A New Open Left UPQC (OL-UPQC) Configuration for Simultaneous Handling of Harmonic Issues from Multiple Load Points and Voltage Disturbance Issues at Voltage Sensitive Load Point

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Received: 21.09.2023 Accepted:26.10.2023

Abstract- This research paper introduces a novel configuration referred to as the "Open Left Unified Power Quality Conditioner" (OL-UPQC) by incorporating features from an open UPQC into a left shunt UPQC setup. The use of separate shunt and series inverters offers distinct advantages, particularly when coupled with a left shunt inverter configuration for mitigating harmonics originating from various individual or specific load points. In an open system, the independent DC-link voltage control of the series inverter underscores the critical role of precise operation in the left shunt configuration, especially for voltage-sensitive loads. To assess the effectiveness of this proposed configuration in mitigating harmonic pollution from multiple load points and addressing current imbalances resulting from unbalanced loads, a comprehensive simulation analysis is performed. Additionally, the paper investigates its ability to provide voltage compensation for voltage-sensitive loads when subjected to different voltage disturbances, including voltage sags, voltage swells, and voltage harmonics.

Keywords Harmonics, unified power quality conditioner, voltage disturbance, synchronous reference frame, unit vector template.

1. Introduction

With the variable voltage and current patterns prevalent in distribution systems, contemporary research is placing a growing emphasis on comprehensive approaches to mitigate power quality degradation [1]. Voltage fluctuations, in particular, pose significant risks to sensitive equipment, including modern medical devices in hospitals, security systems in buildings, and constantly operational industrial machinery [2]. Additionally, the proliferation of nonlinear loads has led to a rise in harmonic content within source currents in recent times. These nonlinear characteristics can induce line current distortions in commonly used devices such as computers, switched-mode power supplies, switching components, and motor drive applications that employ front-end rectifiers. The Unified Power Quality Conditioner (UPQC) has emerged as the most appealing solution for resolving power quality issues [3]. These include reducing harmonic distortions in both current and voltage, rectifying voltage sags and swells, correcting supply voltage and load imbalances, and regulating the increased reactive power needs of certain loads [4] [5].

At the distribution level, PQ, or Power Quality, encompasses the maintenance of a power distribution bus voltage that closely resembles a sinusoidal waveform, maintaining its rated magnitude and frequency [6]. Simultaneously, it necessitates the uninterrupted provision of energy to customers. PQ can be divided into two core

components: voltage quality and supply reliability [1] [7]. Voltage quality encompasses various disturbances, including rapid fluctuations, harmonics, inter-harmonics, flicker, imbalance, and transients [8]. On the other hand, supply reliability deals with longer-lasting phenomena, such as power interruptions, voltage dips and sags, over-voltage, under-voltage, and frequency variations. These factors collectively shed light on the underlying issues that can lead to PQ problems [9]. Also, another significant issue is harmonic distortion, a well-established phenomenon in power systems [10] [11].

Among the several UPQC topologies available, UPQC-R [2], [12]-[15], is the most commonly used for research purposes. The shunt inverter is placed on the right side of the UPQC, with the series one on the left, a positioning carefully chosen to avoid the load current from traveling via injection transformers. The alternate UPQC-L configuration, in which the shunt inverter is located on the left side of the UPQC and the series inverter is located on the right side, is designated for specialist applications [16]. UPQC-L proposed in [17], address the application of UPQC for a specific voltage sensitive load point and current harmonic compensation for loads at multiple load points. However, the inverter operations are not independent of each other as they are coupled through a common DC-link. Thus, it is more likely that both inverters will affect each other performance, which is highly undesirable, to avoid their individual performance degradation. In case of shunt inverter, since it has to manage harmonic compensation of multiple load points, it is preferable to keep it decoupled from series. Also, since the series inverter for voltage sensitive loads should be highly responsive as the voltage disturbances exist for few cycles only. Thus, an independent series inverter is obviously a better choice in such scenario.

As a result, another UPQC architecture, known as open UPQC [18]-[25], which has received less attention in the academic community, does suggest the usage of uncoupled inverter combinations. It can achieve performance qualities equivalent to regular UPQCs. The key advantage of the Open UPQC is its ability to stabilize the load voltage while maintaining sinusoidal supply current and load voltage, all while preserving balance. The flexibility of the Open UPQC architecture is beneficial to field end-users since it allows for the separation of series and shunt converters as needed, reacting to the precise kind of end-user loads and therefore changing penalties correspondingly [19].

This paper presents Open Left UPQC (OL-UPQC), a unique mix of UPQC-L and open UPQC. It makes use of open UPQC capabilities that are largely compatible with the requirements of the UPQC-L application. Figure 1 depicts the suggested arrangement with two distinct load connection points (LP). The first functions as a sensitive point, sensitive to voltage fluctuations, while the second is unaffected by voltage variations but adds harmonics to the source current. Figure 1 shows a distribution system configuration with a number of single-phase and three-phase nonlinear loads at LP1 and a mix of three-phase linear and nonlinear loads at LP2, which is presumed to be the sensitive coupling point. The OL-UPQC design consists of two stand-alone inverter systems, one for voltage compensation (series inverter) and one for current compensation (shunt inverter) coupled to LP1. This architecture is especially designed to handle harmonic correction for non-linear loads at numerous load locations as well as voltage disturbance for a voltage sensitive load at the same time, without interfering with each other's functioning.

2. Proposed OL-UPQC Configuration

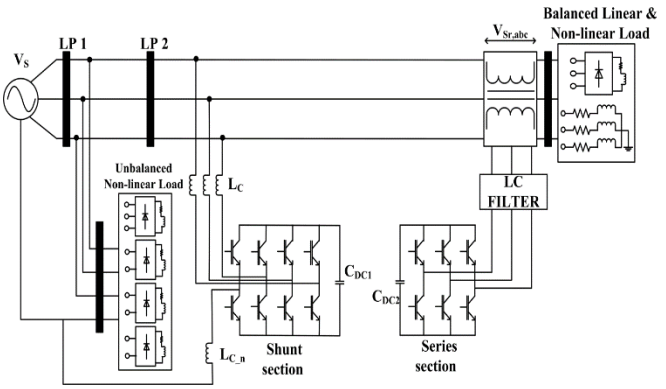


Fig. 1. Proposed configuration of OL-UPQC.

The suggested OL-UPQC arrangement consist of two inverters that are not linked to each other. Shunt inverters include four legs for a three-phase four wire system, a DC-link capacitor, and eight IGBT switches. A series inverter is made up of three legs, six IGBT switches, and a DC-link capacitor. The coupling inductors link the shunt portion to the distribution system. The series inverter is linked in series with the system via an LC filter and a three phase injection transformer.

The load system is made up of two distinct sites, LP1 and LP2. LP2 is coupled to a voltage sensitive balanced nonlinear load. Harmonics would be introduced into the system by the nonlinear load. LP1 is made up of a single-phase and a three-phase non-linear load. The nonlinear nature of the system produces additional harmonics, and the single-phase load causes unbalance in the source current. Harmonics are now introduced by both load points that are coupled. The two inverters are not linked to one another. As a result, they don't interfere with each other's operations. The control mechanism for shunt inverter is based on unit vector template (UVT) control technique [26]. And the control method for series inverter is based on synchronous reference frame (SRF) control technique [27], [28]. Since, the proposed device is taking care of harmonics from two different load point, its control mechanism has to be based on taking feedback of only source current from the supply instead of any load current. Thus, UVT control method has been opted as it involves only source current and not load current.

Major objectives of the proposed configuration are:

- This unique configuration of UPQC combines feature of its two different variants, i.e. open and left UPQC.
- This OL-UPQC is suitable for a specific system setup which consists of multiple load points consisting of nonlinear load; out of which one load point consist of voltage sensitive load.

- It provides voltage compensation due to supply voltage disturbances such as voltage sag, voltage swell and voltage harmonics.
- OL-UPQC offers current harmonic mitigation capabilities from multiple load points due to nonlinear load.

The control configurations of shunt and series inverter are discussed further in the following section.

3. Unit Vector Template (UVT) Based Control for Shunt Inverter

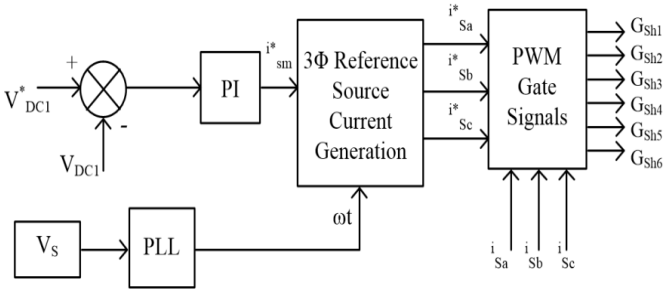


Fig. 2. UVT based control block for shunt inverter.

The control of shunt inverter section of OL-UPQC is based on UVT technique, as this method is most appropriate for the proposed configuration as compared to other methods such as SRF or PQ method. The reason being, it doesn't involve any kind of load current feedback and thus the harmonic mitigation capability entirely depends on DC-link voltage across shunt capacitor and source current drawn from supply. As shown in Fig. 2, the DC-link voltage across shunt capacitor is compared with its reference value and the error is fed to the PI (proportional-integral) controller. The processed error output from the PI controller serves as the foundation for computing the maximum source current.

$$i_{sm}^{*} = (V_{DC1}^{*} - V_{DC1})(K_P + \frac{K_I}{s}) \quad (1)$$

This peak source current value is then utilized in the creation of three reference source current signals.

$$i_{sa}^{*} = i_{sm}^{*} \sin \omega t \quad (2)$$

$$i_{sb}^{*} = i_{sm}^{*} \sin(\omega t - 120) \quad (3)$$

$$i_{sc}^{*} = i_{sm}^{*} \sin(\omega t - 240) \quad (4)$$

These reference source currents are then juxtaposed with the actual respective three-phase source current in a hysteresis controller. In hysteresis controller each phase reference currents are compared with their sensed counterparts and are regulated in a hysteresis band with a tolerance limit of ±2 % to generate the shunt inverter's basic switching pattern (G_{sh1} to G_{sh6}).

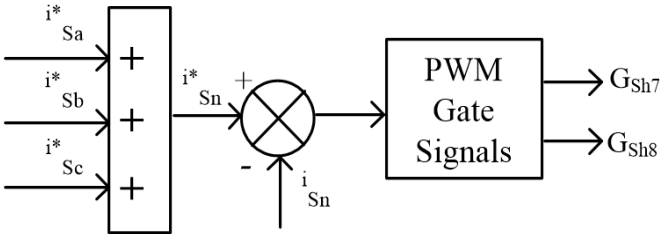


Fig. 3. Pulse generation for the fourth leg of shunt inverter.

Thereafter, as illustrated in Fig. 3, in order to control the fourth leg of inverter, these three-phase reference currents are used to generate the reference neutral current as depicted by the following equation

$$i_{sn}^{*} = i_{sa}^{*} + i_{sb}^{*} + i_{sc}^{*} \quad (5)$$

This is again compared with the actual neutral current to generate the remaining two switching pulses for the fourth leg of inverter, same as obtained for the three-phases discussed.

4. SRF Based Control for Series Inverter

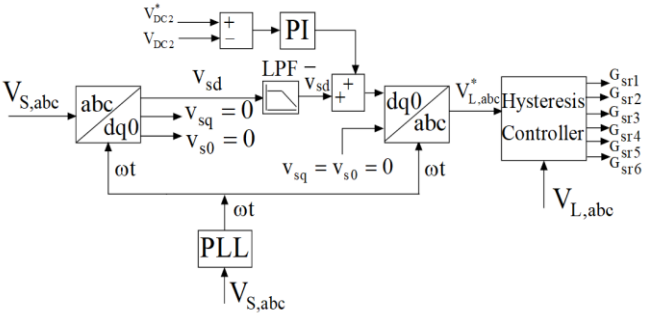


Fig. 4. SRF based control for series inverter.

The series inverter control section is based on SRF algorithm as shown in Fig. 4. Since, the series inverter is linked with DC-link capacitor unlike an external DC source as in [19], its DC-link voltage error has to be taken into account in the control mechanism for quick transient response. SRF method, with its control structure, provides the flexibility to include the same, in contrast to the UVT method [19]. The three-phase source voltage is converted to two-phase with abc-dq transformation, which is again filtered for any harmonics. Using abc to dq transformation, the three phase load voltages are transformed into resultant d axis load voltage as:

$$\begin{bmatrix} V_{l0} \\ V_{ld} \\ V_{lq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} V_{la} \\ V_{lb} \\ V_{lc} \end{bmatrix} \quad (6)$$

ωt is the transformation angle obtained from the PLL.

The filtered d axis magnitude along with null values of q and zero axis quantity is again transformed from two-phase to three-phase quantity with dq to abc transformation. Thus, the three reference load voltages are obtained by using dq-abc transformation as:

$$\begin{bmatrix} V_{La}^{*} \\ V_{Lb}^{*} \\ V_{Lc}^{*} \end{bmatrix} = \begin{bmatrix} \cos \omega t & -\sin \omega t & 1 \\ \cos\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\omega t + \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} \bar{V}_{sd} \\ 0 \\ 0 \end{bmatrix} \quad (7)$$

The three-phase reference load voltage, thus obtained is compared with actual load voltage in a hysteresis controller to generate the switching signals for the series inverter.

Table 1. Parameters for simulation

Source Voltage	Internal Impedance	R = 0.04 Ω, L = 0.2 mH
	Voltage (L-L)	398 V
	Line frequency	50 Hz
Shunt inverter	Coupling Inductor	2.3 mH
Series inverter	L, C Filter	2.4mH, 65 µF
	Transformer	100:100, 3.5 kVA
DC capacitor	Capacitance	C_{DC1}=2500 µF and C_{DC2}=2500 µF
	Reference Voltage	720 V
LP1 Load	One 3 Ø NLL	R = 29 Ω, L = 10 mH & R = 55 Ω, L = 20 mH
	Two 1 Ø NLL	R = 40 Ω, L = 15 mH & R = 55 Ω, L = 25 mH
	3 Ø NLL	R = 29 Ω, L = 10 mH

5. Outcome and Discussion

A simulation analysis is carried out for the proposed OL-UPQC system for different scenarios. An unbalanced load combination of three phase and single phase nonlinear loads is connected at PCC1 for the simulation. The load at PCC2 consists of a balanced nonlinear load. The shunt inverter section of OL-UPQC is tested out for its harmonic compensation ability and series inverter section of the same is tested for voltage compensation ability. Table I lists the simulation parameters.

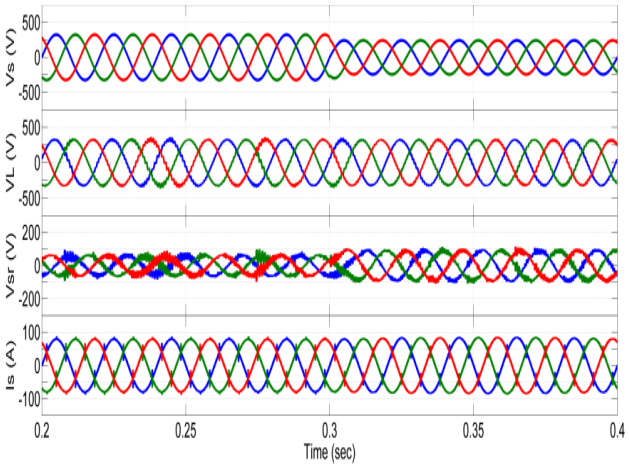


Fig. 5(a) Source voltage sag scenario: supply voltage (V), load voltage (V), series injected voltage (V), source current (A) [top to bottom].

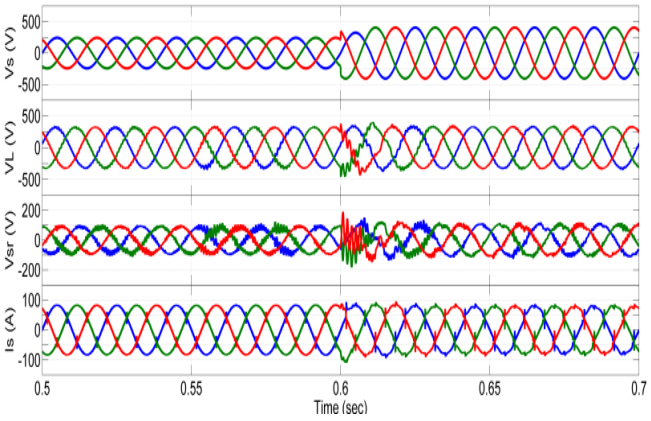


Fig. 5(b) Source voltage swell scenario: supply voltage (V), load voltage (V), series injected voltage (V), source current (A) [top to bottom].

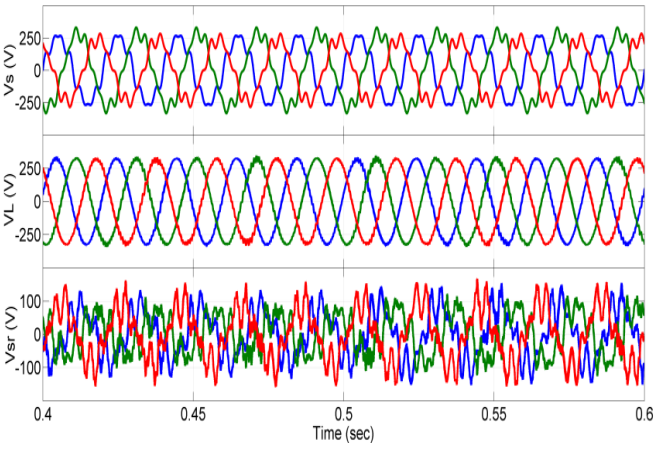


Fig. 5(c) Source voltage harmonic scenario: supply voltage (V), load voltage (V), series injected voltage (V) [top to bottom].

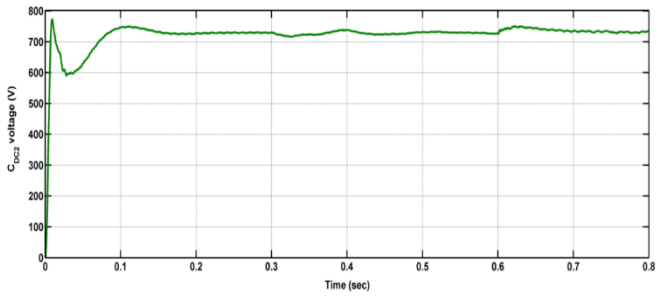


Fig. 5(d) Voltage across DC-link capacitor C_{DC2}.

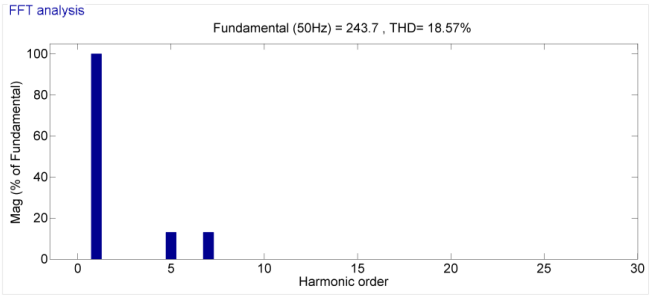


Fig. 5(e) THD spectrum analysis of load voltage without compensation.

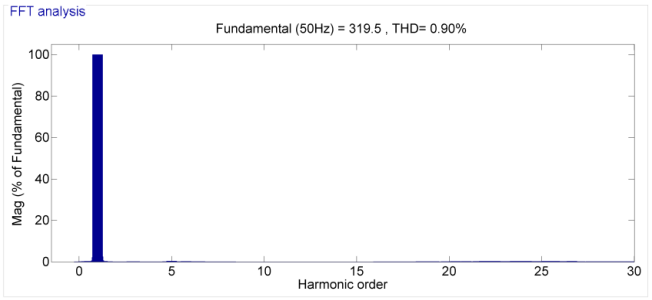


Fig. 5(f) THD spectrum analysis of load voltage after compensation.

5.1. Performance Analysis of Series Inverter Section of OL-UPQC

Performance analysis of OL-UPQC initiates with voltage disturbance in the form of supply voltage sag, thus analyzing the response from series inverter of OL-UPQC. A voltage sag of 20 % is introduced at 0.3 s. Fig. 5(a) illustrates the response of series inverter under sag condition. With quick response from series inverter, the load voltage is compensated and is maintained at the set reference value irrespective of the sag in the supply. Also, the appropriate series injected voltage is shown in the same figure. Fig. 5(b) indicates the simulation waveform under voltage swell condition. A voltage swell of 20 % is introduced with the source voltage at 0.6 s in the waveform depicted between 0.5 s to 0.7 s. With an effective series injection of voltage from series inverter, the load voltage is maintained at the set reference value, shown in the same figure. Moreover, voltage harmonic compensation ability of series inverter is depicted with Fig. 5 (c). As shown in the figure, source voltage is contaminated with harmonics which will also appear across the voltage sensitive load at LP2. With appropriate and quick response from series inverter, the load voltage is free from harmonics as observed from the results. The voltage across DC-link capacitor of series inverter is maintained at its set reference value irrespective of voltage disturbance as shown in Fig. 5(d). Also, on performing THD (total harmonic distortion) analysis on the source voltage, its THD content is found to be around 18.5 % as shown in Fig. 5(e), but the load voltage after compensation has THD of 0.9 % as shown in Fig. 5(f).

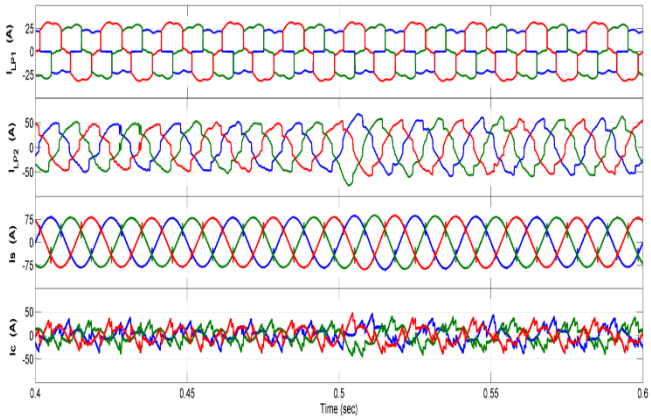


Fig. 6(a) Current harmonic compensation scenario: load current drawn at LP1 (A), load current drawn at LP2 (A), source current drawn from supply (A), compensating current injected from shunt inverter (A).

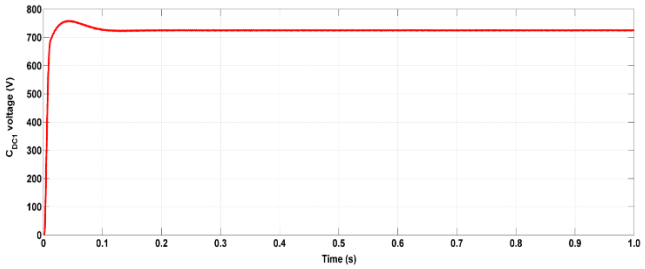


Fig. 6(b) Voltage across DC-link capacitor C_{DC2}.

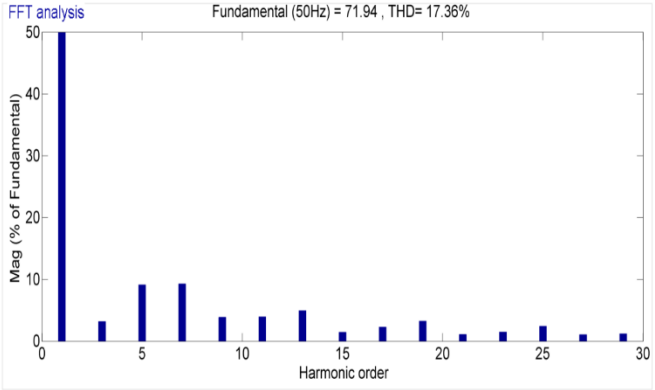


Fig. 6(c) THD spectrum analysis of source current without compensation.

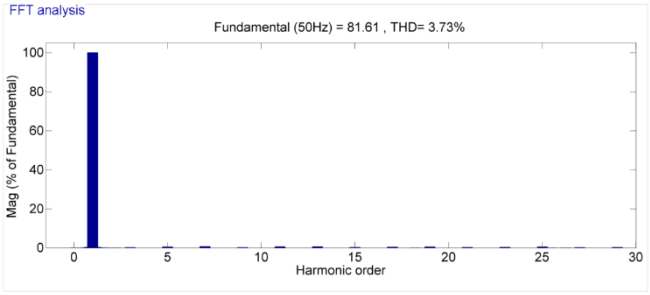


Fig. 6(d) THD spectrum analysis of source current after compensation.

5.2. Performance Analysis of Shunt Inverter Section of OL-UPQC

Performance analysis of shunt inverter section of OL-UPQC is observed in terms of mitigating harmonics being introduced in the source current due to non-linear load at both points, i.e. LP1 and LP2. Fig. 6(a) indicates various current waveforms such as load current at LP1, load current at LP2, source current drawn from the supply and compensating current from the shunt inverter. It is clear from the figure that the load current at LP1 is unbalanced due to unbalanced load, also both load currents are far from sinusoidal pattern of waveform. After compensation from shunt inverter section of OL-UPQC, source current is completely balanced and almost sinusoidal in nature. Also, the compensating current pattern can be observed for mitigating the harmonics. The voltage across DC-link capacitor of shunt inverter is observed to be maintained at its fixed reference value. Fig. 6(c) shows the THD analysis of source current before compensation and is found to be 17.3 % , which is on the higher side. Fig. 6(d) indicates the THD spectrum analysis of source current after compensation which is found to be 3.73 %, which is within IEEE standard limits.

Table 2. Comparative analysis

	Load point applicability (For Harmonic compensation ability)	DC-Link capacitors (No.)	External DC source (No.)	Coupling of series and shunt inverter
UPQC-L [17]	Multiple	One	NIL	Yes
Open UPQC [19]	Single	One	One	No
OL-UPQC	Multiple	Two	NIL	No

5.3. Comparative Performance Analysis of OL-UPQC with UPQC-L [17] and Open UPQC [19]

A comparative analysis is presented in Table 2, in terms of configuration design. The proposed configuration of OL-UPQC is compared with UPQC-L and open UPQC configurations. It is quite evident that UPQC-L [17] and proposed OL-UPQC are suitable for multiple load point systems whereas open UPQC [19] is applicable for single load point when observed for harmonic compensation. The DC-link capacitors used in the proposed design are two in number as compared to one in the other two systems. The open UPQC presented in [19] also relies for its operation on an external DC source where as in other two it is not required. However, in UPQC-L, both inverters are coupled to each other to a common DC-link where as in the proposed design, both inverters are decoupled and thus, it is quite obvious that they do not affect each other's operation.

6. Conclusion

The proposed system is intended to use the specified control approach in a dual load point system. The configuration design includes an open UPQC, an uncoupled set of shunt and series inverter with shunt inverter being unconventionally on the left side of the whole setup and series inverter on the right side. It is observed that such setup is effective in handling harmonic mitigation being introduced from more than an individual load point and handling voltage sensitive load. This combined setup of open and left shunt is quiet effective in response due to existence of their respective DC capacitors and is termed as OL-UPQC. The OL-UPQC system has two functions: it tackles harmonic and unbalancing difficulties caused by the non-linear and unbalanced load linked to LP1 and LP, also it maintains stable voltage levels for the sensitive load attached to LP2. The OL-UPQC system performs admirably in both steady-state and transient settings. The efficacy of the system is validated by simulations testing. Notably, the system responds quickly and dynamically, successfully regulating the Total Harmonic Distortion (THD) in the source current to match specified limitations. Furthermore, even during transient occurrences, it continually balances and maintains the load voltage at the desired reference level. As a result,the OL-UPQC system emerges as a efficient solution for multiple load point systems, especially under voltage sag circumstances.

However, since the proposed configuration comprises of two separate DC-link capacitors, thus increasing the setup size and cost. Also, both control system of shunt and series inverter involves DC-link voltage control for their respective capacitors, thus slightly increasing the control complexity with a benefit of better control of voltage across them. Furthermore, this configuration could be analyzed for varying load conditions, observing their response under transient conditions along with using optimization methods for tuning of PI controllers.

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