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An Investigation into Harmonic Compensation using UPQC

***Abstract**. Due to recent advances in power electronics, many non-linear loads absorb non-sinusoidal or deformed currents from the power supply (harmonics generation). The reduction of this harmful distortion produced by these non-linear loads is very important in an electrical system. In this paper we present a Unified Power Quality Conditioner (UPQC) for the compensation of these voltage and current harmonic disturbances. Generally, UPQC has been considered as a source of current and voltage connected to the load (harmonic source). The approach is based on the principle of injection of harmonic current and voltage in the system, the same amplitude and the same inverse phase as the load current and voltage harmonics. In this article, we will present the operating principle of the UPQC and its modelling. The simulations results in the Matlab-Simulink environment show the efficiency of this device studied.*

***Streszczenie.** Ze względu na najnowsze postępy w energoelektronice wiele obciążeń nieliniowych pochłania z zasilacza prądy niesinusoidalne lub odkształcone (generowanie harmonicznych). Redukcja szkodliwych zniekształceń wytwarzanych przez obciążenia nieliniowe jest bardzo ważna w systemie elektrycznym. W tym artykule przedstawiamy ujednolicony kondycjoner jakości energii (UPQC) do kompensacji zakłóceń harmonicznych napięcia i prądu. Ogólnie rzecz biorąc, UPQC uznano za źródło prądu i napięcia podłączone do obciążenia (źródło harmonicznych). Podejście opiera się na zasadzie wstrzykiwania do układu harmonicznych prądu i napięcia, o tej samej amplitudzie i tej samej fazie odwrotnej, co harmoniczne prądu i napięcia obciążenia. W tym artykule przedstawimy zasadę działania UPQC i jej modelowanie. Wyniki symulacji w środowisku Matlab-Simulink pokazują wydajność badanego urządzenia. (**Badanie kompensacji harmonicznej przy użyciu UPQC**)*

Keywords: Harmonics, Unified Power Quality Conditioner (UPQC), shunt active power filter, p-q theory, series active power filter.
Słowa kluczowe: Harmoniczne, ujednolicony kondycjoner jakości mocy (UPQC), bocznikowy filtr mocy czynnej, teoria p-q.

Introduction

The quality of the electrical power is sensitive to the harmonic distortion, the latter present's one of the main disturbances of the quality of power supply, following the development of the power electronics and the appearance of the nonlinear loads, often encountered by the Utilities, such as thyristor power converters, rectifiers, arc furnaces... [1]. the presence of harmonics leads to electromagnetic interference and solid-state device malfunction, transformer heating. Hence, it is necessary to reduce the dominant harmonics below 5% as specified in IEEE 519-1992 harmonic standard [2].Hence increased severity of harmonic pollution problem attracted the attention of power electronics experts in last one decade and large numbers of publications have appeared on the development of equipment named as Active Power Filter (APF) to provide a dynamic adjustable solution to eliminate harmonics in ac mains [3] the APF allow to compensating the harmonics and unbalance, together with power factor correction. Modern active harmonic filters have superior filtering characteristics, smaller in physical size, more flexible in application compared to their passive counterparts. They are widely used in industrial, commercial, utility networks and in electric traction systems [4]. Active power filters can be classified according to their configurations, or their electronic power circuits or finally after their process control strategies. In general, they are divided into three main categories, namely shunt APF, series APF and hybrid APF [5][6].The APFs control has two main blocks: the first one generates the control reference signals and the second one carries out the control method [7].The harmonic compensation performance of an active filter depends mainly on the technique used to compute the reference, the design of inverter and the control method used to inject the desired compensation into the line [8]. Among the active filters is the UPQC. The unified power quality conditioner (UPQC) is a kind of improvement devices with comprehensive compensation ability, which has functions of voltage recovering, harmonics and reactive power compensating. They are always installed on PCC in distribution system or important power supply inlet to restrain the voltage and current quality problems[9].In this paper the model and control strategy of UPQC is presented.

General structure Unified Power Quality Conditioner

A conventional UPQC topology is developed with the combination of series active filter and shunt active filter connected back-to-back with common dc-link bus capacitor. The dc link capacitor reduces dc ripple current [10] [11]. The function of the shunt active filter keeps the source current constant when a nonlinear load is connected, so that it does not affect any other load connected to the system. The series active filter is to mitigate any harmonics in source voltage and always provides three phase balanced sinusoidal voltage to the load. It also maintains the load voltage constant when there is voltage flicker [12]. The basic configuration diagram of UPQC is shown in Fig.1

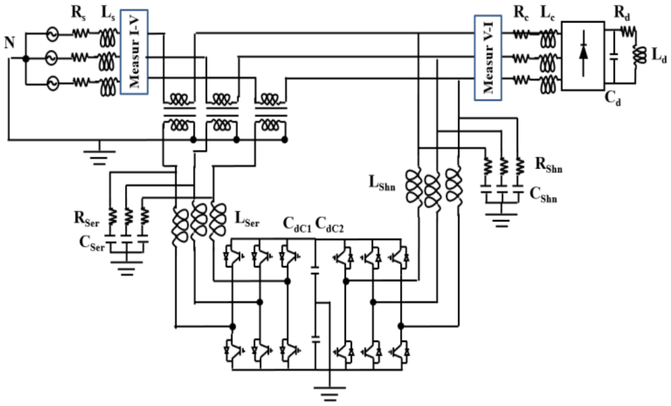

Fig.1. Basic Configuration of UPQC

Reference Current Signal Generation for Shunt APF

The principle of the control strategy for shunt active power filter is to generate the reference current produced by the power filter to compensate for the harmonic currents required by the load [13]. In 1983, Akagi et al. have proposed the "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as p-q theory. It is based in instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms [14].The p-q theory implements a transformation from a stationary reference system in a-b-c coordinates, to a system with coordinate's α-β. It corresponds to an algebraic transformation, known as Clarke transformation, which also produces a stationary reference system, where coordinates α-β are orthogonal to each [15].The voltages and currents in α-β-0 coordinates are calculated as follows:

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{1}$$

Thus:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \tag{3}$$

The instantaneous real and imaginary power is:

$$\begin{cases} p = v_\alpha i_\alpha + v_\beta i_\beta \\ q = v_\alpha i_\beta - v_\beta i_\alpha \end{cases} \tag{4}$$

Rewriting equation (4) in a-b-c coordinates the following expression is obtained:

$$\begin{cases} p = v_{sa} i_{la} + v_{sb} i_{lb} + v_{sc} i_{lc} \\ q = -\frac{1}{\sqrt{3}} \left[(v_{sa} - v_{sb}) i_{lc} + (v_{sb} - v_{sc}) i_{la} + (v_{sc} - v_{sa}) i_{lb} \right] \end{cases} \tag{5}$$

If we put:

$$\Delta = v_\alpha^2 + v_\beta^2 \tag{6}$$

From expression (4):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \left(\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \right) \tag{7}$$

When the voltages are sinusoidal and supplying a nonlinear load, the instantaneous power p and q are expressed as:

$$\begin{cases} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{cases} \tag{8}$$

With:

$\bar{p}, \bar{q}$: Mean value of instantaneous real and imaginary power.

$\tilde{p}, \tilde{q}$: Alternating value of instantaneous real and imaginary power.

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

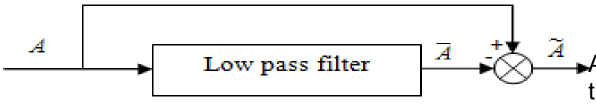

Fig.2. Principle of extraction the component alternative of p and q

If replaced in (7), we find:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} + \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} 0 \\ \bar{q} \end{bmatrix} + \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{9}$$

So the harmonic current will be determined by the relationship:

$$\begin{bmatrix} i_{\alpha,h} \\ i_{\beta,h} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{10}$$

If the inverse transformation is applied (Fig. 4), we write:

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

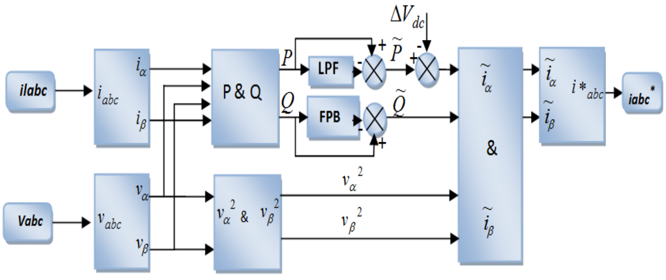

Fig.3. Principle of the p-q method

Reference voltage signal generation for series APF

Series active power filters are operated mainly as a voltage regulator and as a harmonic isolator between the nonlinear load and the utility system. by imposing a high impedance path to the current harmonics which forces the high frequency currents to flow through the LC passive filter connected in parallel to the load and gives obstruction to their stream from both load to source and source to load headings and in this manner goes about as a controlled voltage source[16,17]. The series APF control algorithm calculates the reference value to be injected by the series APF transformers, comparing the positive-sequence component with the load side line voltages. [18] The d-q-o theory is proposed for reference voltage signal generation. There are five steps to calculate the reference [19]:

Step 1: Transform the three-phase voltage (Va, Vb and Vc) to αβ0 frame (Vα, Vβ and V0) by:

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{12}$$

Step 2: Transform the Vα and Vβ to the dq-axis by:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{13}$$

Step 3: the dq voltage consist of two terms:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \bar{V}_d + \tilde{V}_d \\ \bar{V}_q + \tilde{V}_q \end{bmatrix} \tag{14}$$

When $\bar{V}_d, \bar{V}_q$ and $\tilde{V}_d, \tilde{V}_q$ are the DC components and AC component of the voltage on dq-frame, respectively. For this step, the high-pass filter (HPF) is used to separate the harmonic $(\tilde{V}_d, \tilde{V}_q)$ components from the dq voltage (V_d, V_q). Step 4: Transform the harmonic voltage on dq-frame $(\tilde{V}_d, \tilde{V}_q)$ from Step 3 to αβ-frame $(\tilde{V}_\alpha, \tilde{V}_\beta)$ by:

$$\begin{bmatrix} \tilde{V}_\alpha \\ \tilde{V}_\beta \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} \tilde{V}_d \\ \tilde{V}_q \end{bmatrix} \tag{15}$$

Step 5: Calculate the three-phase reference voltage (Va*,Vb*,Vc*)

(16) $$\begin{bmatrix} V_a^* \\ V_b^* \\ V_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} \tilde{V}_\alpha \\ \tilde{V}_\beta \\ \tilde{V}_0 \end{bmatrix}$$

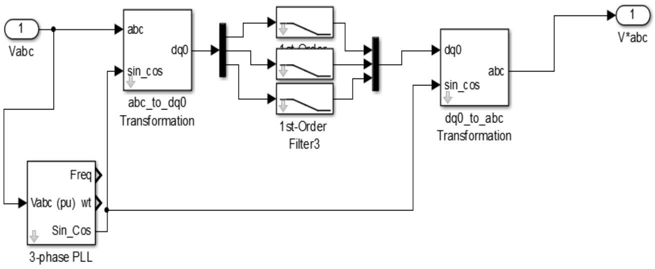

Fig.4. Principle algorithm of the synchronous fundamental dq-frame

Hysteresis control

The hysteresis band current control technique has proven to be most suitable for all the applications of current controlled voltage source inverters in active power filters. The hysteresis band current control is characterized by unconditioned stability, very fast response, and good accuracy [20, 21].It imposes a bang-bang type instantaneous control that forces the UPQC compensation current (if) or voltage (vf) signal to follow its estimated reference signal (if,ref or vf,ref) within a certain tolerance band. This control scheme is shown in a block diagram form in Figure 06 [22, 23, 24, 25, 26, 27].

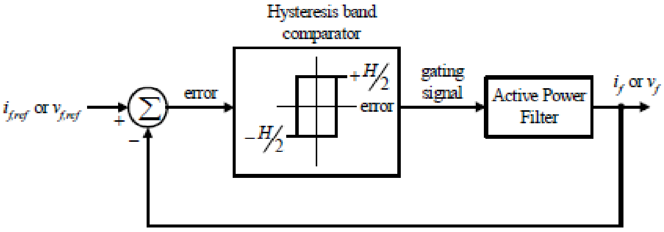

Fig.5. Conventional hysteresis band current controller

Simulation results

The module used for the simulations (See Fig.6) has the following parameters TABLE.1.

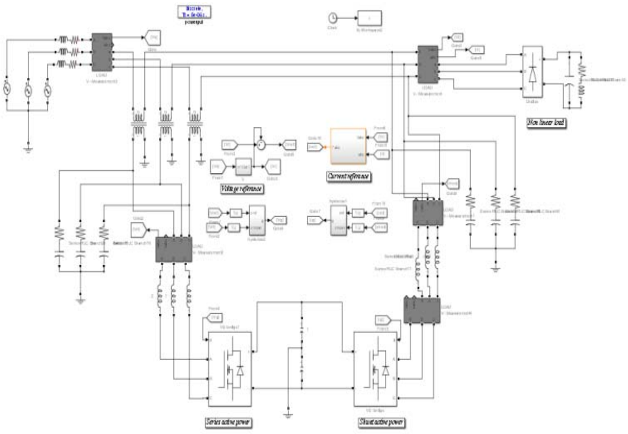

Fig.6. Module used for the simulations in MATLAB/SIMILINK

Table 1. Module parameters

Parameter		Values
Power Source	Voltage source (Vs)	400 V
	frequency (F)	50 Hz
	Source resistance (Rs)	0.5Ω
	Source inductance (Ls)	3m H
Non-linear load	Load resistance (Rd)	10Ω
	Load inductance (Ld)	10mH
	Load capacitor (Cd)	0.24µF
Shunt active filter	Filter inductance (Lshn)	3.5mH
	Filter resistance (Rshn)	5 Ω
	Filter Capacitor (Cshn)	10 µF
DC Link	Voltage reference (Vdcref)	700V
	Two series Capacitor (Cdc1,Cdc2)	2200 µF
Series active filter	Filter inductance (Lser)	3.5mH
	Filter resistance (Rser)	5 Ω
	Filter Capacitor (Cser)	20 µF
	series Transformer	1KVA

In the simulation study, we assume that the source voltages are balanced to show the dynamic response of FAS with two identification methods namely pq and dq controlled by hysteresis.

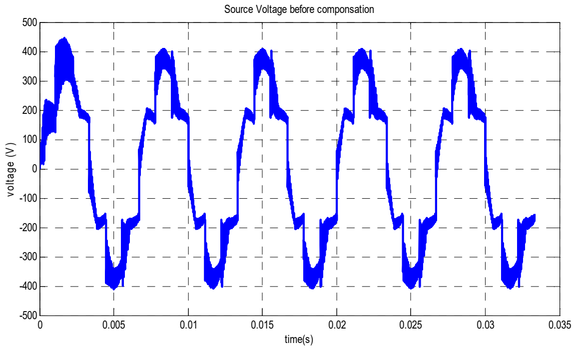

Fig.7. Source voltage before compensation

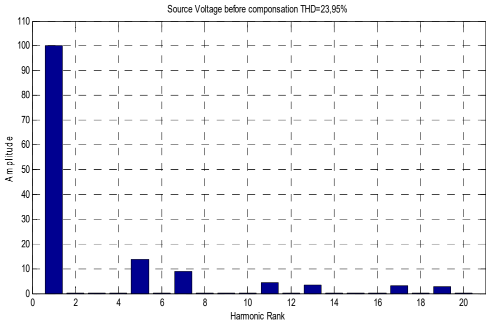

Fig.8. Harmonic spectrum of source voltage before compensation

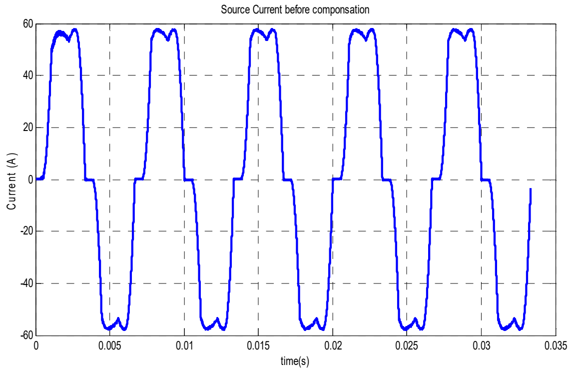

Fig.9. Source current before compensation

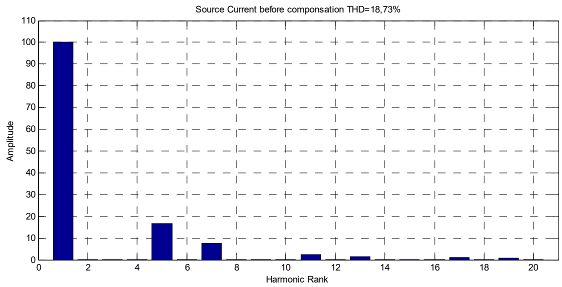

Fig.10. Harmonic spectrum of source current before compensation

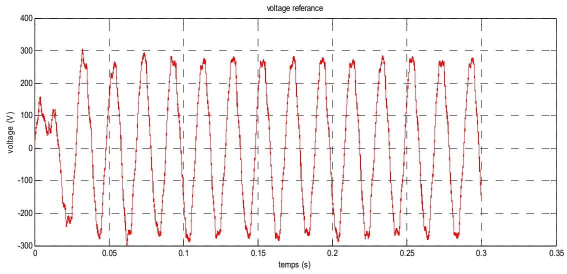

Fig.11. Harmonic voltage

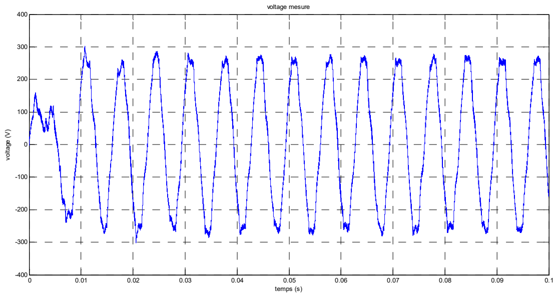

Fig.12. Voltage injected by UPQC

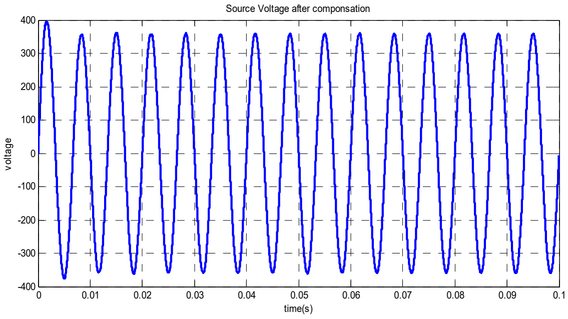

Fig.13. Source voltage after compensation

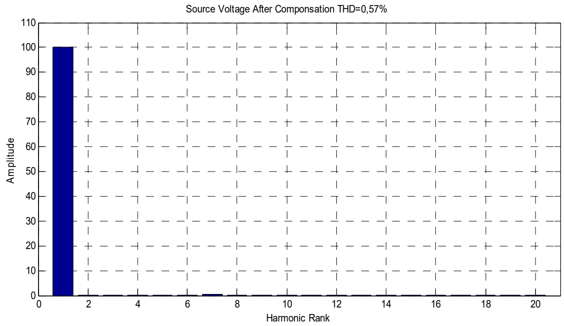

Fig.14. Harmonic spectrum of source voltage after compensation

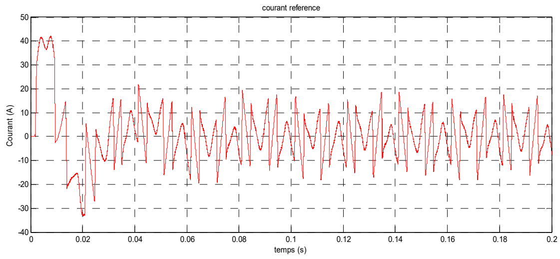

Fig.15. Harmonic Current

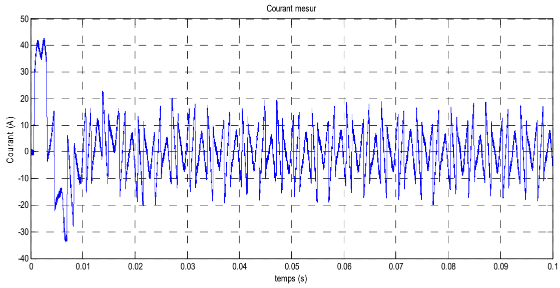

Fig.16. Current injected by UPQC

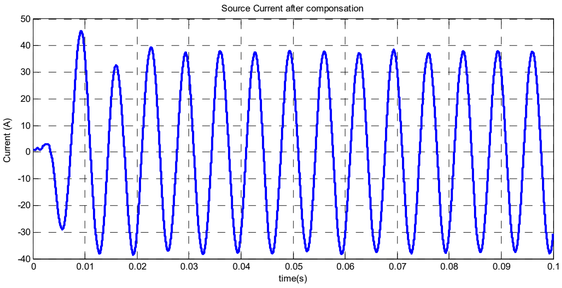

Fig.17. Source current before compensation

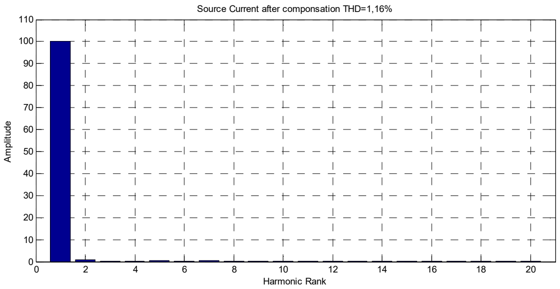

Fig.18. Harmonic spectrum of source current after compensation

DISCUSSION

The simulation results obtained are shown in figures 7 to 18.- Figures 7 and 9 show the waveform of the voltage and the current of the source before the compensation, where we have clearly seen the deformation of their waveform.- According to figures 9 and 10, high values of total harmonic distortion (THD) of the voltage and current source are noted which are respectively 23.99% for the source voltage and 18.73% for the current source higher than the IEEE Standards 519.- After using our proposed device (UPQC), we notice a remarkable improvement on the waveform of the source voltage and the source current, which are becoming almost sinusoidal, as shown in figures 13 and 17, where we noted lower THD values (0.57% for the voltage and 1.16% for the current), which is well within the norm.

Conclusion

This article presents a Unified Power Quality Conditioner (UPQC), the system was designed and modelled successfully using the Matlab / Simulink. The Unified Power Quality Conditioner consists of combined of active power filters series and shunt for simultaneous compensation of the voltage and current harmonic. The simulation results show that the UPQC is a reliable, efficient solution for compensation of harmonics problems , because we obtain at the end of the reduced, acceptable values of THD of the voltage and current (under norm used).

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