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Power Quality Enhancement in Grid-Connected and Islanded Microgrid using MT-UPQC

The increased integration of distributed generations and the complexity of microgrid systems have demanded innovative technologies to ensure high power quality. Microgrids are deliberately developed islands inside a facility or an electrical distribution system that include at least one distributed energy supply and related loads. The Unified Power Quality Conditioner (UPQC) is a powerful instrument for improving the reliability and efficiency of Microgrid operations. Comprehensive research of UPQC utilization in diverse applications to improve power quality in microgrid situations is critical. A microgrid may connect and disconnect from the grid, allowing it to operate in both grid-connected and islanded modes. This paper presents a simulation analysis of power quality enhancement using UPQC in a microgrid. The system is evaluated in both grid-connected and islanded mode to address PQ issues such as voltage sags and swells, harmonic distortions, reactive power needs, and THD. Simulations are carried out using MATLAB software.

Keywords: Microgrid, Distributed Generation (DG), Power Quality (PQ), THD (Total Harmonic Distortion), UPQC (Unified Power Quality Conditioners).

1. Introduction:

The reasons for integrating renewable energy resources (RER) into Microgrids are to tackle climate change, environmental pollution, and rising worldwide demand. RERs include wind turbines, solar panels, hydropower, geothermal energy, and biomass energy [2]. The advantages of microgrids include a significant reduction in energy losses and improved RER use. A dependable and effective grid integration of RES, such as solar and wind energy, is being used around the world, and their installed capacity is expanding every year [3].

Various customized power devices are documented in the literature to address power quality concerns. Reactive power and harmonic current correction are two uses for active power filter technology, which has greatly advanced. When the harmonic spectra fluctuate due to fluctuating loading, these power filters are applied. [4].

Active power filters are categorized into two main types based on their compensation approach: (i) shunt active filters (DSTATCOM) and (ii) series active power filters (DVR).

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DSTATCOM mitigate harmonic currents and compensate for reactive power, addressing current-related power quality issues [5]. In contrast, series active power filters, mitigate sag, swell, and harmonics in the supply voltage, addressing voltage-related power quality issues. [8].

The UPQC is a cutting-edge custom power device that integrates the capabilities of both Shunt Active Filters and Dynamic Voltage Restorers. This powerful device effectively addresses a wide range of PQ issues, including harmonic current and voltage mitigation, reactive power compensation, and voltage sag and swell alleviation. By combining these functions into a single device, the UPQC provides a comprehensive solution for ensuring high power quality, reliability, and efficiency in industrial and commercial power systems [9]. Different power topologies and control systems for UPQC have been documented by Khadkikar, Mohammed, Rao and Nallagownden, Liu et al., Fujita and Akagi [10, 11, 12 & 13].

Khadem, Basu, and Conlon introduced a novel approach for the deployment, connection, and management of UPQC in microgrid systems that are based on distributed generation (DG), whether they are grid-connected or operating in island mode. The PCC contains the DG converters (which include storage) as well as the DSTATCOM of the UPQC. The DVR of the UPQC is connected to the grid upstream of the PCC. Additionally, the storage system can be linked to the DC link. The UPQC also features a sophisticated mechanism for detecting islanding and facilitating reconnection (IR) as an added control function. Consequently, this configuration is referred to as $UPQC_{\mu G\text{-}IR}$. In grid-connected mode, the proposed $UPQC_{\mu G\text{-}IR}$ addresses issues such as supply interruptions, voltage fluctuations (sags/swells), harmonics, and reactive power compensation [14]. The DG Converter equipped with storage will exclusively supply active power in both interconnected and islanded configurations, while the shunt component of the UPQC will address the reactive and harmonic power requirements of the load. Additionally, it allows the DG Converter to stay connected amidst fluctuations in voltage. The $UPQC_{\mu G}$ presents several benefits compared to traditional UPQC systems [15]. The integration process of a proposed UPQCμG to a grid-connected and DG-integrated microgrid system is simulated in this paper, and the power quality performance is evaluated.

2. Configuration of UPQC

The existing power system has several challenges, prompting ongoing research aimed at

enhancing power quality (PQ). The advancement of Flexible AC Transmission Systems (FACTS) and custom power devices has emerged from the ongoing efforts to boost PQ. FACTS are utilized at the transmission level. "Custom Power Devices" denotes the use of power electronics in a power distribution network to benefit a specific customer or community. The UPQC, a compensator based on power electronics, functions on the principle of active filtering. It consists of shunt (SHUN) and series (SERC) compensators linked through a DC link capacitor. Based on the positioning of the SHUN, two configurations can be established: L-SHUN UPQC and R-SHUN UPQC. Most of the research regarding UPQC emphasizes the implementation of the right shunt UPQC, which exhibits superior characteristics compared to the left shunt UPQC. [18].

3. Control of UPQC

i) SHUN control

The SHUN section of the UPQC operates as a regulated current source, providing the necessary current component at the PCC to ensure that the source current at that location is sinusoidal and maintains a unity power factor. This is achieved by applying instantaneous reactive power theory (p-q theory). The control process is intricate and time-consuming due to the multiple stages involved, such as calculating the real power component, computing the positive sequence, determining the real power component of the load current, managing DC-link voltage, and applying low-pass filters [16].

1. The voltage at the PCC is measured and converted into d-q components.

2. Filter out fundamental frequency components that manifest as DC when converted to d-q.

3. To determine the reference harmonic compensatory current, multiply harmonic voltage components by the appropriate gain. This mitigates the transmission of voltage harmonics.

4. The VSI employs a sine PWM technique for switching.

ii) SERC control

The UPQC's SERC serves as a regulated voltage supply. A predetermined setting is used to manage the voltage at the PCC. As a result, if the PCC voltage deviates from the set value, SERC injects the required voltage.

1. One of the following predefined PCC value voltage references may be selected:

a. The PCC's preference voltage

b. The post-fault voltage of the PCC or the positive sequence voltage after a fault.

2. PLL facilitates a seamless voltage reference transfer both before and after a malfunction.

4. 3T-UPQCμG CONFIGURATION:

The incorporation of the 3T-UPQC, which consists of one series and two shunt active filters, into a utility-connected Microgrid system is illustrated in Figure 1 [22]. Its primary function is to operate in two modes.
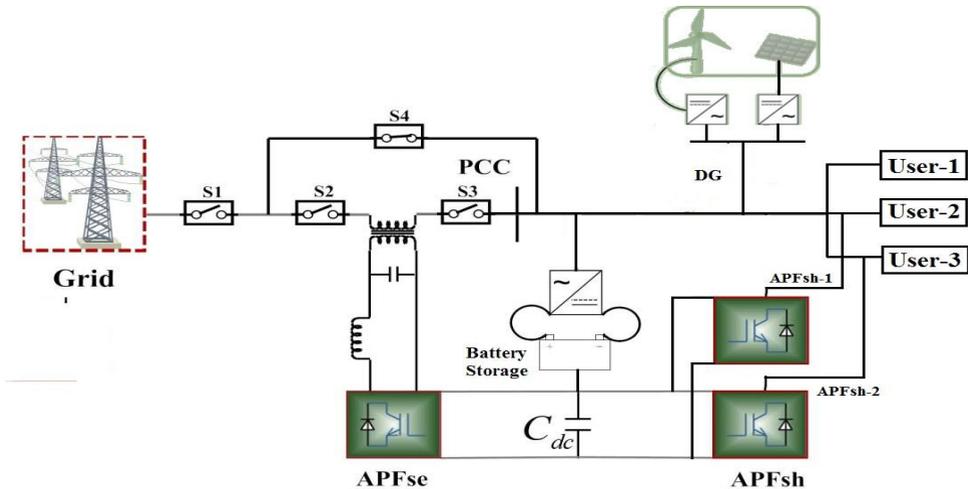
Figure 1: Schematic diagram of the 3T-UPQCμG

The proposed 3T-UPQC$_{μG}$ has two basic operating modes.

Interconnected mode

- The DG source provides the actual power to the load and storage. The grid's basic active power is also supplied by the DG source.

- The series portion of UPQC (APF$_{se}$) compensates for voltage sag, flickers, voltage swell, and transients by transmitting active power from storage or the grid.

- The shunt portion of the UPQC (APF$_{sh}$) compensates for the reactive power of the non-linear load and eliminates harmonic distortions to maintain the THD within the bounds.

- The UPQC delivers a signal to a small Microgrid system with distributed generations to respond to an emergency (blackout) caused by a sudden interruption or breakdown.

Islanded mode

- When the grid fails, the series section of the UPQC is disconnected, while the DG converter balances the voltage at the PCC level.

- To ensure smooth current at the PCC, the nonlinear load reactive component is compensated by the shunt part of the UPQC while remaining connected.

- The DG converter delivers only active power with storage. It isn't unplugged from the system.

- When grid power is restored, the UPQC series is reconnected.

5. Simulations results

A 3-phase, 3-wire active distribution system (400VL-N) featuring the suggested UPQC$_{\mu G}$ and μG, illustrated in Figure 2, has been created within the MATLAB environment. Details of the performance with the simulation results in grid-connected and Island mode are given below. All the simulations have been performed for up to 0.2 sec.
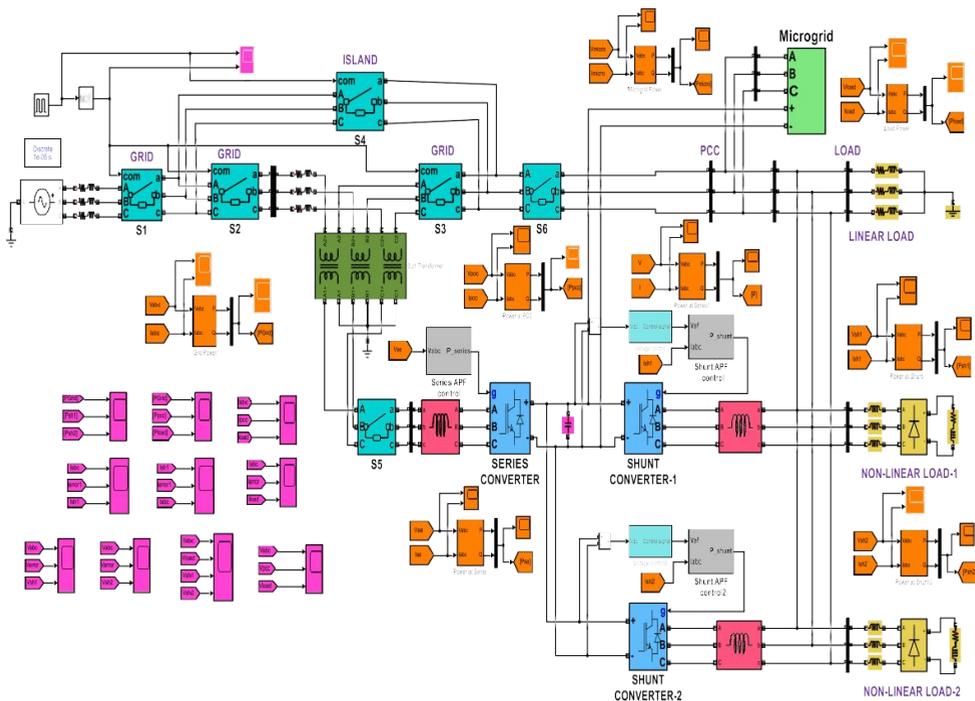
Figure 2: Micro-grid with Three terminal UPQC

a. Harmonics compensation by Shunt converter for load current

Shunt converters are employed to mitigate current harmonics generated by nonlinear loads. Initially, the source and load currents have similar waveforms. The Total Harmonic Distortion (THD) of the source current before compensation is approximately 25% (Figure 4) for Nonlinear Load-1 and 29.31% (Figure 7) for Nonlinear Load-2. However, with the

introduction of Shunt converters, they inject the necessary current component to render the source current virtually harmonic-free, as depicted in Figure 3. Consequently, the source current becomes almost sinusoidal after compensation. The THD of the source current decreases significantly to 0.62%, as shown in Figure 8. Table 1 summarizes the THD values before and after DSTATCOM compensation.

Table 1: Total Harmonic Distortion of Source and Load Currents

Non-linear Load	THD before mitigation		THD after mitigation	
	Source current	**Load current**	**Source current**	**Load current**
1	24.99%		4.37%	24.99%
2	29.31%		4.37%	29.31%
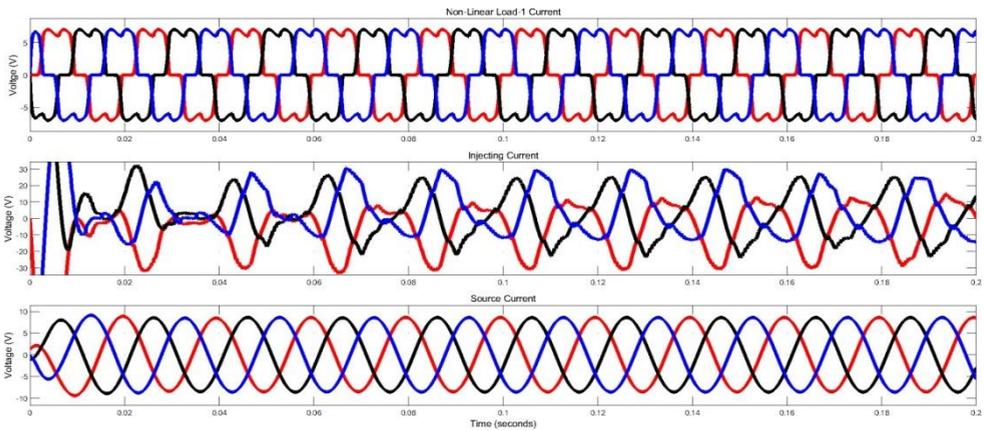
Figure 3: Non-linear load-1, Injecting and Source currents
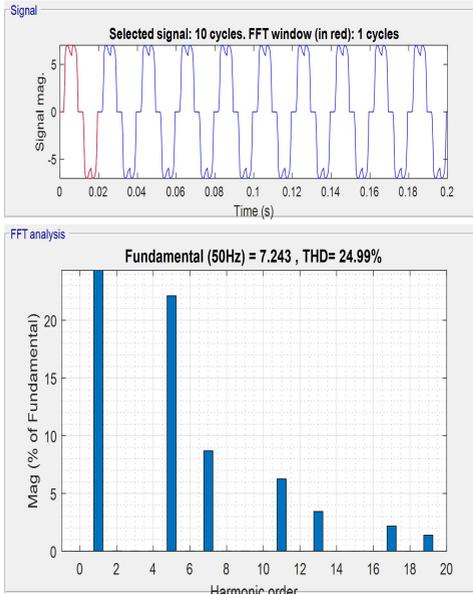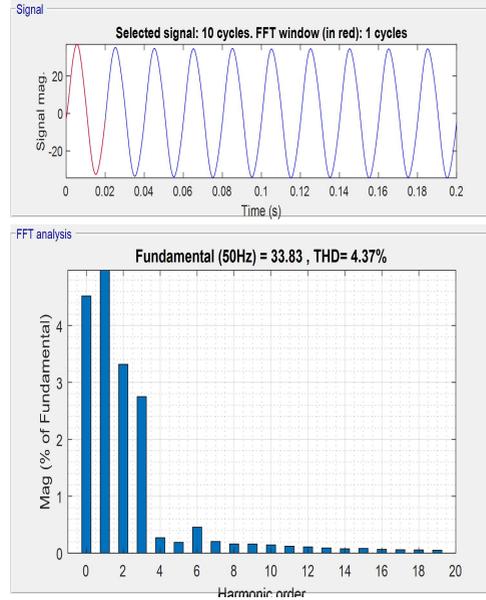

Figure 4: THD of the Load-1 Current

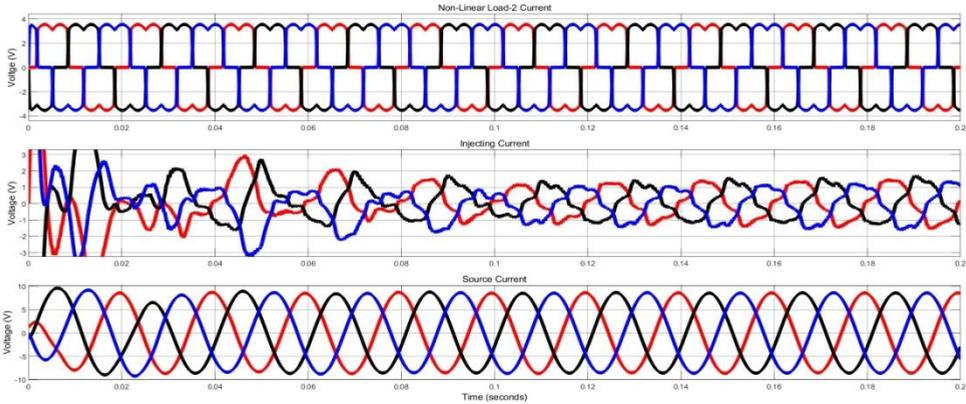Figure 5: THD of the Source Current

Figure 6: Non-linear load-2, Injecting and Source currents
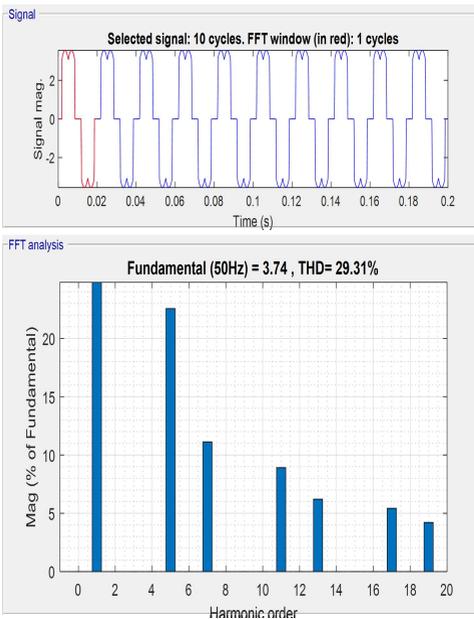

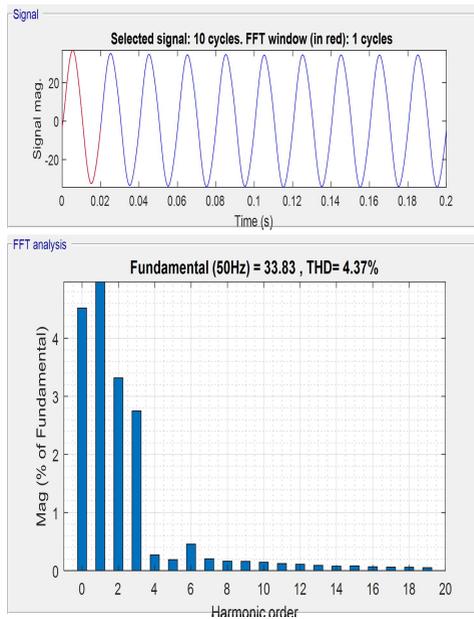Figure 7: THD of the Load-1 Current   Figure 8: THD of the Source Current

b. Voltage Harmonics injected at Source

The performance of UPQC series compensators in Microgrids is evaluated to mitigate supply voltage distortion. The supply voltage is deliberately distorted with 30% 3rd harmonic and 20% 5th harmonic components. Figures 9 show the three-phase supply, compensation, and load voltages. At t = 0.02 sec, the series compensator is activated, and the load voltage waveform at bus-2 becomes nearly sinusoidal (Figure 9c). The Total Harmonic Distortion (THD) of the load voltage decreases significantly from 36.06% to 0.08% after DVR adjustment (Figures 10 and 11). This demonstrates the UPQC's effectiveness in reducing THD and improving power quality.
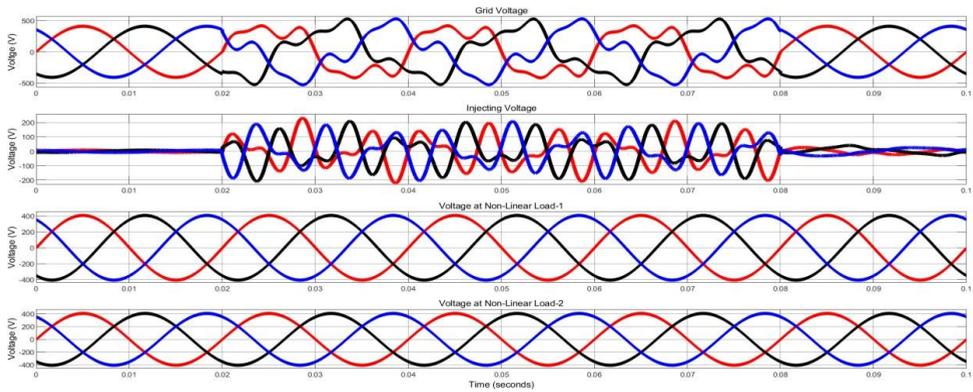
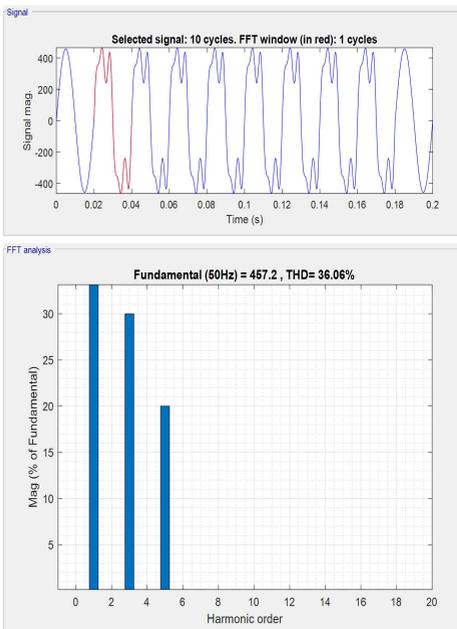Figure 9: Grid, Injecting, Voltage at Non-linear load-1 and load-2
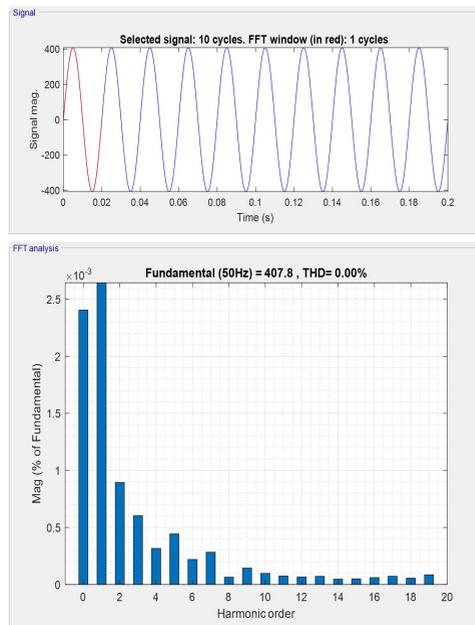

Figure 10: THD of Grid Voltage

Figure 11: THD of Load-1 Voltage

c. Voltage Sag at the Grid

In this scenario, the supply voltage experiences a 0.2 p.u voltage sag from 0.02 to 0.08 seconds, as shown in Figure 12. The DVR promptly detects the sag and injects compensating voltages, as seen in Figure 12(b), to maintain the load voltages at the desired level with minimal distortion, as shown in Figures 12(c) and 12(d).
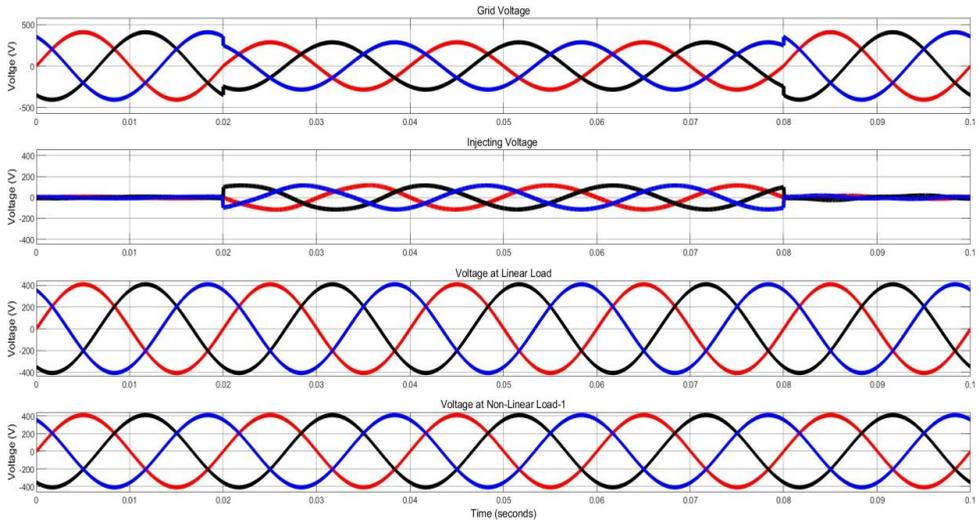
Figure 12: Grid, Injecting, Voltage at linear and Non-linear load-1

d. Voltage Swell at the Grid

When a voltage swell of 0.2 p.u occurs between t = 0.02 sec and t = 0.08 sec (Figure 13), the DVR swiftly detects the anomaly and applies the necessary mitigation voltages (Figure 13b). As a result, the load-2 voltage is effectively regulated to the desired level, with harmonic components removed, resulting in a nearly sinusoidal waveform (Figure 13c and 13d).
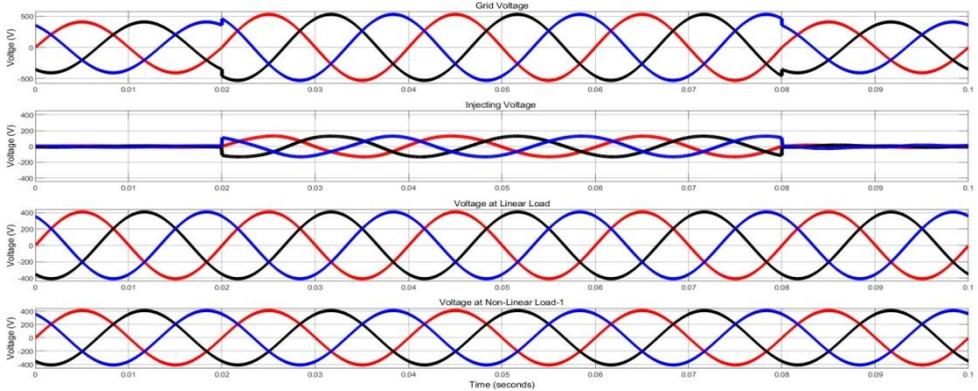

Figure 13: Grid, Injecting, Voltage at linear and Non-linear load-1

e. Interconnected and Island Mode

Based on the integration method and signal generation for islanding detection and reconnection, the switch position (open=0, close=1) is observed to operate in both grid-connected and islanded modes from 0 to 0.5 seconds. During Interconnected or normal

conditions switch S1, S2 and S3 are operated in closed conditions and S4 is operated in open conditions and during Island mode, these states are reversed as shown in below figure. In figure, DC link capacitor voltage is also shown Figure 14. Initially normal condition is operated for the duration of 0.1 sec, later 0.1 sec voltage swell, 0.1 sec voltage sag, 0.1 sec Islanding mode and later system is connected to grid at 0.4 sec. These different operating conditions are demonstrated in below Figure 15.

Table 2: Different Operating Conditions

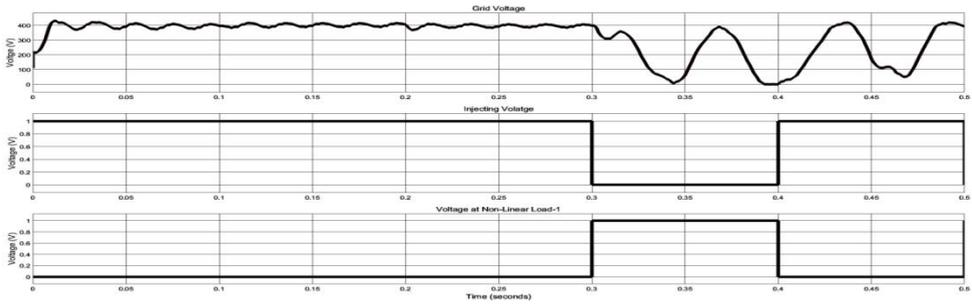| Operating Conditions	Time in seconds
Normal	0.0-0.1
Swell	0.1-0.2
Sag	0.2-0.3
Islanding	0.3-0.4
Reconnection	0.4-0.5

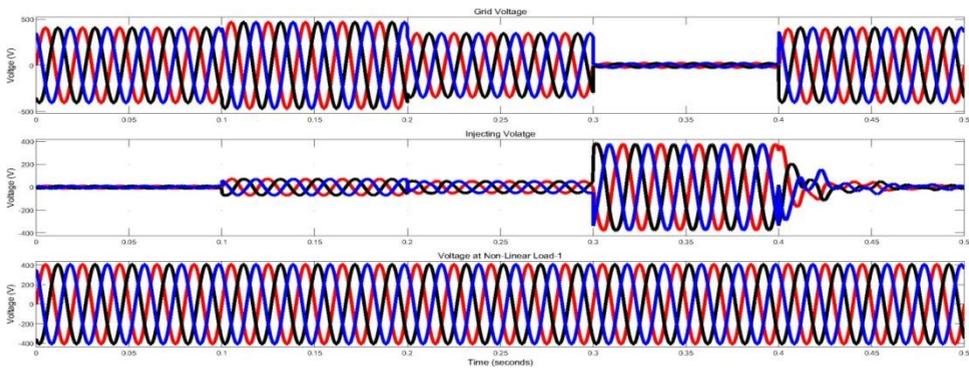Figure 14: Voltage at DC-Link Capacitor, Switch S1, S2, S3 and S4 Positions

Figure 15: Grid, Injecting and Non-linear load-1 voltages during different Operating condition

f. Complete Island condition

In order to assess the performance of Microgrid, switches S1, S2, and S3 are in the open state and system is operating now in island mode. Island mode is demonstrated for the

duration of 0.2 sec during this situation Microgrid is now supplying required power for the loads and load voltage are maintained at the rated voltage as shown in Figure 16.
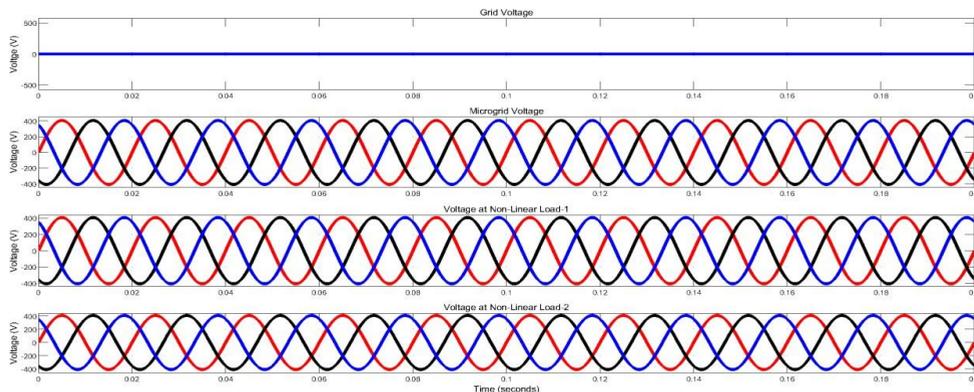

Figure 16: Grid, Micro-grid, Non-linear load-1 and load-2 Voltage

5. Conclusions:

This work illustrates that the UPQC is a highly effective technology for addressing the diverse power quality challenges faced by modern Microgrids. By leveraging the combined capabilities of DVR and APF, UPQC provides a robust solution for voltage regulation, harmonic reduction, and reactive power compensation. In this simulation study of enhancing the power quality using UPQC in Microgrid system, in grid connected and islanded mode to tackle PQ issues such as voltage sags & swells, harmonic distortions, and reactive power demands are studied. The results obtained found to be within the IEEE standards.

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