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# PV Integrated UPQC

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***Abstract—*** This paper presents the design and simulation of a PV- integrated Unified Power Quality Conditioner (UPQC) for improving power quality in distribution networks. The Conventional UPQC systems are effective in mitigating harmonics, voltage sags and swells, and reactive power problems, but they depends on grid power to maintain the DC link voltage and current, which limits efficiency and sustainability. To overcome this limitations, the proposed system integrating photovoltaic (PV) generation with battery storage system, to reduce grid dependency and enhancing reliability.

A DC-DC converter with Perturb and Observe (P&O) MPPT control method is used to maximize energy extraction from the PV source, meanwhile the battery ensures the stable DC link voltage during low irradiance or nighttime conditions. The shunt inverter (STATCOM mode) which compensates harmonics and reactive power using Synchronous Reference Frame (SRF) theory, and the series inverter (DVR mode) which injects compensating voltage to regulate supply and protect sensitive loads from disturbances.

The Simulation carried out in MATLAB/Simulink validate the effectiveness of the proposed configuration under varying load and irradiance conditions. Results shows reduced Total Harmonic Distortion (THD), improved voltage regulation, power factor balanced to unity, and minimized dependency on grid power. These outcomes establish the PV- integrated UPQC as a reliable and sustainable solution for sensitive loads in modern distribution systems, while also opening avenues for future research in AI-based controllers, hybrid renewable integration, and smart grid applications.

**Keywords-** PV- Integrated UPQC, Power quality improvement, MPPT control, STATCOM, DVR, THD reduction, Power factor correction, Battery.

## I. INTRODUCTION

The increasing demand for the reliable and high-quality power in modern distribution systems has made power quality improvement a critical area of research in this era. The Sensitive loads such as medical equipment, data centers, and advanced industrial processes are highly vulnerable to disturbances like voltage sags, swells, harmonics, and poor power factor. Traditional solutions often rely on grid-dependent compensators, which provide partial mitigation but fail to address sustainability concerns in the system.

To overcome these limitations, the integration of renewable energy sources with advanced power conditioning devices has emerged as a promising approach to this field. Photovoltaic (PV) systems, when combined with battery storage which will not only reduce dependency on the grid but also provide stable support to the DC link during fluctuating solar conditions. This hybrid configuration enhances both reliability and sustainability.

The Unified Power Quality Conditioner (UPQC) is recognized as one of the most effective custom power devices for comprehensive Power quality issues.

## II. OPERATION OF UPQC

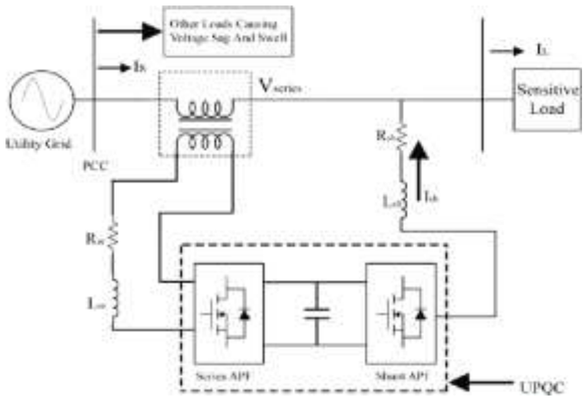


**Figure 1:** Block Diagram of UPQC

### 1. Series Inverter – DVR Function

The series inverter of the UPQC operates as a Dynamic Voltage Restorer (DVR)**.** It is connected in series with the supply line through a coupling transformer as shown in figure 1. Its work is to inject a compensating voltage whenever the system experiences disturbances such as sags, swells, or unbalances. By doing this, the DVR ensures that the sensitive load always receives a stable and regulated voltage, protecting equipment from supply fluctuations.

### 2. Shunt Inverter – STATCOM Function

The shunt inverter of the UPQC functions as a Static Synchronous Compensator (STATCOM). It is connected in parallel with the supply as shown in figure 1 and it is responsible for compensating current-related problems such as harmonics and reactive power. Using Synchronous Reference Frame (SRF) theory**,** the STATCOM generates compensating currents that cancel distortions, thereby improving the power factor and ensuring sinusoidal source currents.

### 3. DC Link Support

Both the DVR and STATCOM are tied together through a common DC link capacitor as shown in figure 1. In a conventional UPQC, this DC link is supported only by grid power. In this proposed system, the DC link is energized by a PV array with MPPT control and a battery unit**.** This arrangement ensures stable operation even during low irradiance or sudden load changes, making the system more reliable and sustainable.

## III. PV INTEGRATION WITH MPPT TECHNIQUE

### 1. Role of PV Array

The photovoltaic (PV) array serves as the renewable energy source for the proposed UPQC system. It directly converts solar irradiance into DC power, which is then supplied to the DC link. However, the output characteristics of a PV array are nonlinear and highly dependent on environmental factors such as solar irradiance and temperature. Without proper control, the PV system may operate away from its maximum power point, leading to inefficient utilization of available solar energy. Therefore, an MPPT mechanism is essential to continuously track and extract the maximum possible power from the PV source [1], [2].

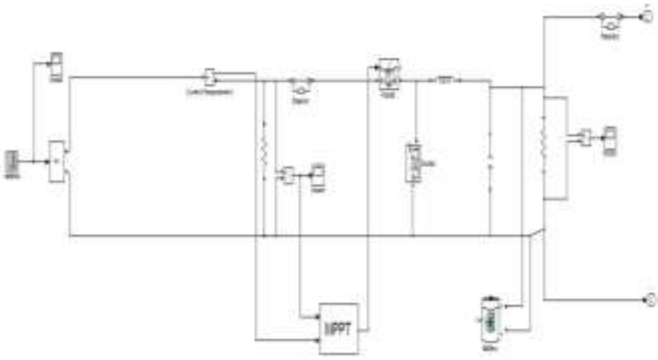


**Figure 2:** PV Integration with MPPT

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### 2. Perturb and Observe (P&O) MPPT

Among the various MPPT algorithms, the Perturb and Observe (P&O) method is widely adopted due to its simplicity and ease of implementation. In this technique, the operating voltage of the PV array is perturbed slightly, and the corresponding change in output power is observed. If the power increases, the operating point is shifted further in the same direction; if the power decreases, the operating point is reversed. This iterative process continues until the system converges at the maximum power point. The P&O method ensures that the PV array operates at its optimal point under varying irradiance and temperature conditions, thereby improving energy harvesting efficiency [3], [4].

### 3. DC-DC Converter Integration

The PV array is interfaced with the DC link through a DC-DC converter, which adjusts its duty cycle based on the MPPT algorithm. The converter plays a crucial role in regulating the DC link voltage and ensuring that the PV array operates at its maximum power point. In the proposed system, the duty cycle of the converter is controlled by the P&O MPPT algorithm, which dynamically adapts to environmental changes. This arrangement guarantees stable DC link voltage and reliable energy transfer to the UPQC system [5], [6].

### 4. Battery Support

To enhance reliability, a battery unit is integrated in parallel with the DC link. The battery provides backup power during periods of low irradiance or nighttime conditions, thereby maintaining uninterrupted operation of the UPQC. It also helps in stabilizing the DC link voltage during sudden load variations. The hybrid PV-Battery arrangement ensures that the UPQC can deliver consistent performance even under fluctuating renewable energy conditions [7].

## IV. Results and Conclusion

### 1. Case 1: Distribution Network without UPQC

In this case, the distribution system operates without any compensating device as shown in figure 3. Sensitive loads are directly connected to the grid, and the network is exposed to disturbances such as voltage sags, swells, harmonics, and poor power factor. The absence of compensating devices results in unbalanced currents source, unstable voltage regulation, and high Total Harmonic Distortion (THD) as shown in figures 4,5,6,7 and 8.

**a) Simulation Model:**

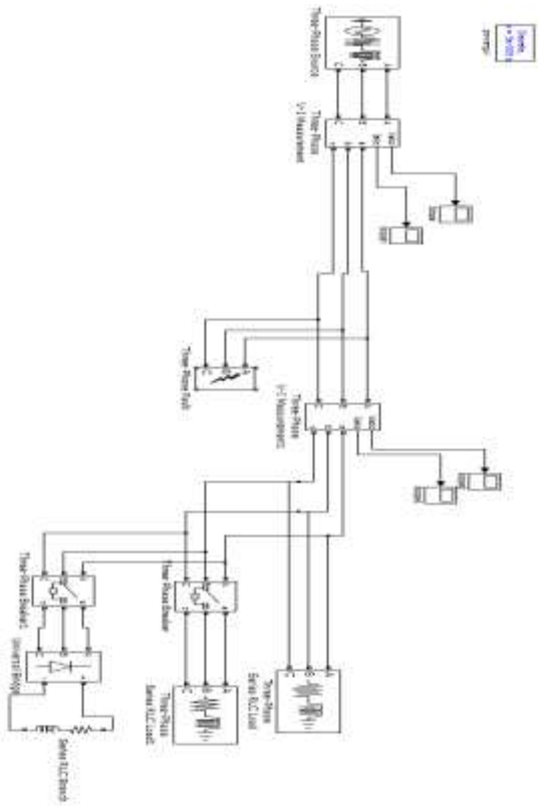

**Figure 3:** Simulation Circuit for distribution network without UPQC

**b) Results:**

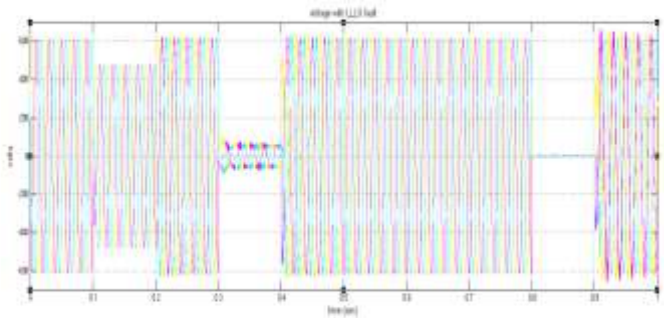

**Figure 4:** Voltage waveforms

The above figure-4 shows the system voltages are normal and balanced before the fault occurs. At around 0.3 seconds, an LLLG fault is applied, and all three phase voltages suddenly drop close to zero, this shows the disturbances during the fault period, the waveforms are distorted and unstable. Once the fault is cleared after 0.4 seconds, the voltages gradually recover back to their sinusoidal shape.

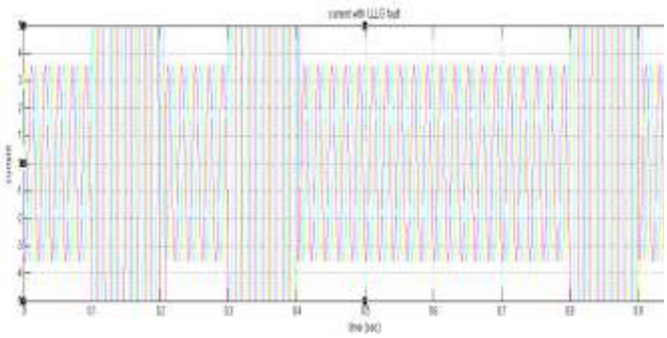

**Figure 5:** Current Vs Time(sec) of without UPQC

The above figure 5 shows the three-phase current behavior when an LLLG fault occurs in the system. Before the fault, the currents are balanced and sinusoidal as it can be seen in figure indicating normal operation. At around 0.3 seconds, the fault is introduced, and the current magnitude rises sharply due to the short-circuit condition. The waveform becomes distorted and unstable during this period, showing the high fault current flowing through the system. After the fault is cleared at about 0.4 seconds, the currents gradually return to their normal balanced form.

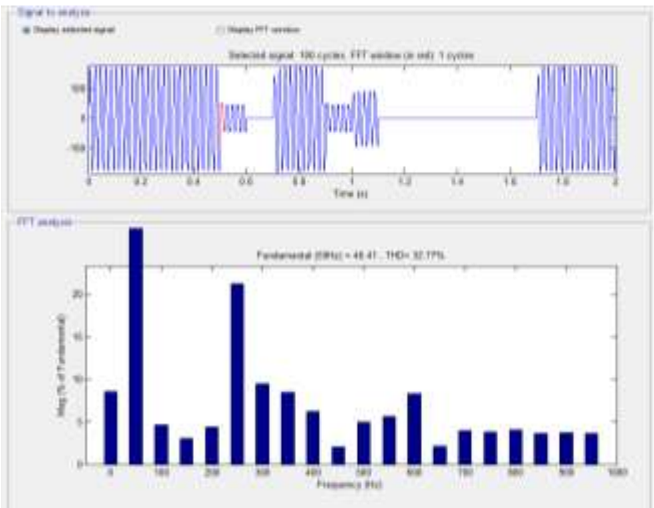

**Figure 6:** THD value of without UPQC

The above Figure 6 shows the time-domain signal and its frequency-domain analysis using FFT. The upper plot represents the voltage waveform selected for analysis, where the red portion indicates the FFT window. The lower plot shows the harmonic spectrum of the same signal. As we can see the fundamental component is at 50 Hz, with a magnitude of 46.41, and the Total Harmonic Distortion (THD) is 32.77 %**,** which indicates a high level of distortion during the fault condition. The presence of multiple harmonic peaks at higher frequencies represents that the system voltage is severely affected by the LLLG fault.

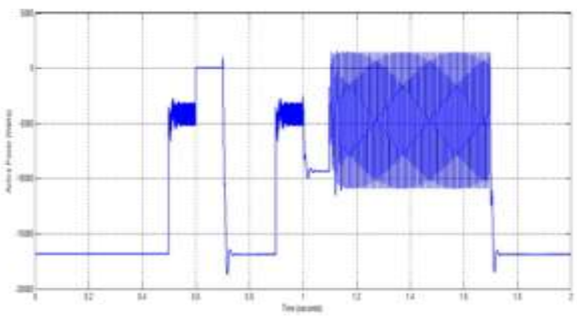

**Figure 7:** Active power (Watts) of without UPQC

The above figure 7 shows the variation of active power in the system when an LLLG fault occurs. Initially, the power remains steady, indicating normal operation. Due to fault at around 0.4 seconds, the active power drops sharply, showing a sudden disturbance in power flow. During the fault period, the waveform becomes oscillatory and unstable, which represents high fluctuations due to the fault current. After the fault is cleared, the power gradually returns to its normal level.

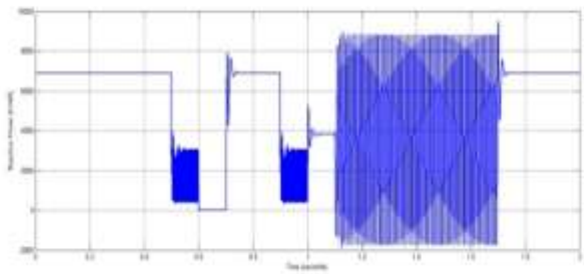

**Figure 8:** Reactive power(Watts) of without UPQC

The above figure 8 shows the variation of reactive power in the system when an LLLG fault occurs. Initially, the power remains steady, indicating normal operation. Due to fault at around 0.4 seconds, the reactive power drops sharply, showing a sudden disturbance in power flow. During the fault period, the waveform becomes oscillatory and unstable, which represents high fluctuations due to the fault current. After the fault is cleared, the power gradually returns to its normal level.

2. **Case 2: Conventional UPQC (STATCOM + DVR)**

In this second case, a conventional Unified Power Quality Conditioner (UPQC) added to the circuit. The UPQC consists of two main components:

The series inverter which operates as a Dynamic Voltage Restorer (DVR) injects compensating voltage to mitigate sags, swells, and unbalances.

The shunt inverter which functions as a Static Synchronous Compensator (STATCOM) it injects compensating currents to eliminate harmonics and improve the power factor.

As we can see in figures 10,11 and 12 the simulation results shows that the conventional UPQC significantly improves voltage regulation and current waveform quality compared to Case 1.

**a) Simulation Model:**

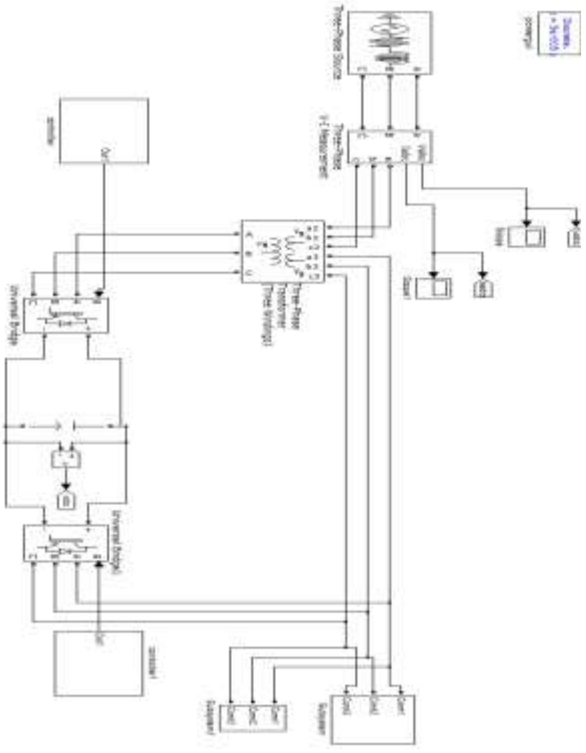

**Figure 9:** Simulation Circuit for Conventional UPQC

The above figure 9 shows the simulation setup of the conventional UPQC system. As shown above the three-phase source is connected to the load through the UPQC, which consists of a series inverter acting as a DVR and a shunt inverter functioning as a STATCOM and the DC link is contains only the grid supply, without any renewable integration. As The DVR injects compensating voltage to handle sags and swells, meanwhile the STATCOM provides harmonic elimination and reactive power compensation. The Scopes are used to observe voltage, current, and power waveforms during normal and fault conditions.

**b) Results:**

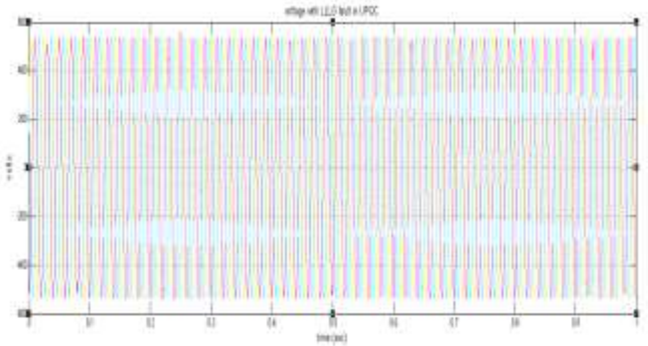

**Figure 10:** Voltage waveforms for conventional UPQC

The above figure 10 shows that the voltage waveform when an LLLG fault occurs in the system using a conventional UPQC. Before the fault, the voltages are balanced and sinusoidal. When the fault is applied, the waveform shows a small disturbance and partial voltage drop, but the UPQC compensates and maintain the voltage stability. After the fault is cleared the voltages quickly return to normal condition proving that the conventional UPQC Is effectively handles voltage sags and swells during fault conditions.

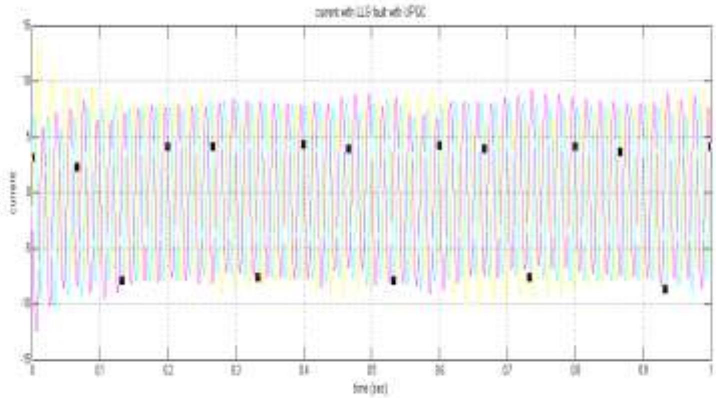

**Figure 11:** Current waveforms for conventional UPQC

The above figure 11 shows the current waveform of the system when an LLG fault occurs while the UPQC is operating. As we can see Before the fault the currents are balanced and sinusoidal which indicates normal operation. When the fault is applied a small disturbance appears, but the current does not rise sharply because the UPQC compensates effectively. The shunt inverter (STATCOM) controls the current flow and limits the fault current. when the fault is cleared, the waveform quickly returns to its normal balanced form which proves that the UPQC maintains current stability and protects the system during fault conditions.

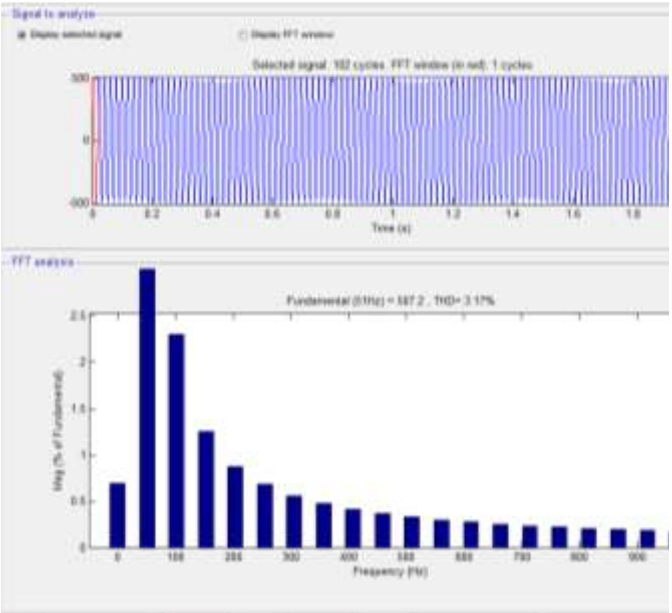

**Figure 12:** THD value for Conventional UPQC

The above figure 12 shows the FFT analysis of the voltage waveform under LLLG fault using the conventional UPQC. The upper plot representing the time-domain signal selected for analysis, and the lower plot shows the harmonic spectrum. The fundamental component which is at 50 Hz with a magnitude of 507.2, and the THD is 3.17 %**,** which indicates that the UPQC effectively reduces harmonic distortion compared to the fault condition.

### 3. Case 3: PV-Battery Integrated UPQC

In the third case as shown in figure 13, the proposed PV- integrated UPQC is implemented. The DC link is energized by a photovoltaic array equipped with Perturb and Observe (P&O) MPPT control, along with a battery unit for additional backup support.

As The DVR continues to inject compensating voltage, ensuring stable supply to sensitive loads.

The STATCOM eliminates harmonics and provides reactive power compensation and The PV array supplies renewable energy to the DC link, while the battery maintains voltage stability during low irradiance or nighttime conditions.

As the Simulation studies confirm that this configuration achieves reduced THD, near-unity power factor, and stable voltage regulation under varying load and irradiance conditions. The integration of renewable energy not only improves power quality but also reduces grid dependency, making the system more reliable and sustainable. this is our proposed solution — UPQC integrated with PV and battery. It delivers clean, stable, and sustainable power to sensitive loads, while reducing dependency on the grid."

#### a) Simulation Model:

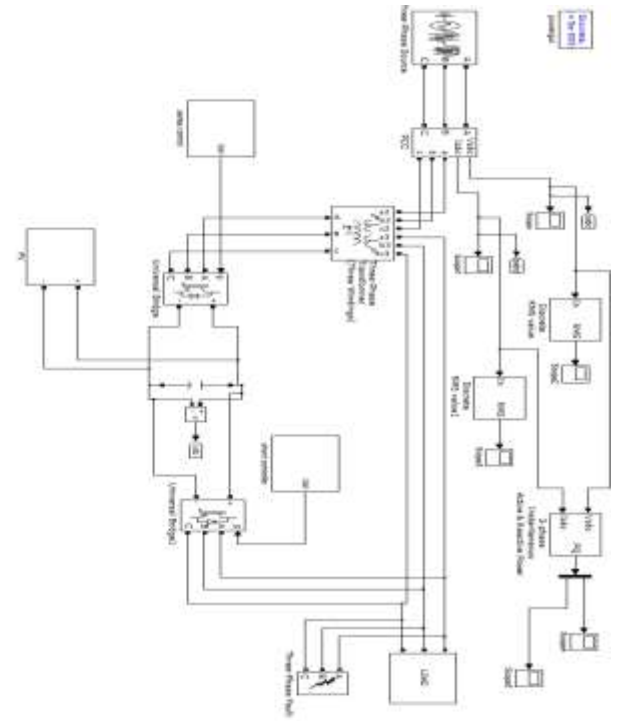

**Figure 13:** Simulation Circuit for PV integrated UPQC

The above figure 13 shows the simulation model of the proposed UPQC system with PV and battery integration. As the three-phase source supplies power to the load through the UPQC, which includes a series inverter (DVR) and a shunt inverter (STATCOM). The DC link is attached by a PV array with MPPT control and a battery unit, providing continuous DC voltage even during faults or voltage fluctuations. The PV system supplies active power, while the battery maintains voltage stability during transients. This model shows how the proposed UPQC improves power quality and ensures reliable operation for sensitive loads.

#### b) Results:

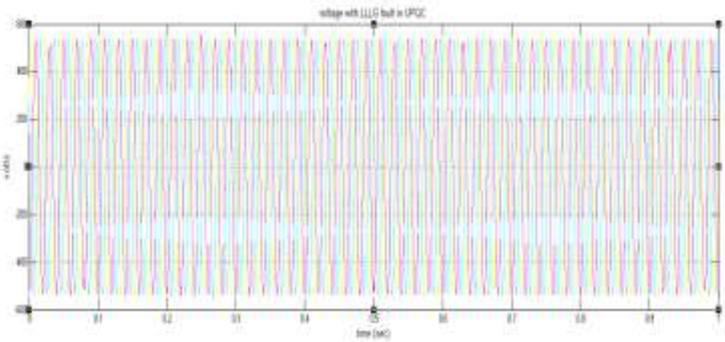

**Figure 14:** Voltage waveforms for PV integrated UPQC

The above figure 14 shows the voltage waveform when an LLLG fault occurs in the system using the proposed PV integrated UPQC. As the figure shows before the fault occurs the voltages are balanced and sinusoidal. When the fault is applied, just a small disturbance appears, and the voltage remains nearly constant because the UPQC compensates effectively. The PV and battery units supply the required energy to maintain voltage stability during the faulty conditions. After the fault is cleared, the waveform quickly returns to its normal position, which proves that the proposed UPQC provides better voltage regulation and power quality compared to the conventional system.

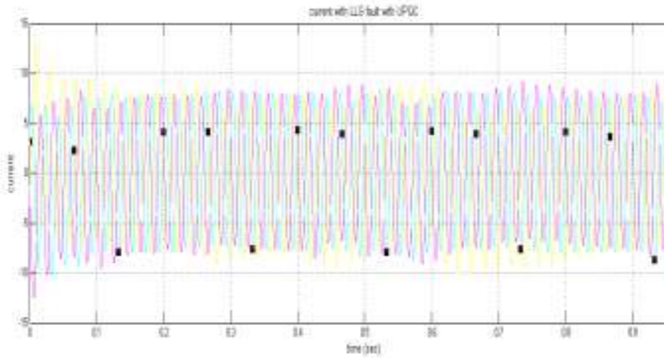

**Figure 15:** Current waveforms for PV integrated UPQC

The above figure 15 shows the current waveform when an LLLG fault occurs in the system using the proposed UPQC. As we can see before the fault occurs, the currents are balanced and sinusoidal. When the fault occurs, only a small disturbance appears in the waveforms, and the current remains stable and within the limits because the UPQC compensates effectively. As the shunt inverter (STATCOM) controls the current flow while the PV and battery units supply the required energy to maintain current stability in the system. After the fault is cleared the waveform quickly returns to its normal balanced position, which proves that the proposed UPQC limits fault current and improves system reliability.

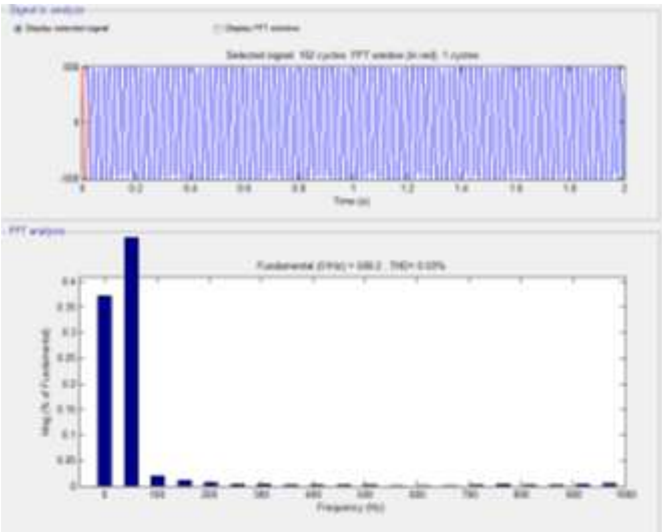

**Figure 16:** THD value with PV integrated UPQC

The above figure 16 shows the FFT analysis of the voltage waveform under LLLG fault using the proposed UPQC. As the upper plot represents the time-domain signal, and the lower plot shows the harmonic spectrum. The fundamental component is at 51 Hz with a magnitude of 508.2**,** and the THD is only 0.03 %**,** which indicating excellent harmonic compensation. The PV and battery units help maintain a clean sinusoidal voltage, which proves that the proposed UPQC achieves superior power quality compared to the conventional system.

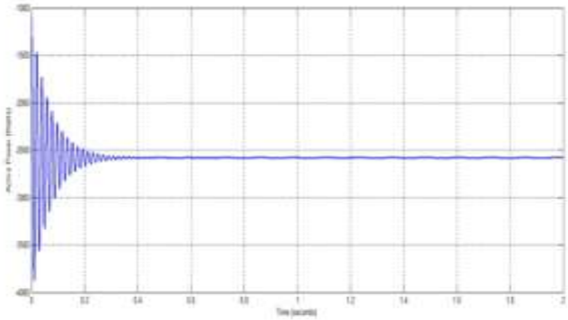

**Figure 17:** Active Power (Watts) for PV integrated UPQC

The above figure 17 shows that the active power variation when an LLLG fault occurs in the system using the proposed UPQC. At the beginning, the power fluctuates sharply due to the higher faults, but it quickly stabilizes as the UPQC compensates efficiently. The PV and battery units supply the required power to maintain the system, and the waveform become linear after the transient period. Which indicates effective fault compensation and improved power stability with the PV integrated UPQC.

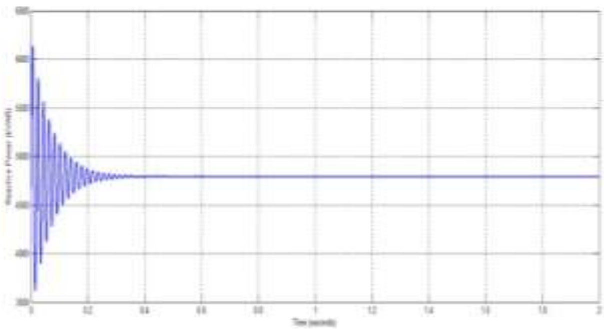

**Figure 18:** Reactive Power(Watts) for PV integrated UPQC

The above figure 18 shows the reactive power variation when an LLLG fault occurs in the system using the proposed UPQC. At the starting the waveform shows oscillations due to the fault occurs in the system, but it quickly stabilizes as the UPQC compensates the overall parameters of the system. The PV and battery units supporting the DC link which helps the system to maintain a balance reactive power. After the transient period, the waveform becomes steady which indicates the effective compensation and improved system stability.

4. **Comparison of Three Cases**

| Parameter | Case 1: Without UPQC | Case 2: Conventional UPQC | Case 3: PV-Battery UPQC |
|---|---|---|---|
| **Voltage** | Distorted, collapses during faults | Partly compensated, some disturbance | Almost constant, well compensated |
| **Current** | Highly distorted and unbalanced | Small disturbance, recovers after fault | Very stable, minimal disturbance |
| **Active Power** | Fluctuates heavily, unstable | Oscillations present, settles slowly | Stabilizes quickly, smooth recovery |
| **Reactive Power** | Large oscillations, poor control | Oscillatory, settles after delay | Rapid stabilization, steady response |
| **THD** | Very high (>10%) | Reduced to 3.17% | Very low, only 0.03% |
| **Overall Quality** | Poor, not suitable for sensitive loads | Improved but limited | Best performance, highly reliable |

**Conclusion:** Based on the results obtained from the three cases it is observed that the system without UPQC (Case 1) performs very poor with distorted voltage and current, unstable power, and very high THD which is not suitable for sensitive loads. The conventional UPQC which is Case 2 improves performance by compensating voltage and current and reducing THD to 3.17% as shown in figure 12, but still shows disturbances and slower stabilization. The PV integrated UPQC which is Case 3 gives the best performance, maintaining stable voltage and current all conditions, quickly stabilizing active and reactive power, and reducing THD to only 0.03% as shown in figure 16.

Therefore, the proposed PV integrated UPQC ensures superior power quality and reliability compared to the conventional system. Which gives a stable operation under fault conditions and it is highly suitable and effective for sensitive load applications, as its an advantage to a modern solution for power quality improvement.

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