POWER QUALITY ENHANCEMENT USING UNIFIED POWER QUALITY CONDITIONER (UPQC) CONTROLLED BY BACKSTEPPING CONTROLLER

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Nowadays due to remarkable development in power electronics, the use of non-linear loads has become prominent. These loads draw distorted (non-sinusoidal) currents from the power supply (harmonics generation) resulting in an increase in harmonics injected into the power system. This article presents the Unified Power Quality Conditioner (UPQC) for compensation voltages and current disturbances. Our dispositive study has dual benefits of series and shunts active filters as it improves the power quality. The approach consists in injecting harmonic current and voltage into the system with the same magnitude and inverse phase as the load current and voltage harmonics to cancel out the undesired harmonic components. In this article, we use a nonlinear controller called a backstepping controller for the DC bus. The results of simulations obtained under MATLAB/Simulink show the effectiveness of the controller used.

Keywords: Backstepping Controller, Harmonics, Power Quality, Power System, UPQC, Voltage Sag

1. Introduction

Power quality is in the limelight due to the persistent use of power electronics-based equipment, especially non-linear loads such as rectifiers, adjustable machine drives, saturated transformers, and arc furnaces. The proliferation of these adulterating loads has led to current harmonics and voltage distortion which aggravated the major concern of power quality. The presence of these harmonics results in equipment dysfunctions, low power factor, reactive power, and electromagnetic interference, leading to premature component failure and increasing the level of harmonic pollution within the power supply [1]. Thus, mitigating harmonics is a key priority. Several international standards have been set with regard to power quality like IEEE 519 standard that limited the dominant

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harmonics current below 5% [1, 2]. In the beginning, it ameliorates the power quality and mitigates harmonic disturbances. Passive filtering was used for the problems of reactive power and harmonic distortion although they have many disadvantages such as non-adaptation with the variation of the load, tuning problems, series and parallel resonance, harmonic amplification, and possible overload. For all these reasons, the active power filters became an excellent technology for power quality enhancement as they perform better with further regulation capability and flexibility. The unified power quality conditioner (UPQC) combines the functionality of both series and shunts filters enhancing the power quality and ensuring the correct operation of other sensitive non-linear loads [3,4].

2. Unified Power Quality Conditioner (UPQC)

The general structure of the unified power quality conditioner (UPQC) on a three-phase system is presented in Fig. 1. This configuration of (UPQC) is a shunt-series filter connected in a back-to-back manner with a common DC link bus. The shunt active power filter is positioned at the load side, via interfacing inductors (L_f) while the series filter or series compensator is located at the grid side and connected to a series injection transformer via interfacing inductors (Lr). The series active filter purpose is to eliminate voltage unbalanced, (sags/swell), interruption with harmonics voltages compensation. [5]. Moreover, the shunt active filter's major purpose is to inoculate harmonics of current and reactive power originating from the load side as well as adjust the voltage among the two filters.

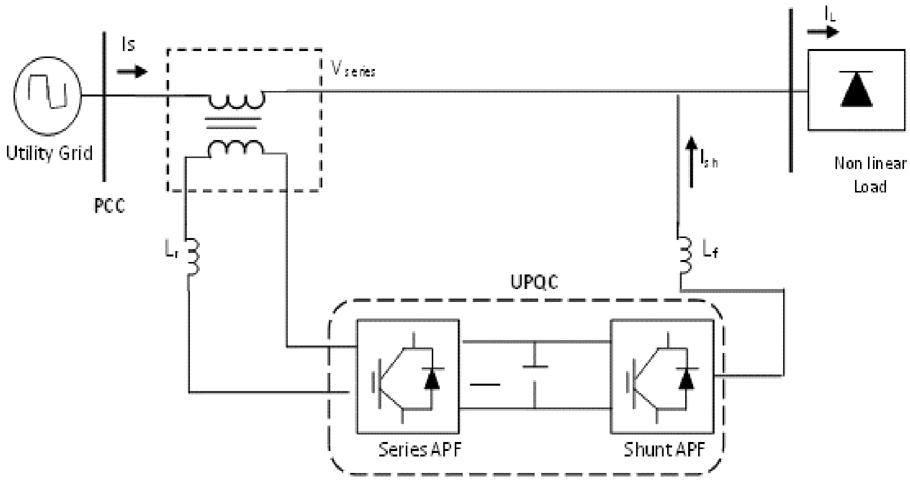


Fig.1. General Structure of UPQC

2.1. Control Strategy for Shunt and Series Active Filters

The control strategy is very important for active power filters (APF). Among the considerable control methods in the time domain, the theory of Instantaneous Active and Reactive Power also known as (PQ) theory is used to identify harmonics current (shunt APF) and harmonics voltage (series APF). The main idea is to convert the three-phase system (a-b-c) to two frames (α-β-0) using Concordia transformation. The three-phase α-β-0 transformation allows to write the following relations: [6,7].

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (2)$$

Components with subscript (0) represent the zero sequence sequences of the three-phase current and voltage system. The advantage of the α-β-0 transformation is the separation of the homopolar sequences from the three-phase current or voltage system. Similarly, the instantaneous real and imaginary power can be written in the following forms:

$$\begin{aligned} p(t) &= v_\alpha i_\alpha + v_\beta i_\beta \\ q(t) &= v_\alpha i_\beta - v_\beta i_\alpha \end{aligned} \quad (3)$$

In the three-phase system (a-b-c) equation (3) can be written as follows:

$$\begin{aligned} p(t) &= v_{sa} i_{la} + v_{sb} i_{lb} + v_{sc} i_{lc} \\ q(t) &= -\frac{1}{\sqrt{3}} \left[(v_{sa} - v_{sb}) i_{lc} + (v_{sb} - v_{sc}) i_{la} + (v_{sc} - v_{sa}) i_{lb} \right] \end{aligned} \quad (4)$$

If we put: $\Delta = v_\alpha^2 + v_\beta^2$ (5)

From expression (3):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta}\left(\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} p \\ q \end{bmatrix}\right) \quad (6)$$

We can decompose the powers p and q into two parts according to the following equations:

$$\begin{aligned} p &= \bar{p} + \tilde{p} \\ q &= \bar{q} + \tilde{q} \end{aligned} \quad (7)$$

With:

$\bar{p},\bar{q}$: Mean value (fundamental) value active and reactive power.

$\tilde{p},\tilde{q}$: Alternating (harmonic) value of active and reactive power.

The filtering method used for extracting the alternative power is shown in Fig..2.

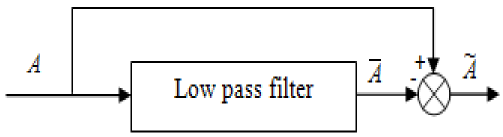


Fig 2. Principle of extraction the component alternative of p and q.

If replaced in (6), we find:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} + \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} 0 \\ \bar{q} \end{bmatrix} + \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (8)$$

Thus, the reference current will be calculated by the relationship:

$$\begin{bmatrix} i_{ref-\alpha} \\ i_{ref-\beta} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (9)$$

Applying the inverse transformation, we can write:

(10)

By the same principle we find the reference voltages injected by the series active filter as follows:

$$\begin{bmatrix} v_{ref-a} \\ v_{ref-b} \\ v_{ref-c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} -1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{ref-\alpha} \\ v_{ref-\beta} \end{bmatrix} \tag{11}$$

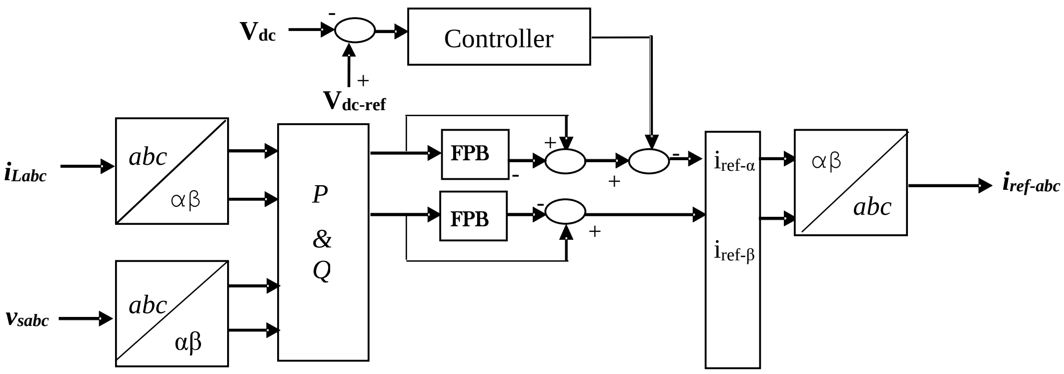


Fig 3. P-Q theory for shunt APF

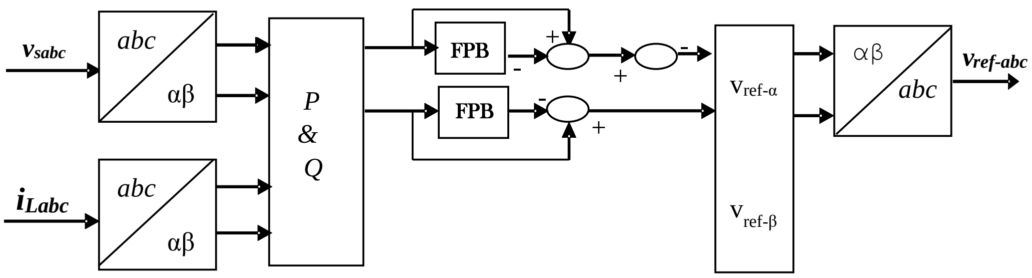


Fig 4. PQ theory for series APF

2.2. Hysteresis control

Switching control of the current-controlled voltage source inverter (VSI) is mandatory to acquire the necessary current waveform. Thus, the hysteresis controller also known as the bang-bang controller is used. This technique ensures robustness and a very rapid dynamic response along with unconditioned stability [8,9]. His role is to force the UPQC current (i_f) or voltage (v_f) reimbursement signal to follow its estimated reference signal (i_{f-ref} or v_{f-ref}) within a fixed tolerance acceptable band. The concept is represented in Fig. 5.

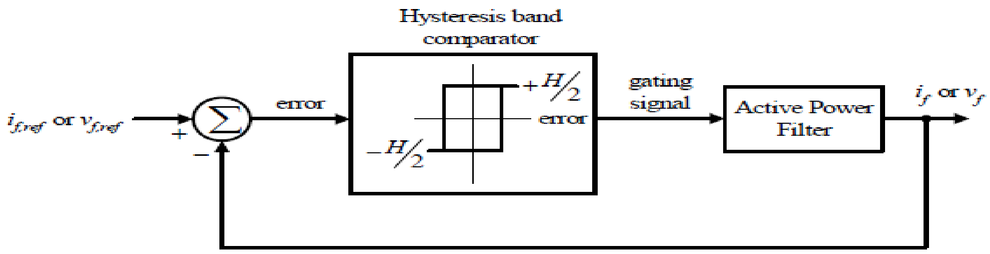


Fig 5. Conventional hysteresis band current controller

2.3 DC Voltage Control by using Backstepping Controller

$$\frac{dv_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} = -\frac{P_{dc}}{C_{dc}.v_{dc}} \tag{12}$$

v_{dc} , P_{dc} : Voltage and power across the capacitor.

We give the error "e" by this formula:

$$e = v_{dc}^* - v_{dc} \tag{13}$$

$$\frac{de}{dt} = \frac{d}{dt} v_{dc}^* - \frac{d}{dt} v_{dc} = 0 - \frac{P_{dc}^*}{C_{dc}.v_{dc}} \tag{14}$$

$\frac{d}{dt} v_{dc}^* = 0$: Reference voltage

$P_{dc} = P_{dc}^*$: Reference power

The Lyapunov function is written as follow:

$$v = \frac{1}{2} e^2 \tag{15}$$

The derivative will be given by:

$$\frac{dv}{dt} = e\frac{de}{dt} = e\left[-\frac{P_{dc}^{*}}{C_{dc}.v_{dc}}\right] = -K.e^{2} \tag{16}$$

If we achieve the quality of the equation below, we obtain better stability of the system [10] by choosing the constant “K” positive.

$$\frac{dv}{dt} = -\frac{P_{dc}^{*}}{C_{dc}.v_{dc}} = -K.e \tag{17}$$

K: constant positive.

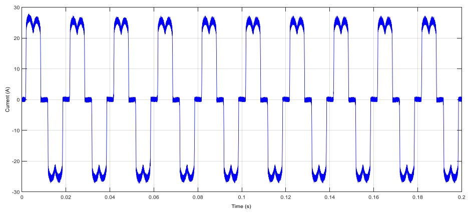
In the end we found the command as follow:

$$\begin{aligned} P_{dc}^{*} &= C_{dc}.v_{dc}.K.e \\ i_{dc}^{*} &= C_{dc}.K.e \end{aligned} \tag{18}$$

3. Simulation Results

Parameters of UPQC studied

Parameter		**Values**
Power Source	Source Voltage	230 V
	frequency	50 Hz
	Source resistance	0.5Ω
	Source inductance	3m H
Non-linear load	Load resistance	10Ω
	Load inductance	10mH
Shunt APF	Filter inductance	3.5mH
Series APF	Filter inductance	3.5mH
	Series Transformer	1KVA
DC Link	DC Voltage reference	800V
	Capacitor	2200 µF



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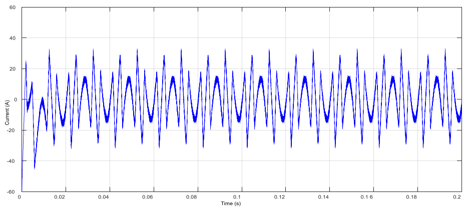

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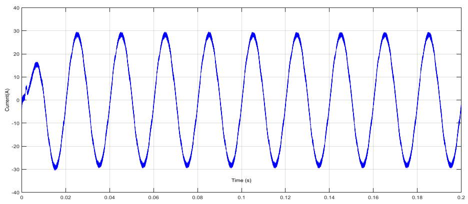
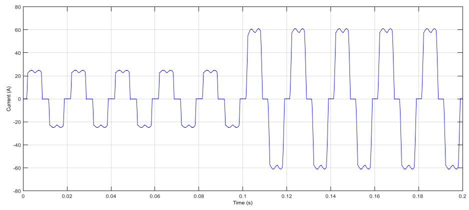


(c)

Fig 6. Load, injection and source current



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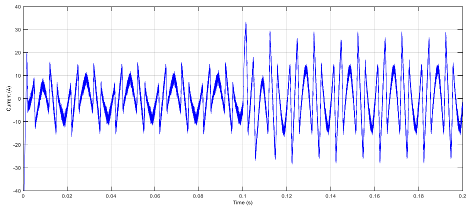

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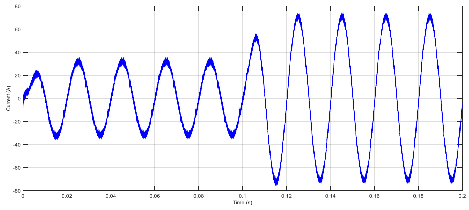

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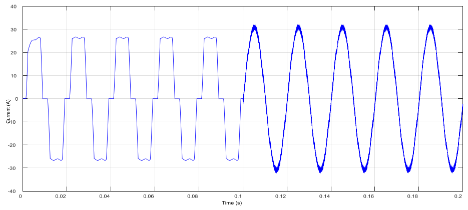
Fig 7. Load, injection and source current



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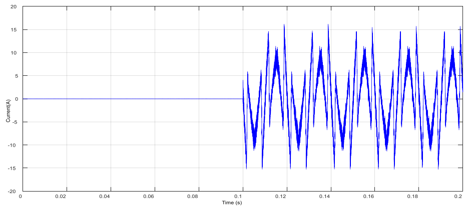

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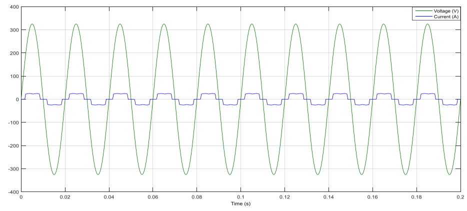
Fig 8. Injection, source current



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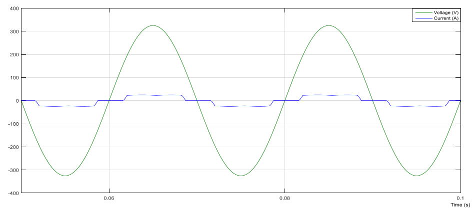
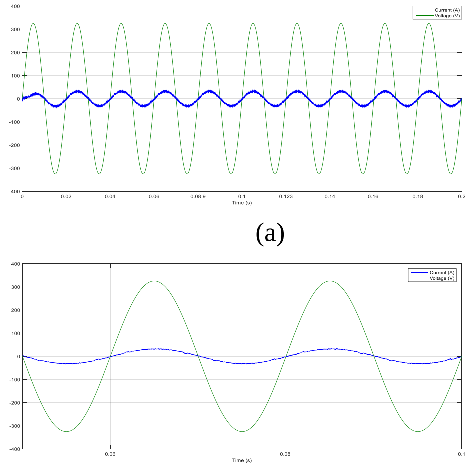


(b)

Fig 9. Delay phase between voltage and current before using UPQC



(a)

(b)

Fig 10. Delay phase between voltage and current after using UPQC

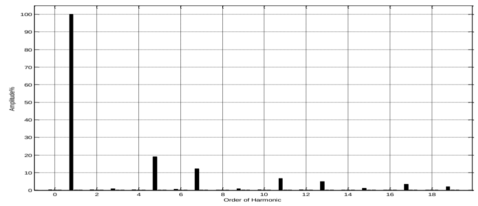


Fig 11. Harmonic spectum befor using UPQC

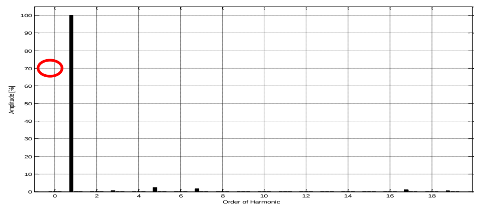


Fig 12. Harmonic spectrum after using UPQC

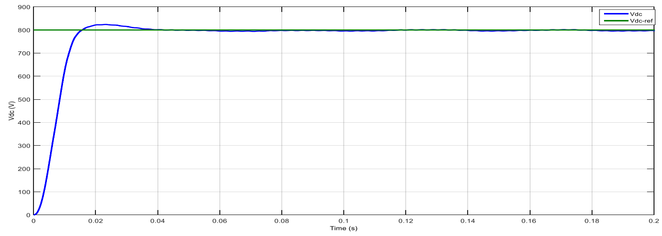


Fig 13. DC Bus with backstepping controller

In order to test the efficiency of the series part of our UPQC device we cause a fault which is a voltage sag between 0.4s and 0.6s as shown in the Fig. 14.

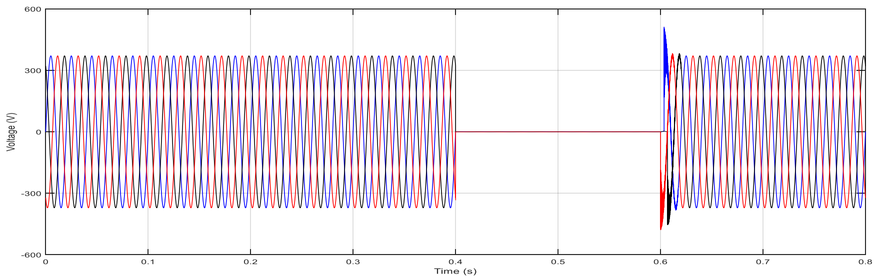


Fig 14. Sag voltage between 0.4 s and 0.6 s

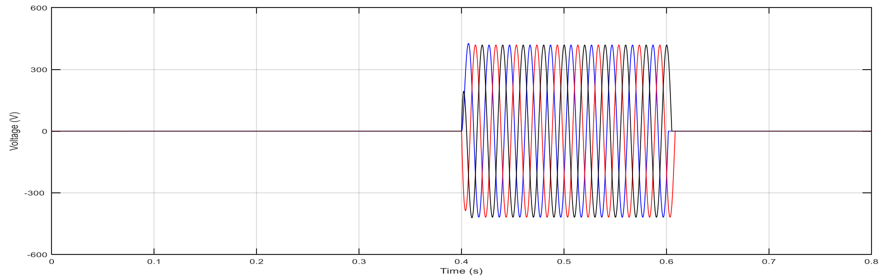


Fig 15. Voltage injected for sag voltage compensation

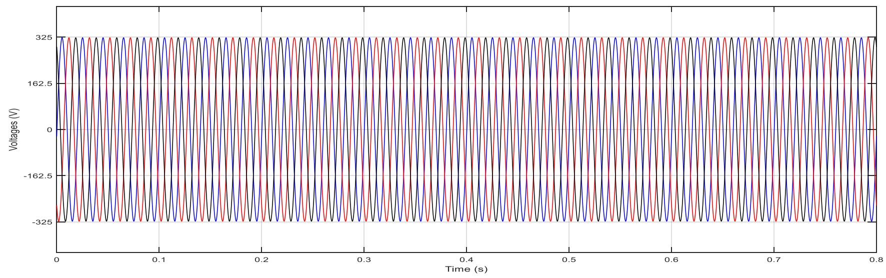


Fig. 16. Voltages after compensation

4. Discussions

- We notice a great degradation of the waveform of the source current (Fig. .6.a), because of the presence of the nonlinear load (polluting).
- According to Fig. (11), the current harmonic spectrum shows the existence of odd type harmonics not multiple of three (5, 7, 11, 13, 17 and 19) with significant amplitudes. We note a very high harmonic distortion rate (THD), **26.21%** which is higher than the standard norm
- According to the Fig. (9.a&b) we note the existence of a delay phase between the current and the source voltage which explains the existence of reactive power which degrade the power factor.
- We notice a great improvement in the waveform of the source current (Fig. 6.b), and that comes down to the shunt part of the UPQC which injects an equal current and in phase opposition (Fig. 6 c).
- We note that the rate of harmonic distortion (THD) decreases in a very remarkable value ,we record **2.35%.**
- From the Figs. (10 a and b) we notice that the delay phase between the current and the source voltage disappears which explains the total compensation of the reactive energy and the correction of the power factor.

- The results obtained during the dynamic regime (variation of the load) show that our UPQC adapts with this variation and continues the filtering of the harmonics and the compensation of the reactive power (Figs. 7).
- The DC bus voltage V_{dc} at the terminals of the capacitor is kept constant, and it follows its reference value ($V_{dc\text{-}ref}$ = 800V) which shows the robustness of our regulation used.
- Fig. (15) shows the waveforms of the voltage injected by the series part of our UPQC which completely compensates for the voltage sag problem presented in Fig. (14) in order to obtain balanced and sinusoidal voltages (Fig. 16).

5. Conclusion

In this paper, we investigated a unified photovoltaic power quality conditioner (UPQC), using MATLAB's Simulink environment. This device presented consists of the association of two filters (shunt and series) fed by a single DC bus source. The UPQC proposed in this work compensates for the harmonic currents, and the reactive power by its shunt part, while its series part compensates for the disturbance of the voltage such as the voltage sag. The simulation results obtained show good performance of the UPQC for the compensation of harmonic disturbances; there is a significant decrease in the Total Harmonic Distortion of current as well as reactive power and voltage sag.

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