# Power Quality Analysis of a Distributed Generation System Using Unified Power Quality Conditioner

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**Abstract.** This paper deals with power quality profile analysis of distributed generation (DG) system using unified power quality conditioner (UPQC). Despite the several benefits of DG like excellent energy supply, reducing the expansion of power distribution system, environmentally friendly, and so on, there are several challenges existing due to the integration of DG with the grid or operating it in stand-alone mode. Power quality (PQ) issue is one of the main technical challenges in DG power system. In order to provide improved PQ of energy supply, it is necessary to analyze the harmonics distortion of the system as well as the voltage sag and swell. The UPQC has been extensively useful and it is verified to be the best solution to diminish this PQ issue. This paper explores the detail of PQ impacts in a DG (comprising of Solar PV and Fuel cell) system operates in stand-alone mode. The voltage sag compensation with current and voltage harmonics are estimated at varying load conditions with different control scheme like the synchronous reference frame (SRF) and modified SRF technique. The proposed model is developed in MATLAB/SIMULINK[R] and the result obtained validates the superiority of the proposed technique over others in terms of harmonics elimination and sag compensation.

**Keywords:** Distributed generation · Power quality · Harmonics · Sag · MSRF

## 1 Introduction

Distributed generation (DG) can be represented as a small-scale power system that contains loads, energy sources, energy storage units and control, and protection systems [1]. Using DG is more attractive as it improves the system quality, decreases the carbon emission and reduces the losses in transmission and distribution systems [2]. When DG is connected to the utility grid, the control systems required to maintain the active and reactive power output from the energy sources connected to DG is simple. However, under autonomous operation, the DG is disconnected from the utility grid and operates


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in islanded condition. Usually, a stand-alone DG system used to supply power to isolated areas or places interconnected to a weak grid. The application of the above DG other hand reduces the probability of energy supply scarcity. The proposed DG consists of renewable energy sources (RES) based power sources (i.e., solar PV, and fuel cell) and storage device as battery along with controllable loads [3, 4]. Solar PV is depended upon climatic conditions, hence to get an uninterrupted power supply at any time and maintaining the continuity of load current, one of the most developed energy sources like fuel cell is combined with these RES [5]. However, electric power system is mostly affected by nonlinear loads, mostly arc furnaces, power electronics converters, and household electronic equipment plays a key role in polluting the supply voltages and currents. The increase of power electronics-based equipment in household appliances and industries are the main cause of pollution of power system [6]. The research in the area of power electronics makes sure that a unified power quality conditioner (UPQC) plays a vital role in achieving superior power quality levels. In the present scenario, the series active power filters (APFs) and shunt APF normally termed as SAPF, alone do not meet the requirement for compensating the PQ distortions. A UPQC consists of two inverters integrated with the DC-link capacitor where the series APF is integrated though a series transformer and the shunt is through interfacing inductor. The series inverter acts as a voltage source whereas the shunt one is acts as a current source. Simultaneous compensation of voltage and current related PQ distortions using UPQC is achieved by proper controlling of series APF and shunt APF [7]. The shunt APF is employed for providing compensating currents to PCC for generation/absorption of reactive power and harmonics suppression. Moreover, the operation of SAPF is depended upon three main parts which are momentous in its design; these consist of the control method used for generation of reference current, a technique used for switching pulses generation for the inverter and the controller used for DC-link capacitor voltage regulation. Different control strategy is explained in the literature as follows. The use of SAPFs for current harmonic compensation typically in domestic, commercial, and industrial applications has been explained in Montero et al. [7]. The experimental study and simulation design of a SAPF for harmonics and reactive power compensation is explained by Jain et al. [8]. The power balance theory for active and reactive power compensation has developed by Singh et al. [9]. The instantaneous reactive power techniques of three-phase shunt active filter for compensation of source current harmonics have been explained by Akagi et al. [10]. Sag is the most significant PQ problem facing lots of industrial consumers. The control for such a case can be analyzed by protecting sensitive loads in order to preserve a load voltage without a sudden phase shift [11]. Different control strategies for series APF are analyzed by Benachaiba et al. [12] with importance on the reimbursement of voltage sags with phase jump. Different control techniques to reimburse voltage sags with phase jump are also projected and compared by Jowder et al. [13]. To ensure stable operation and improve the system performance of DG in island mode, a comparative study of two different control techniques used in UPQC like reference current generation, i.e., synchronous reference frame (SRF) method and modified synchronous reference frame (MSRF) method in conjunction with pulse width modulation based hysteresis band controller is proposed in this paper by using Matlab simulation software [7, 14]. The PQ issues like voltage sag compensation, current and voltage harmonics were analyzed both at linear and nonlinear load are the main contribution of this paper.

## 2 Proposed System

The projected DG system (comprising of solar and fuel cell based energy sources) is shown in Fig. 1 where DG system generates DC power to the DC bus and by using a power inverter this DC power is converted to AC. The AC bus delivers the power to the load which may be linear or nonlinear. The UPQC is located in between the DG and nonlinear load which manage the power quality of the system by using different control techniques.

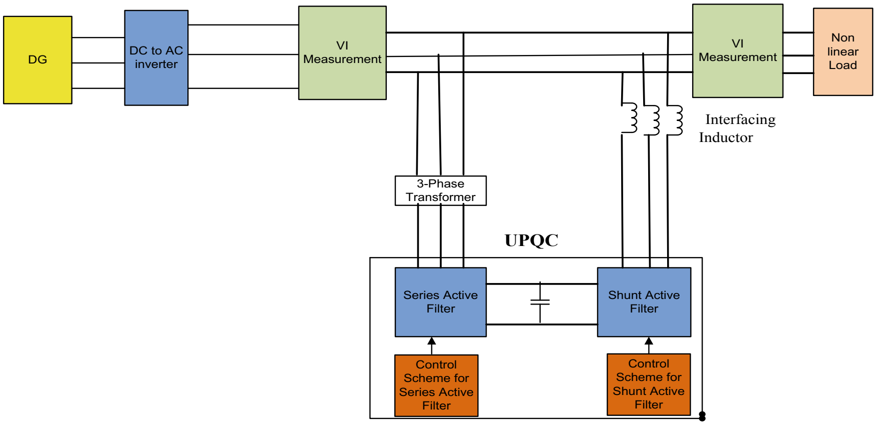


**Fig. 1.** Basic block diagram of DG with UPQC

### 2.1 Modeling of Solar PV

A single diode model based PV cell is used for design of DG]. Figure 2 represents the single diode equivalent model of solar PV system. The basic equation for design of PV system is given below [15].

$$\mathrm{I_{PV}} = \mathrm{N}_P \times \mathrm{I_{Ph}} - \mathrm{N}_P \times \mathrm{I}_O\left[\exp\left\{\frac{q \times V_{\mathrm{PV}} + \mathrm{I_{PV}} \times R_{\mathrm{se}}}{\mathrm{N}_s \times Ak\mathrm{T}}\right\} - 1\right] \quad (1)$$

Figure 3 shows the MATLAB simulation of PV with MPPT and boost converter and Fig. 4 shows its corresponding output voltage where the required voltage of 230 V is achieved. The parameters required for the design of solar PV system is illustrated in Table 1 [16].

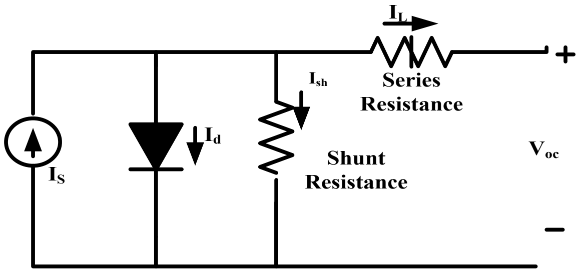


**Fig. 2.** Solar cell single diode model

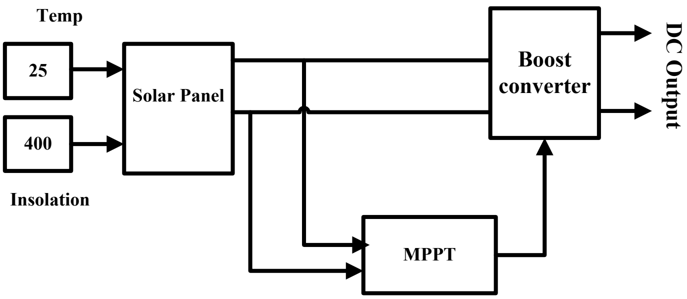


**Fig. 3.** Simulation of solar PV system

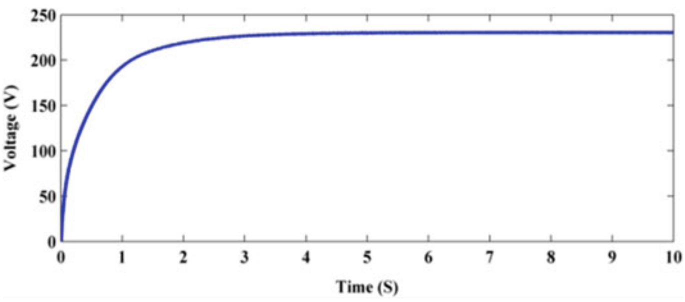


**Fig. 4.** Output voltage of boost converter

## 2.2 Modeling of Fuel Cell System

Proton exchange membrane (PEM) fuel cell is considered as another energy source of the DG. The fuel cell consists of two electrodes, i.e., positive cathode, negative anode, and an electrolyte. The pressurized hydrogen gas enters as the anode of the fuel cell and oxygen enters the cathode. In a basic PEM fuel cell diagram is shown in Fig. 5, and its chemical reactions are shown in Eqs. (2–4).

$$(2H^{+} + 2e^{-}) \rightarrow H_2 \tag{2}$$

$$(2H^{+} + 2e^{-} + 1/2O2) \rightarrow H_{2O} \tag{3}$$

**Table 1.** Different parameters and their ratings to carry out the simulation work of solar PV

| Different parameters | Ratings |
|---|---|
| No. of Cells in series ($N_P$) | 72 |
| Cells in parallel ($N_s$) | 01 |
| Short circuit current ($I_{sc}$) | 10.2 A |
| Open circuit voltage ($V_{oc}$) | 90.5 V |
| Voltage at maximum Power ($V_{mp}$) | 81.5 V |
| Current at maximum Power ($I_{mp}$) | 8.6 A |
| Output voltage | 230 V |

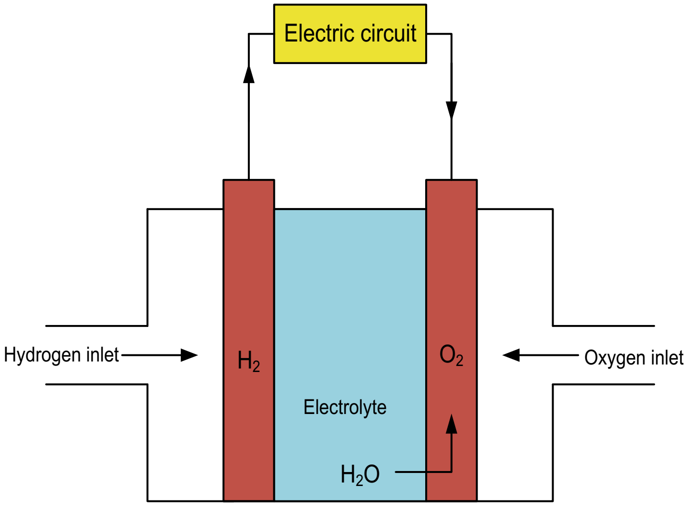


**Fig. 5.** Fuel cell model

$$H_2 + 1/2O2 \rightarrow H_{2O} \quad (4)$$

The simulation fuel cell with boost converter is shown in Fig. 6 and the output voltage which matches with the output voltage of other DGs is shown in Fig. 7. Table 2 represents different parameters of fuel cell.

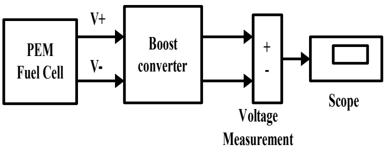


**Fig. 6.** Fuel cell with boost converter

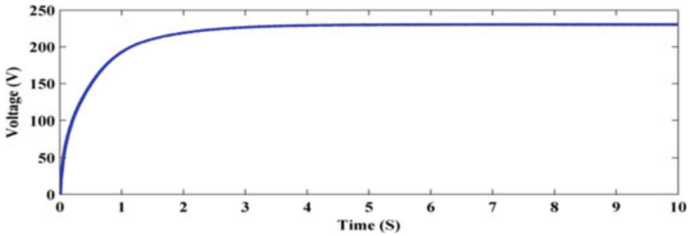


**Fig. 7.** Output voltage of boost converter

**Table 2.** Parameters of the Fuel cell

| Different parameters | Values |
|---|---|
| Load resistance ($R_l$) | 5 Ω |
| Oxygen percentage in air ($O_2$) | 59.3% |
| Each cell voltage ($v_s$) | 1.128 V |
| Cell resistance ($R_t$) | 0.70833 Ω |
| Number of cell ($k$) | 65 |
| Hydrogen percentage in fuel ($H_2$) | 99.56% |
| Fuel cell voltage ($V_{fc}$) | 230 V |

### 2.2.1 Modeling of UPQC

This chapter begins with system configuration and a detailed description of UPQC. The basic structure of UPQC is shown in Fig. 8 which consists of two inverters connected to a common DC-link capacitor. The series inverter is connected through a series transformer and the shunt inverter is connected in parallel with the point of common coupling. The series inverter acts as a voltage source whereas the shunt one is acts as a current source. The main function of UPQC is to control the power flow and reduce the harmonics distortion both in voltage and current waveform.

The series APF topology is shown in Fig. 9. The series APF protects the load from the utility side disturbances. In case of series APF Park's transformation method is used for generation of unit vector signal. A PWM generator, generating synchronized switching pulses, is given to the six switches of the series converter.

Figure 10 shows the basic structure of shunt active filter. The shunt active power filter injects compensating current to the PCC such that the load current becomes harmonics free. The SAPF generates compensating current which is in opposition to the harmonic current generated by nonlinear load. This compensating current cancel out the current harmonics caused and makes the load current sinusoidal. So the SAPF is used to eradicate current harmonics and reimburse reactive power at the source side so as to make load current harmonics free.

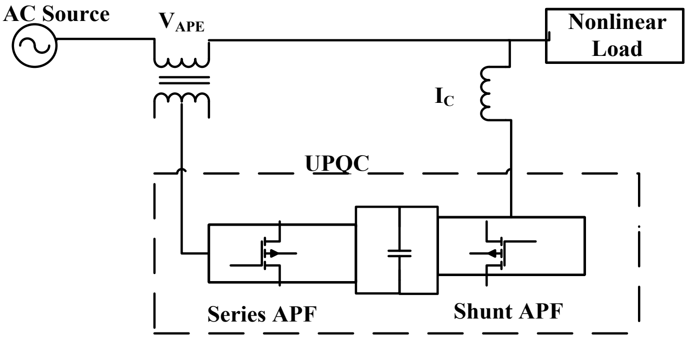


**Fig. 8.** Basic UPQC system block diagram

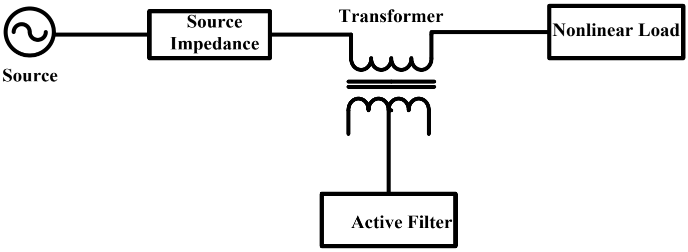


**Fig. 9.** Block diagram of series active filter

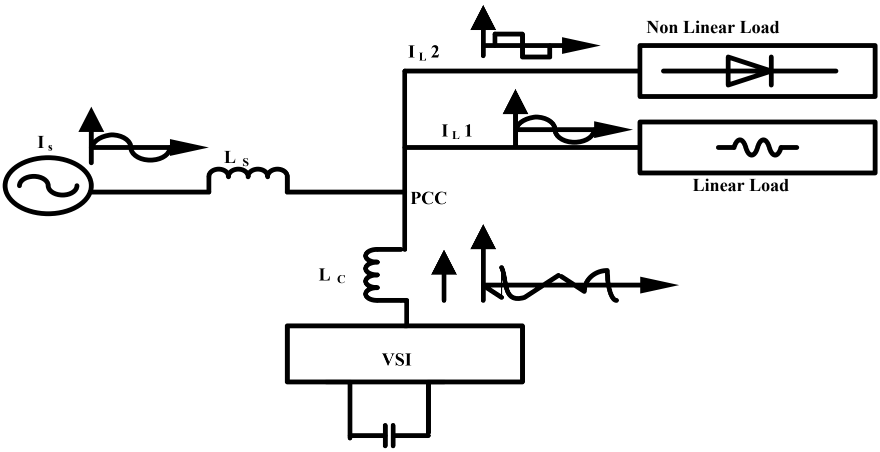


**Fig. 10.** Block diagram of shunt active filter

The Eqs. (5) and (6) show instantaneous current and the source voltage.

$$Is(t) = IL(t) - IC(t) \tag{5}$$

$$Vs(t) = Vm \ \sin \omega t \tag{6}$$

Fourier series method is used for expressing the nonlinear load current as shown in Eq. (7).

$$Is(t) = I1\mathrm{Sin}(\omega t + \Phi 1) + \sum_{n=2}^{\varepsilon} In\mathrm{Sin}(n\omega t + \Phi n) \tag{7}$$

The compensation current of the active filter should be expressed by

$$Ic(t) = IL(t) - Is(t) \tag{8}$$

Hence, for the exact compensation of reactive power and harmonics, it is essential to determine $Is(t)$. The instantaneous value of source, load, and compensation current can be expressed by, $Is(t)$, $IL(t)$ & $IC(t)$ where $Vs(t)$ and $Vm$ corresponds to instantaneous value and peak value of source voltage.

### 2.3 Control scheme of UPQC

The MSRF controller scheme works in steady-state as well as in dynamic conditions exquisitely to manage the active, reactive power and reduce the harmonics in load current.

The literature in review reveals that MSRF technique has much more advantages as compare to SRF scheme, so the authors have selected this control scheme for UPQC operation. The control scheme not uses the PLL circuit as used by SRF scheme, which makes the system more compatible and may be operated in load changing condition. The MSRF scheme with its control algorithm is given below.

#### 2.3.1 Modified Synchronous Reference Frame (MSRF) Method

Figure 11 shows the block diagram of modified SRF method for unit vector generation. The unit vector is generating by vector orientation method, not by PLL. Figure 12 shows the block diagram to generate a unit vector by sensing the supply voltage." The unit vector generation is defining by the following equation.

$$\cos\theta = \frac{V_{\alpha}}{\sqrt{(V_{s\alpha}2)} + \left(V_{s\beta}2\right)} \tag{9}$$

$$\sin\theta = \frac{V_{\beta}}{\sqrt{(V_{s\alpha}2)} + \left(V_{s\beta}2\right)} \tag{10}$$

#### 2.3.2 Hysteresis Band Current Controller

Figure 13 shows the block diagram of hysteresis current regulator which generates the required pulses for inverter. In the current regulator, the error signal is generated by comparing the reference current $I^{*}_{\mathrm{sa}}$and actual current $I_{\mathrm{sa}}$.

The switching pulses required for the inverter is design in such a way that when the error signal goes beyond the upper band of hysteresis loop the lower switches of inverter are ON and upper switches are OFF and similarly the upper switches are ON and lower switches OFMatlab simulation software he lower band [17]. So the actual current is always tracked with respect to reference current inside the hysteresis band.

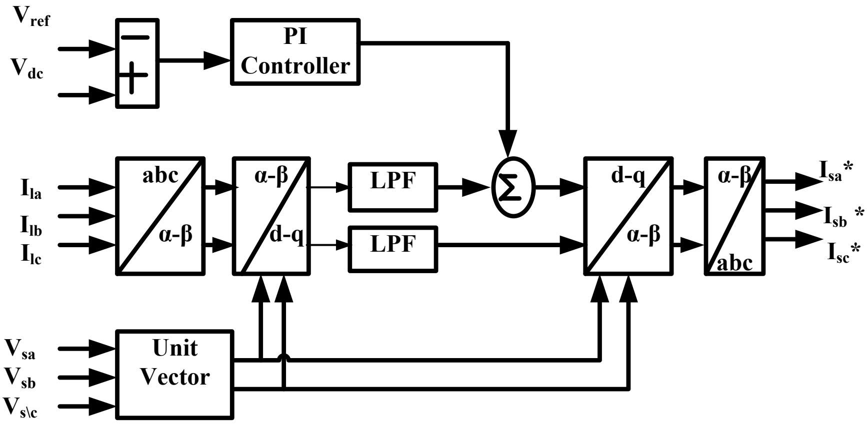


**Fig. 11.** Block diagram of MSRF method

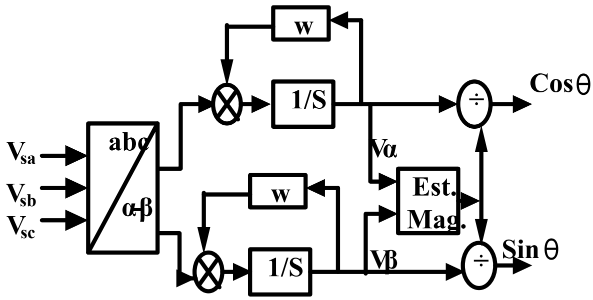


**Fig. 12.** Unit vector generation block diagram

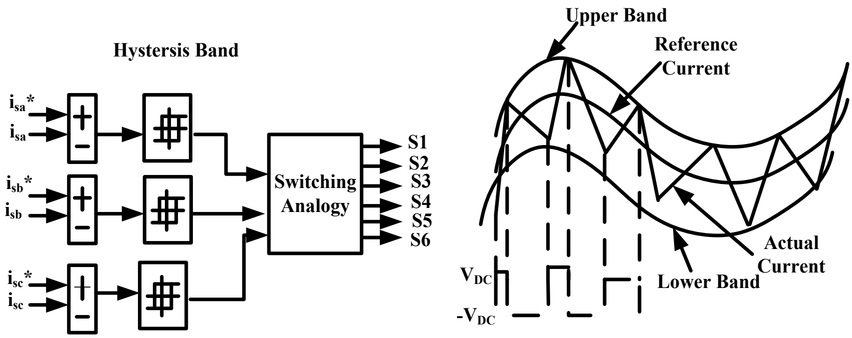


**Fig. 13.** Hysteresis current controller scheme

# 3 Simulation Results and Discussion

## 3.1 Performance Analysis of DG Connected to Nonlinear Load With MSRF Based UPQC

In this case, the system performance is analyzed by connecting nonlinear load with the DG system first without UPQC and then with MSRF based UPQC. The performance of series APF can be evaluated by introducing voltage sag into the system. The profile of load voltage shown in Fig. 14a conforms that voltage sag is introduced from 0.1 s to 0.3 s of the load voltage waveform. For sag condition, the series APF detects the voltage drop and inject the required voltage through the series coupling transformer. It maintains the rated voltage across the load terminal. In order to compensate for the load voltage sag, UPQC (employing MSRF scheme) is turned on, which injects compensating voltage at the PCC as displayed in Fig. 14b as a result the load voltage is the same as that of source voltage. The load voltage after compensation is shown in Fig. 14c. In general, the operation of the series part of the UPQC can be described as rapid detection of voltage variations at source and it injects the compensation voltage which maintains rated voltage across the load terminal.

The shunt VSI in the UPQC is realized as shunt APF and is applied to solve the current related PQ distortions current harmonic distortion, reactive power demand, etc. In order to investigate the performance of shunt APF a rectifier based nonlinear load is introduced into the system and the level of harmonics is checked. It is observed from Fig. 15a that the source current waveform has a total harmonic distortion (THD) of 16.60% as per the FFT analysis of the source current shown in Fig. 15b. In order to make source current to be sinusoidal the shunt APF of the UPQC with conventional MSRF technique is turned on, at $t = 0.1$ s which injects compensating current as displayed in Fig. 15c. Hence, the THD level comes down to 2.54% as shown in Fig. 15d.

# 4 Conclusion

The research reveals that MSRF technique of UPQC makes it possible for improving the power quality of a DG system connected with nonlinear load. The advantage of MSRF technique is that the production of sine and cosine angles for synchronization purpose instead of using PLL circuit it uses a basic unit vector generation scheme. The suggested method delivers superior output than the existing method in terms of harmonic mitigation and compensation of active and reactive power. In future, the work may be extended by integrating different control approaches for reference current generation of UPQC and DC-link voltage control algorithm may be implemented for better PQ mitigation purpose.

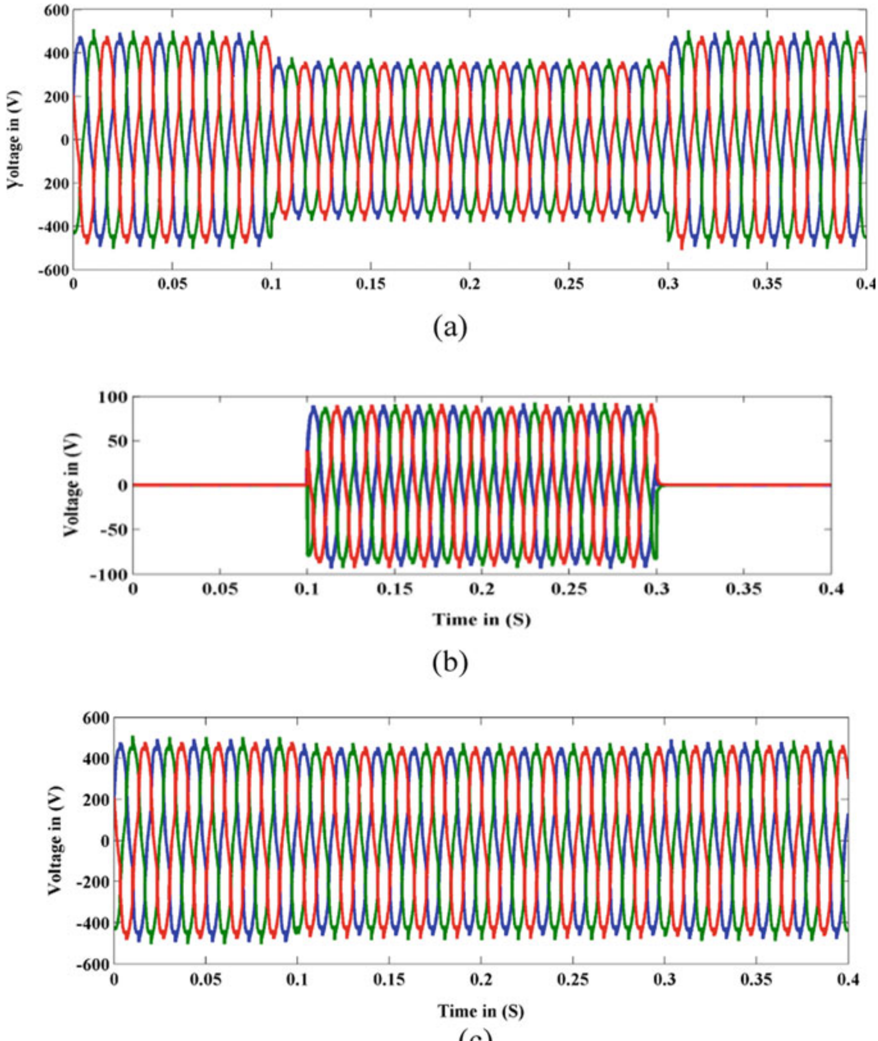


**Fig. 14.** Profile obtained under (sag compensation) **a** Load voltage before compensation, **b** Compensating voltage injected by UPQC, **c** Load voltage after compensation

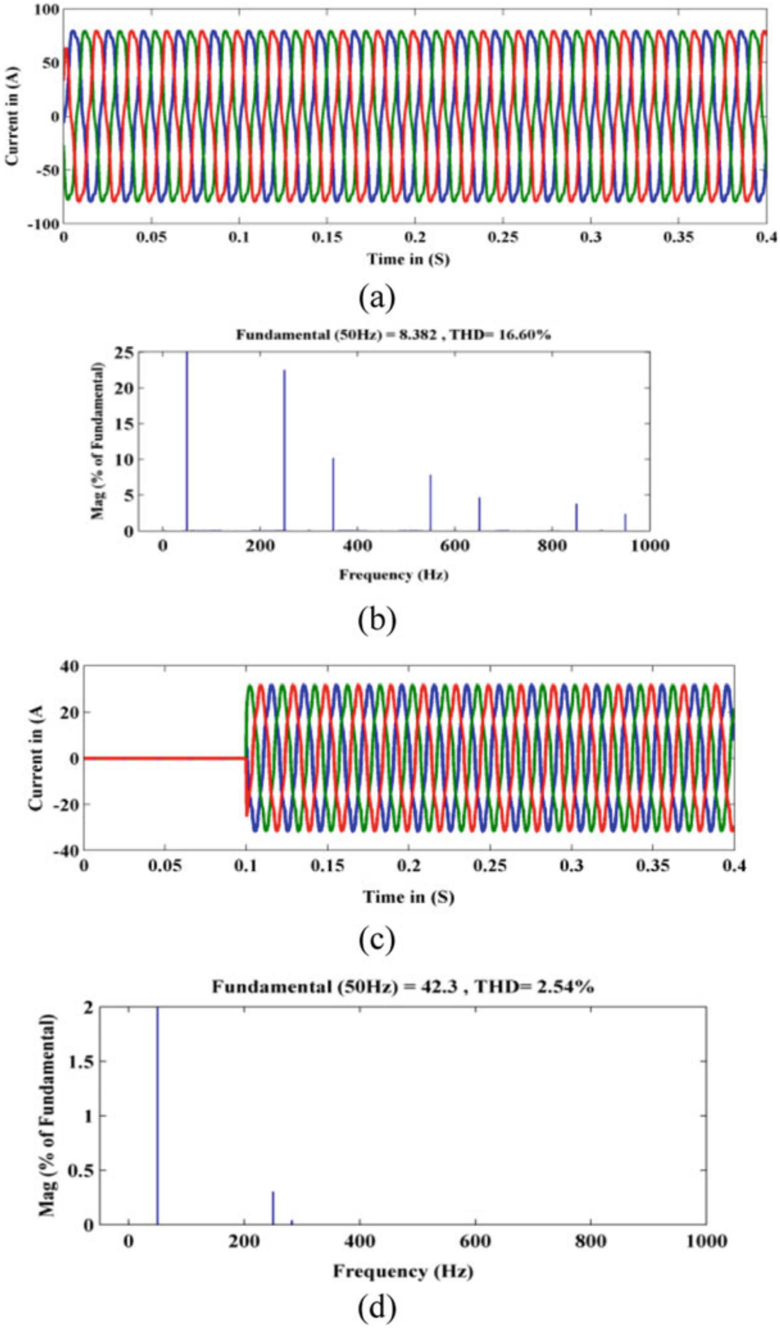


**Fig. 15.** Profile obtained under (Harmonics Mitigation) **a** Source current before compensation, **b** Harmonics content before compensation, **c** Compensating current injected by UPQC, **d** Harmonics content after compensation

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