequence component is subtracted from the load current to produce the fundamental positive sequence components (FPSCs). After the FPSCs of three-phase load current are estimated, they are transformed into direct-quadrature (d-q) axis coordinate [22] using the phase and frequency data acquired from the phase-locked loop (PLL). The PLL input is the pure sinusoidal load voltage. The d-component corresponds to the magnitude of the load current active components. The shunt compensator's reference signal (I_g^*) is essentially the desired power system current (I_g). Therefore, the reference signals must be balanced and maintained at the unity power factor (UPF). The magnitude of the power system currents comprises of three fundamental active components, namely power system currents corresponding to fundamental active load power at nominal PCC voltage (I_{Lg}), power system currents equivalent to PV array power (I_{pv}) and loss component (I_{loss}) equal to converter switching action losses, ripple filter losses, etc. These currents are shown in (7)-(9).

$$I_g^* = I_{Lg} - I_{pv} + I_{loss} \quad (7)$$

$$I_{Lg} = I_{Ld-fund}^{(1)} \quad (8)$$

$$I_{pv} = \frac{2 P_{PV}}{3 V_g} \quad (9)$$

where (P_{pv}) is the PV array power, and V_g is the grid voltage magnitude. The UPQC-PV dc-bus voltage is controlled at the preferred value by a proportional-integral (PI) controller. The PI controller generates the component corresponding to the converter and filter circuit losses. The mathematical expression of the dc-link PI controller is shown in (10).

$$I_{loss}(n) = I_{loss}(n-1) + K_p \Delta e_{vdc}(n) + K_i e_{vdc}(n) \quad (10)$$

where I_{loss} is the PI controller output, representing the UPQC-PV system loss component, K_p and K_i are the PI controller gains, and Δe_{vdc} means the voltage error difference in the dc-link between the previous and present sampling times. e_{vdc} is the actual dc-link voltage error. Next, the unit vector templates of PCC voltage are multiplied with reference magnitude to produce the shunt compensator instantaneous reference currents (I_{ga}^* , I_{gb}^* , I_{gc}^*). Finally, the error between (I_{ga}^* , I_{gb}^* , I_{gc}^*) and the actual power system current (I_{ga} , I_{gb} , I_{gc}) are fed into a hysteresis controller to produce the gating signals for the shunt compensator control.

B. Control Configuration of Series Compensator

The schematic diagram for series compensator control is shown in Fig. 3. The load voltages are defined as fundamental

positive sequence components using a phase-locked loop (PLL) based simplified approach. The grid voltages are detected and multiplied by $1/V_m$. V_m represents the peak amplitude of the grid voltage under consideration. Therefore, unity source voltages are obtained. The unity source voltage signals are sent to a PLL which generates $\sin$ and $\cos$ output signals at the fundamental frequency of 50 Hz. Additionally, the $\sin$ and $\cos$ signals are of the same magnitude. The $\sin$ term represents an ideal sinusoidal voltage signal. Therefore, the three-phase unit vector templates of the system are given in (11)-(13).

$$U_a = \sin(\omega t) \quad (11)$$

$$U_b = \sin(\omega t - 120^\circ) \quad (12)$$

$$U_c = \sin(\omega t + 120^\circ) \quad (13)$$

Fig.3. Series compensator control configuration

The constant term V_{Lm} is the desired peak amplitude of the load voltage at the nominal steady-state condition. Therefore, the reference load voltage signal is produced by multiplying the unit vector template generation (UVTG) of (11)-(13) with the constant term V_{Lm} as given in (14).

$$V_{Labc}^* = V_{Lm} * U_{abc} \quad (14)$$

The desired pure sinusoidal load voltage (V_{Labc}) must be equivalent to the reference load voltage (V_{Labc}^*). Therefore, the reference load voltage (V_{Labc}^*) and the sensed load voltage (V_{Labc}) are compared in the hysteresis controller to generate switching signals for the series compensator control.

C. DC Boost Converter Control

The PV array is operated at maximum power by the dc boost converter. The control of a dc boost converter is accomplished using a maximum power point tracking (MPPT) algorithm. Perturb and observe (P&O), incremental conductance, and fractional open-circuit voltage are the most often utilized MPPT algorithms [14]. Therefore, a P&O approach is used to track the PV array's maximum power operating point in this work. This algorithm detects the PV array's present and previous power and voltages as well as produces an appropriate duty ratio to regulate the boost converter. The duty ratio for the subsequent cycle is calculated using the P&O method as shown in (15).

$$d_{boost}(n+1) = d_{boost}(n) + D_{step} \cdot \text{sgn}(\Delta P_{pv}) \quad (15)$$

where $d_{boost}(n+1)$ is the duty ratio for the subsequent dc boost converter MPPT sampling time, $d_{boost}(n)$ is the duty ratio in the present MPPT sampling time, D_{step} is the step size duty

ratio, and ΔP_{pv} is the PV array power difference between the present and the previous sampling time.

III. SIMULATION RESULTS AND DISCUSSION

The proposed UPQC-PV system in Fig. 1 is simulated in MATLAB-Simulink to evaluate its performance. The simulation discrete solver step size is $1e-6s$. The parameters used for the simulation are listed in Table I. The steady-state and dynamic operation of the UPQC-PV system is investigated extensively under several distribution system disturbances to confirm its conformity with the IEEE-519 standard.

TABLE I: SIMULATION PARAMETERS

Specifications	Values
Utility	3- ϕ , 415 V (L-L), 50 Hz
Source R-L	$R = 0.1 \Omega$ and $L = 0.4 \text{ mH}$
Linear loads	11 kW and 7 kVAR
Nonlinear load	$R = 30 \Omega$ and $L = 50 \text{ mH}$
DC-link	$C = 9400 \mu\text{F}$
Shunt compensator	2.5 mH, $R = 5 \Omega$, $C = 20 \mu\text{F}$
Series compensator	7.5 mH, $R = 5 \Omega$, $C = 20 \mu\text{F}$
PV array	27.4 kW
PI controller gains	$K_p = 1.5$, $K_i = 20$

A. Case 1: Comparative analysis of the Proposed UPQC-PV with and without SCD method.

A comparative analysis of the UPQC-PV system performance with and without sequence component detection method for grid current harmonic elimination by the shunt compensator under steady-state conditions is conducted in this study. The simulation results in Fig. 4 show (a) the load current, (b) the grid current without SCD method and (c) the grid current with sequence component detection method. As shown in Fig. 4 (c), the shunt compensator control with the proposed SCD had a better performance than the shunt compensator control without SCD. In addition, the grid current waveforms were kept purely sinusoidal by eliminating the harmonics injected by the nonlinear loads. The percentage THD of the comparative analysis result is shown in Table II.

Fig. 4. Comparative analysis of UPQC-PV with and without SCD for harmonic current elimination.

TABLE II: THD (%) FOR THE COMPARATIVE ANALYSIS FOR CASE 1

	Total Harmonic Distortion (%THDi)					
	I_{La}	I_{Lb}	I_{Lc}	I_{ga}	I_{gb}	I_{gc}
Without Proposed SCD	23.98	23.97	24.01	7.43	7.27	7.89
With Proposed SCD	23.98	23.97	24.01	1.14	1.57	1.03

B. Case 2: Voltage Sag/Swell and Current Harmonic Elimination

The performance of the UPQC-SPV during grid voltage sags/swells condition is shown in Fig. 5. A sun irradiance of 1000 W/m² is maintained in this study.

Fig. 5. Performance of the UPQC- SPV under grid voltage sag/swell and harmonic current elimination.

A voltage sag of 0.8 per unit was initiated from $t = 0.4$ s to 0.45 s, and a voltage swell of 1.2 per unit was initiated from $t = 0.5$ s to 0.55 s. As shown in Fig. 5, the load voltages were controlled at their desired value under each of these conditions. The grid currents were maintained at purely sinusoidal. It is observed that the grid current increased during voltage sags and decreased during voltage swell to maintain power balance. Therefore, the PV array power was stable throughout the occurrence of the disturbances at the grid.

C. Case 3: Voltage Sag/Swell, Distortion and Current Harmonic Elimination

Fig. 6 shows the performance of the UPQC-PV under grid voltage sags/swells with severe distortion. The distortion in utility voltages is initiated intentionally by injecting 7th (10%) and 11th (15%) order voltage harmonics to evaluate series inverter performance. A sun irradiance of 1000 W/m² is maintained as in the previous study. A voltage sag of 0.8

per unit was initiated from $t = 0.4$ s to 0.45 s, and a voltage swell of 1.2 per unit was initiated from $t = 0.5$ s to 0.55 s. The series compensator keeps the load voltage at the desired magnitude and prevents voltage harmonics from flowing into the load.

Fig. 6. Performance of the UPQC-SPV under grid voltage sag/swell, distortion, and harmonic current elimination.

TABLE III: THD (%) FOR LOAD VOLTAGE COMPENSATION FOR CASE 3

	Total Harmonic Distortion (%THDv)					
	V_{ga}	V_{gb}	V_{gc}	V_{La}	V_{Lb}	V_{Lc}
Before compensation	29.03	29.03	29.03	5.43	5.27	4.89
After compensation	29.03	29.03	29.03	2.29	2.29	2.28

D. Case 4: Load Current Unbalance Compensation

In this study, the performance of the UPQC-PV during unbalanced load conditions is shown in Fig. 7. The system load is made up of three-phase nonlinear loads and single-phase nonlinear loads. During the simulation, the unbalance in the load current was initiated between $t = 0.4$ s and $t = 0.55$ s. The shunt compensator maintains the dc-link voltage at a fixed reference value of 800 V and injects compensating currents to realize a distortion-free balanced grid current. The grid current details before and after compensation are shown in Table IV. It can be observed from the simulation results that the unbalancing in the load caused some current to flow into the neutral phase of the load. However, the shunt compensator efficiently kept the neutral transformer phase at a near-zero potential.

Fig. 7. Performance of the UPQC-PV during load unbalance.

TABLE IV: GRID CURRENT DETAILS BEFORE AND AFTER COMPENSATION FOR CASE 4

Current	RMS	Peak	%THD	P.F
Before Compensation				
I_{ga}	16.53 A	23.38 A	9.79 %	0.90
I_{gb}	12.47 A	17.64 A	12.85 %	0.88
I_{gc}	9.51 A	13.45 A	16.86 %	0.85
After Compensation				
I_{ga}	26.30 A	37.20 A	1.07 %	0.99
I_{gb}	26.17 A	37.01 A	1.08 %	0.99
I_{gc}	26.23 A	37.10 A	1.02 %	0.99

E. Case 5: Three-phase to Single-phasing Condition

The response of the UPQC-PV system during single-phasing conditions is described in this study. The distribution system is prone to experiencing single phasing situations. This situation usually causes frequent tripping of local distribution feeders. Modern power quality improvement devices must be capable of mitigating these problems and balance the network effectively. Fig. 8 shows the simulation results when phase-a is opened at $t = 0.4s$, followed by phase-b at $t = 0.45s$. From $t = 0.5s$ and $t = 0.55s$, the two-phases were reconnected. The disconnection of the two phases from the network caused ripple effects in the dc-link voltage. The grid current also increased respectively. As observed, the sudden disconnection of phase-a and phase-b did not affect the UPQC-PV performance. In addition, the shunt compensator efficiently maintained the transformer neutral phase at a near-zero potential. Thus, the relative grid effect is always a three-phase balanced load even as load changes from three-phase to single-phase.

Fig. 8. Performance of the UPQC-PV during three-phase to single phasing condition.

F. Case 6: Dynamic Power Flow Analysis

In this study, the power flow and dynamic performance of the UPQC-PV system are analyzed under different conditions. Possible, practicable grid conditions based on the PV system output power, source voltage, and load voltage are described and listed in Table V. These possible grid conditions are categorized in 8 modes. The system analysis is conducted by simulating each of the eight modes in sequence. The simulation results are shown in Fig. 9. Each mode runs for 0.5s; therefore, the total simulation time is 4.0 s.

Fig. 9. Simulated dynamic power flow analysis.

TABLE V: SIMULATED DIFFERENT OPERATING MODES

Modes	Time period (s)	RMS voltage	PV (kW)	Load (kW)	Load (kVAR)
1	0.5-1.0	$V_s = V_L$	$P_{pv} = 0$	9.9	4.9
2	1.0-1.5	$V_s < V_L$	$P_{pv} = 0$	9.84	4.96
3	1.5-2.0	$V_s > V_L$	$P_{pv} = 0$	10	5
4	2.0-2.5	$V_s = V_L$	$P_{pv} < P_L$	9.92	4.96
5	2.5-3.0	$V_s = V_L$	$P_{pv} > P_L$	9.92	4.96
6	3.0-3.5	$V_s = V_L$	$P_{pv} > P_L$	17.85	8.42
7	3.5-4.0	$V_s = V_L$	$P_{pv} < P_L$	19.82	8.42
8	4.0-4.5	$V_s = V_L$	$P_{pv} = 0$	17.86	8.42

In mode 1, the PV output power is zero due to no irradiation, and the source voltage is equal to the load voltage. In this case, the system should operate as a grid-supported UPQC, suppressing load current harmonics and supporting the load's reactive power to keep the load voltage stable. The load consumes 9.9 kW of active power and 4.9 kVAR reactive power. The shunt compensator is responsible for meeting all the load reactive power demand, thereby zeroing the grid reactive power supply. The load is deliberately doubled to verify the system performance under sudden load change. The resultant power flow for mode 8 is shown in Fig. 9. The dc-link voltage was effectively maintained at the desired value.

In mode 2, a source voltage sag ($V_s < V_L$) is considered. The PV output power is zero, while the load is kept the same as the previous. The source voltage is decreased from 415 V to 332 V (L-L) at time $t = 1$ s, and the performance of the series compensator is evaluated. The series compensator

injects voltage in the opposite direction of the grid voltage disruption to maintain the desired load voltage magnitude. By absorbing 2.5 kW of active power from the grid, the shunt compensator continuously regulates the dc-link voltage to the reference value. Furthermore, the shunt compensator compensated for the reactive load power completely.

In mode 3, a voltage swell ($V_s > V_L$) was implemented at time $t = 1.5$ s. The grid voltage is increased from 415 V to 498 V; therefore, the series compensator absorbs excess active power to compensate for the surplus voltage.

In mode 4, the solar irradiation was increased from $G = 0 \text{ W/m}^2$ to $G = 250 \text{ W/m}^2$. Therefore, the PV array output power is 6.15 kW, and the same load is maintained as in mode 3. In this condition, the generated PV power is less than the load active power demand, i.e., ($P_{pv} < P_L$). Therefore, the grid meets the remaining load power demand. The PI controller regulates the dc-link voltage. Mode 4 demonstrates the efficient mitigation of power quality problems and integrating clean energy by the UPQC-PV.

Mode 5 shows an increase in PV array output power to 18.9 kW due to increased irradiance of $G = 700 \text{ W/m}^2$, while the load remains unchanged. The excess power is fed to the utility grid because PV power generation is higher than load power demand.

Modes 6, 7, and 8 are very comparable to modes 5, 4, and 1. The dissimilarity is that the irradiance is increased to $G = 1000 \text{ W/m}^2$ in mode 6, while the load is increased twice. The operation of the UPQC-PV is examined. The system power flow result is shown in Table VI.

TABLE VI: SIMULATED DIFFERENT OPERATING MODES

Modes	Utility side			Load side			Series side		Shunt side		PV side	Irradiance
	P_s (kW)	Q_s (kVar)	V_s (L-L)	P_L (kW)	Q_L (kVar)	V_L (L-L)	P_{sr} (kW)	Q_{sr} (kVar)	P_{sh} (kW)	Q_{sh} (kVar)	P_{pv} (kW)	
Mode 1	10.3	0.05	415	9.9	4.9	415	0.02	-0.02	-0.4	4.9	0	0
Mode 2	10.6	0.05	332	9.84	4.86	415	2.15	-0.08	-2.5	4.85	0	0
Mode 3	10.0	0.01	498	10.0	5	414	-1.02	-0.08	0.7	4.9	0	0
Mode 4	4.42	0.01	414	9.92	4.96	415	-0.01	-0.001	5.5	4.86	6.15	250
Mode 5	-8.18	0.01	414	9.92	4.96	415	0.04	-0.007	18.1	4.95	18.9	700
Mode 6	-8.55	0.008	416	17.85	8.42	415	0.04	-0.007	26.4	8.44	27.3	1000
Mode 7	7.45	0.008	416	19.82	8.42	415	-0.02	-0.01	12.45	8.36	13.5	500
Mode 8	18.28	0.02	416	17.86	8.42	415	-0.02	-0.01	-0.35	8.43	0	0

IV. CONCLUSION

This paper presents the implementation of a solar photovoltaic integrated unified power quality conditioner UPQC-PV to address the current and voltage-based power quality problems in a distribution network. Reference current and reference voltage signals have been generated under appropriate compensation strategies. The fundamental positive sequence components of nonlinear load currents are extracted using a sequence component detection method. The series compensator is controlled using a simplified PLL-based unit vector template generation approach. The shunt compensator effectively extracts the PV array active power during low and high solar irradiance. The steady-state and dynamic performance of UPQC-PV is appropriately analyzed under various disturbances from the grid side, load side, and PV power fluctuations. The simulation results show that the proposed system can serve a dual purpose of power quality improvement with clean energy generation.

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