Active Power Filter for Power Compensation Under Non-Ideal Mains Voltages

Engin Özdemir, *Member, IEEE*, Murat Kale, Şule Özdemir

Abstract **In this paper, a new Active Power Filter (APF) control scheme has been proposed to improve the performance of the APF. This paper presents a new technique with instantaneous power theory (p-q theory) in order to control of APF under non-ideal mains voltage conditions. Performance of the proposed scheme has been found feasible and excellent to that of the instantaneous reactive power algorithms under various non-ideal mains test scenarios. MATLAB/SIMULINK power system toolbox is used to simulate the proposed system. The proposed method's performance is compared with conventional instantaneous power (p-q) theory. The simulation results are presented and discussed showing the effectiveness of the control algorithm.**

Index Terms- **Active power filter, non-ideal mains voltage, instantaneous power (p-q) theory.**

I. Introduction

In a modern power system, increasing of loads and non-linear equipment's have been demanding the compensation of the disturbances caused for them. These nonlinear loads may cause poor power factor and high degree of harmonics.

Active Power Filter (APF) can solve problems of harmonic and reactive power simultaneously. APF's consisting of voltage-source inverters and a DC capacitor have been researched and developed for improving the power factor and stability of transmission systems. APF have the ability to adjust the amplitude of the synthesized ac voltage of the inverters by means of pulse width modulation or by control of the dc-link voltage, thus drawing either leading or lagging reactive power from the supply. APF's are an up-to-date solution to power quality problems. Shunt APF's allow the compensation of current harmonics and unbalance, together with power factor correction, and can be a much better solution than conventional approach (capacitors and passive filters). The simplest method of eliminating line current harmonics and improving the system power factor is to use passive LC filters. However, bulk passive components, series and parallel resonance and a fixed compensation characteristic are the main drawbacks of passive LC filters.

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In APF design and control, instantaneous reactive power theory was often served as the basis for the calculation of compensation current [1]. In this theory, the mains voltage was assumed to be an ideal source in the calculation process. However, in most of time and most of industry power systems, mains voltage may be unbalanced and/or distorted. In this theory, non-ideal mains voltages affect all line currents, under such scenario.

The *pq* theory, since its proposal, has been applied in the control of three-phase active power filters [1]. However, power system voltages being often non-ideal, in distorted voltage systems the control using the *pq* theory does not provide good performance [2]. The proposed control algorithm gives adequate compensating current reference even for non-ideal voltage system. Consequently, this paper is primarily concerned with the development of APF performance under non-ideal or distorted mains voltage. This paper presents a new technique with instantaneous power theory (p-q theory) as a suitable method to the analysis of non-linear three-phase systems and for the control of APF. Performance of the proposed scheme has been found feasible and excellent to that of the instantaneous reactive power algorithms under various non-ideal mains test scenarios.

As mentioned in other section of the paper, in Turkish electrical energy distribution system harmonic problems caused by power electronic devices are very important. Inherently, mains voltages usually have non-ideal waveforms, and have different levels of harmonics. As shown in Fig. 3 mains voltages have 3., 5., 7. and 11. harmonics.

II. ACTIVE POWER FILTER

Fig.1 shows basic APF block diagram including non-linear load on three-phase supply condition. In this study, three-phase uncontrolled diode bridge rectifier with resistive loading are considered as a non-linear load on three phase ac mains. This load draws non-sinusoidal currents from ac mains.

APF overcome the drawbacks of passive filters by using the switching mode power converter to perform the harmonic current elimination. Shunt active power filters are developed to suppress the harmonic currents and compensate reactive power simultaneously. The shunt active power filters are operated as a current source parallel with the nonlinear load. The power converter of active power filter is controlled to generate a compensation current, which is equal but opposite the harmonic and reactive currents generated from the nonlinear load. In this situation, the mains current is sinusoidal and in phase with mains voltage.

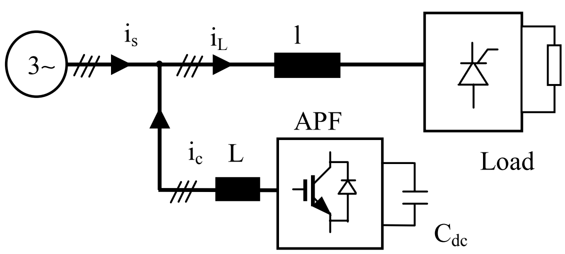

Fig. 1. Block diagram of APF.

A voltage source inverter having IGBT switches and an energy storage capacitor on DC bus is implemented as a shunt APF. The main aim of the APF is to compensate harmonics, reactive power and to eliminate the unwanted effects of non ideal ac mains supplies only unity power factor sinusoidal balanced three-phase currents.

III INSTANTANEOUS POWER THEORY

In three-phase circuits, instantaneous currents and voltages are converted to instantaneous space vectors. In instantaneous power theory, three-phase currents and voltages are calculated as following equations. These space vectors are easily converted to α-β coordinates [2].

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

In equation (1) and (2), α and β are orthogonal coordinates. e_α and i_α are on α axis, e_β and i_β are on β axis. In three-phase conventional instantaneous power is calculated as follows:

$$p = e_\alpha . i_\alpha + e_\beta . i_\beta \tag{3}$$

In fact, active power (p) is equal to following equation:

$$p = e_a . i_a + e_b . i_b + e_c . i_c \tag{4}$$

Instantaneous real and imaginer powers are calculated as equation (5).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{5}$$

In equation (5), $e_\alpha . i_\alpha$ and $e_\beta . i_\beta$ are instantaneous powers. Since these equations are products of instantaneous currents and voltages in the same axis. In three-phase circuits, real instantaneous active power is p and its unit is watt (VA). In contrast $e_\alpha . i_\beta$ and $e_\beta . i_\alpha$ are not instantaneous powers. Since these are products of instantaneous current and voltages in two orthogonal axis. q is not conventional electric unit like W or Var. q is instantaneous imaginary power.

Equation (5) can be written as equation (6).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \tag{6}$$

From equation (6), instantaneous compensating currents on α and β coordinates, are given by,

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \tilde{p} \\ -q \end{bmatrix} \tag{7}$$

IV. THE PROPOSED METHOD

The block diagram of Fig. 2 presents the calculations required in this method. The proposed method block diagram is depicted in Fig. 2.

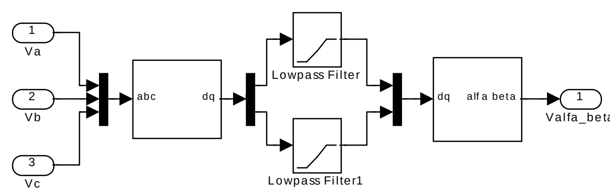

Fig. 2. Block diagram of the proposed method.

The proposed method must be used when the voltages are distorted or unbalanced and sinusoidal currents are desired. Schematic diagram of proposed method controlled shunt APF is shown in Fig. 3.

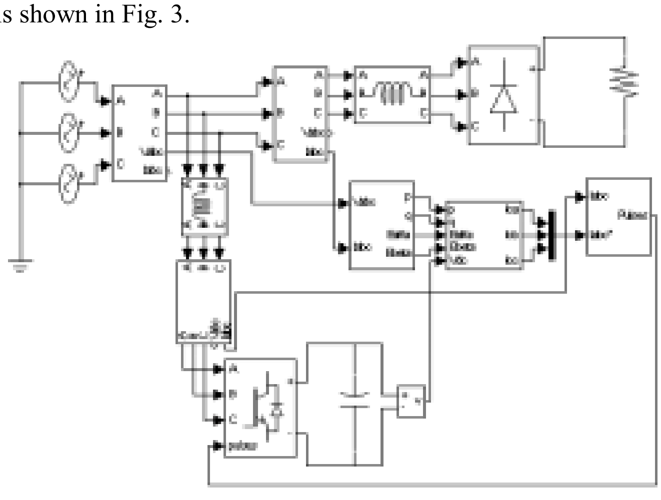

Fig. 3. Schematic diagram of shunt APF.

In proposed method, instantaneous voltages are first converted to α-β coordinates and then to stationary d-q coordinates. The produced d-q components of voltages are filtered and reverse converted α-β coordinates (as expressed in equation 8). These filtered α-β components of voltages are used in conventional instantaneous power theory (equation 6).

Hence, the non-ideal mains voltages are converted to ideal sinusoidal shape by using low pass filter in d-q coordinates. So, the mains voltages assumed to be an ideal source in the calculation process.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos\varphi & -\sin\phi \\ \sin\phi & \cos\varphi \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \tag{8}$$

The three-phase reference currents, which the active power filter configuration should supply to the three-phase actual power system, should be obtained. These reference currents, calculated by the control algorithm equations should be supplied to the power system by switching of the power transistors of the inverter. The method for generation of the switching pattern is achieved by the instantaneous current control of the active power filter line currents. The actual active power filter line currents are monitored instantaneously, and then compared to the reference currents generated by the control algorithm. In order to get precise instantaneous current control, the current control method must supply quick current controllability, thus quick response. For this reason, a hysteresis band current control, for active power filter line currents, can be implemented to generate the switching pattern the inverter. There are various current control methods proposed for such active power filter configurations, but in terms of quick current controllability and easy implementation hysteresis band current control method has the highest rate among other current control methods such as sinusoidal PWM. Hysteresis band current control is the fastest control with minimum hardware and software but even switching frequency is its main drawback.

V. SIMULATION RESULTS

The presented simulation results were obtained by using Matlab Simulink Power System Toolbox software, for a three-phase power system with a shunt APF. The proposed method has been simulated under three scenarios, including ideal mains voltage, unbalanced three-phase mains voltage and distorted mains voltage condition. The simulation results are discussed below.

A. Ideal Mains Voltage

Fig. 4 and Fig. 5 show the simulation results of this algorithm under ideal mains voltages when ohmic loaded three-phase rectifier load is connected. The three-phase mains currents after compensation are balanced sinusoidal and in phase with three-phase mains voltages. The instantaneous reactive power theory and proposed method are feasible. After compensation the THD of source current is reduced to 3.7% from 27.6%.

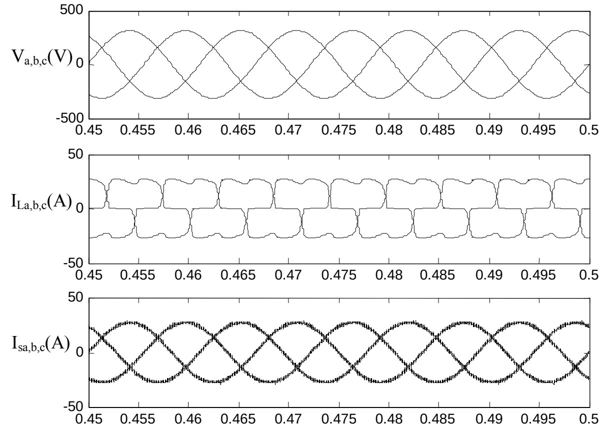

Fig. 4. Ideal mains voltage simulation results with proposed method.

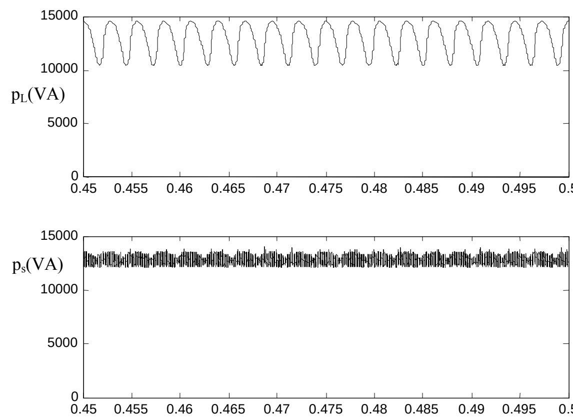

Fig. 5. Load and supply active power variations with ideal mains voltage with proposed method.

B. Unbalanced three-phase voltages

When the three-phase mains voltages are unbalanced, the mains voltage can be expressed as positive and negative sequence components. For this case, the unbalanced three-phase mains voltages are:

$$\begin{aligned} e_{ua} &= 311\sin(\omega t) + 31\sin(\omega t) \\ e_{ub} &= 311\sin(\omega t - 120^o) + 31\sin(\omega t + 120^o) \\ e_{uc} &= 311\sin(\omega t + 120^o) + 31\sin(\omega t - 120^o) \end{aligned} \tag{9}$$

Fig. 6 and 7 show simulation results of 10% unbalanced mains voltages scenario with proposed method and pq theory respectively. The three-phase compensated mains currents are non-sinusoidal and unbalanced in instantaneous power theory The compensated mains currents are sinusoidal in proposed method in unbalanced mains voltages case. Total Harmonic Distortion (THD) of source current after compensation is 10.5% and 3.7% with conventional and the proposed methods respectively. Proposed method has very good harmonic limit imposed by the IEEE-519 standard. Fig. 8 and Fig. 9 show load and source instantaneous active and reactive power waveforms with p-q theory respectively. The total instantaneous active power supplied has high ripple content.

Fig. 10 and Fig. 11 show load and source instantaneous active and reactive power waveforms with proposed method respectively. The total instantaneous active power supplied is not made constant, but it presents only a small ripple. The total instantaneous reactive power is almost zero and has only a small ripple.

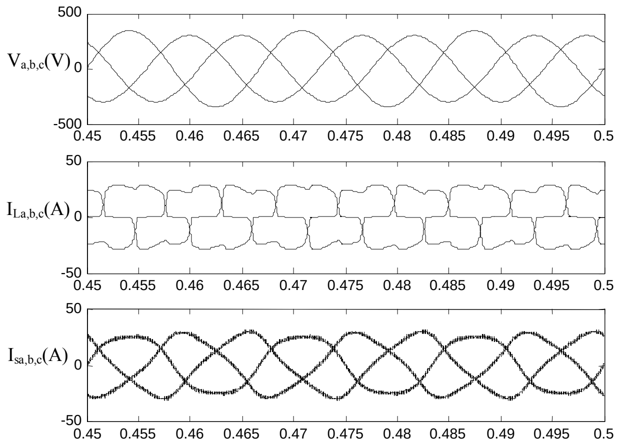

Fig. 6 . Unbalanced mains voltage simulation result with pq theory.

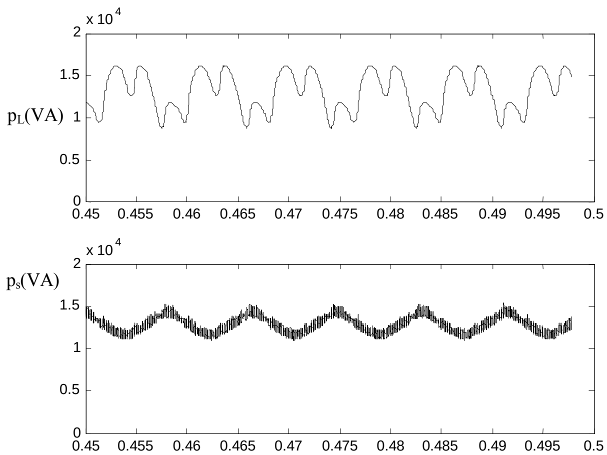

Fig. 7. Load and source instantaneous active power waveforms with pq theory.

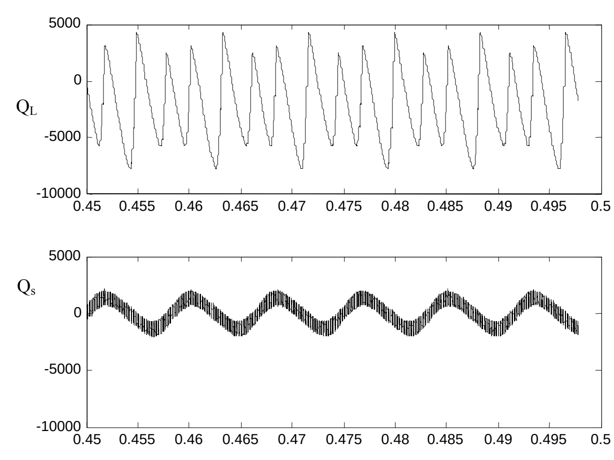

Fig. 8. Load and source instantaneous reactive power waveforms with proposed method.

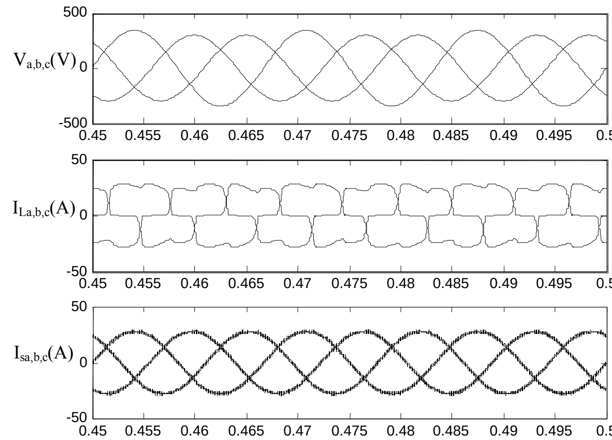

Fig. 9. Unbalanced mains voltage simulation result with proposed method.

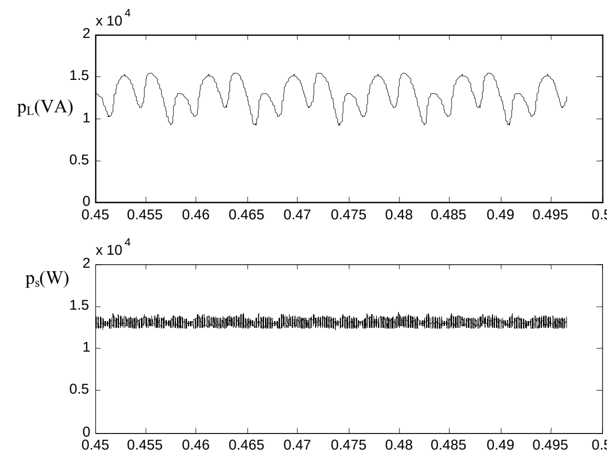

Fig. 10. Load and source instantaneous active power waveforms with proposed method.

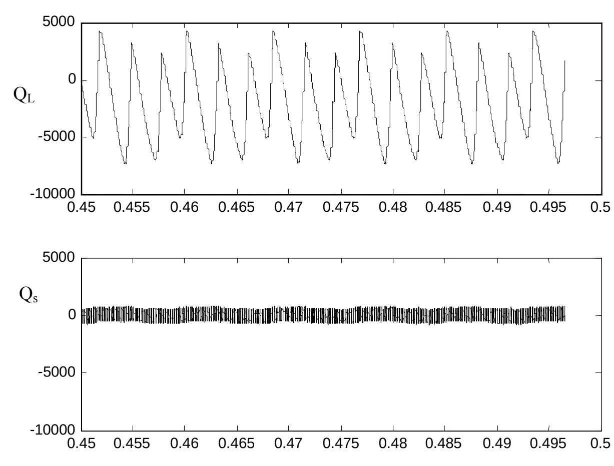

Fig. 11. Load and source instantaneous reactive power waveforms with proposed method.

From the Figures, mains currents are balanced and sinusoidal after compensation. The voltage unbalanced in e three-phase system will not affect the APF performance.

C. Distorted Mains Voltages

When the three-phase mains voltages are distorted, the mains voltages have harmonic components and unbalanced. In order to simulate a real case distortion level, mains voltages are measured with a harmonic analyzer. The measured real mains voltage, THD level and its harmonic spectrum is shown in Fig. 12. The mains voltages have dominant fifth harmonic component and %10 unbalanced. For this case, the distorted three-phase mains voltages are expressed as:

$$
\begin{aligned}
& e_{da} = 311\sin(\omega t) + 31\sin(\varpi t) + 4\sin(3\omega t) + 18\sin(5\omega t) + \\
& 4.6\sin(7\omega t) + 3.1\sin(11\omega t) \\
& e_{db} = 311\sin(\omega t - 120^o) + 31\sin(\omega t + 120^o) + 4\sin(3\omega t - 120^o) + \\
& 18\sin(5\omega t - 120^o) + 4.6\sin(7\omega t - 120^o) + \\
& 3.1\sin(11\omega t - 120^o) \\
& e_{dc} = 311\sin(\omega t + 120^o) + 31\sin(\omega t - 120^o) + 4\sin(3\omega t - 240^o) + \\
& 18\sin(5\omega t - 240^o) + 4.6\sin(7\omega t - 240^o) + \\
& 3.1\sin(11\omega t - 240^o)
\end{aligned}
\tag{10}
$$

Fig. 13 and Fig. 14 show simulation results of distorted mains voltages scenario with and without proposed algorithm respectively. The performance of the instantaneous power algorithm for this case is shown not qualified. The three-phase compensated mains currents have 16.1% THD level in instantaneous power theory. After compensation, these currents have sinusoidal waveform and have 3.7% THD level for proposed method in distorted mains voltages scenario a smaller value than that is regulated by any power quality standard. There is a significant reduction in harmonic distortion level. Average switching frequencies are 27.9 KHz and 21.2 KHz with conventional and the proposed method respectively. Fig. 15 and Fig. 17 show load and source instantaneous active and reactive power waveforms with proposed method respectively. Fig. 16 shows load and source instantaneous active power waveforms with instantaneous power theory. The total instantaneous active power supplied is not made constant, but it presents only a small ripple. The total instantaneous reactive power is almost zero and has only a small ripple. The unsymmetrical distorted voltage system is the most severe condition. However, good results can be obtained by the proposed theory.

The design specifications and the essential parameters of the system used in the simulation are indicated in Table I.

TABLE 1.
THE PARAMETERS OF THE SYSTEM

Parameter	Value
V_s(rms/phase) (V)	220
f(Hz)	50
R_L (ohm)	20
C_{DC} (µF)	1500
L (mH)	1
V_{DC} (V)	600

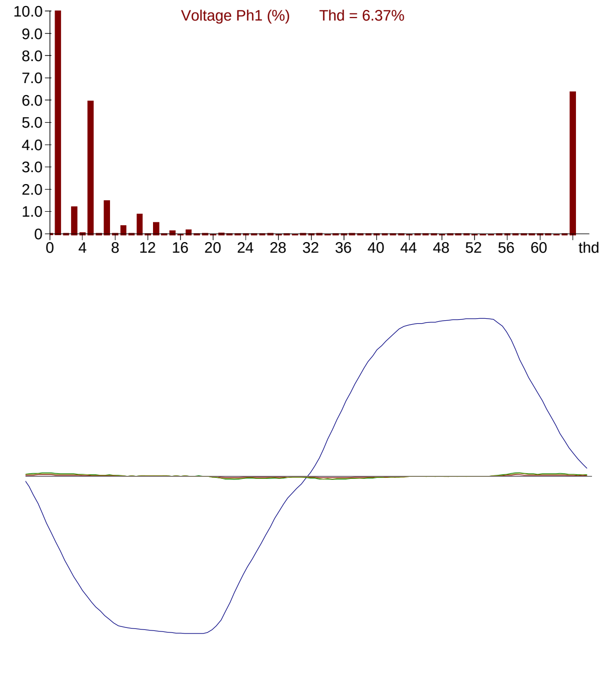

Fig. 12. Measured mains voltage and THD level.

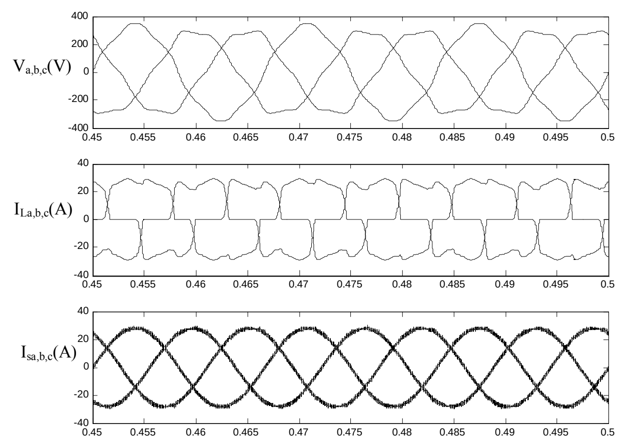

Fig. 13. Distorted mains voltage simulation result with proposed method.

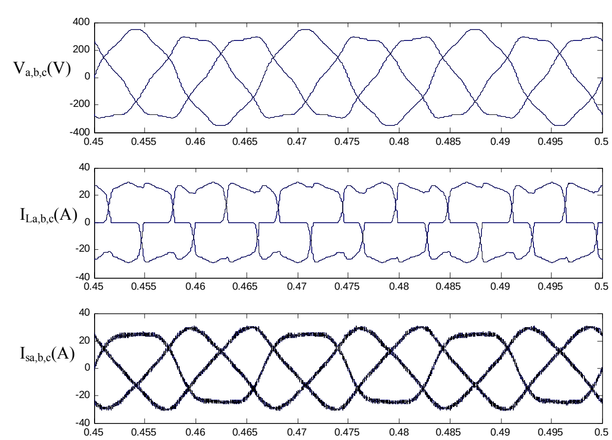

Fig. 14. Simulation results with instantaneous power theory for distorted mains voltages.

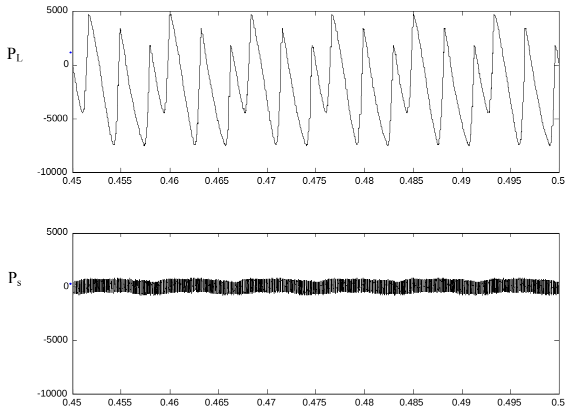

Fig. 15. Load and sources instantaneous active power variations with proposed method for distorted mains voltages.

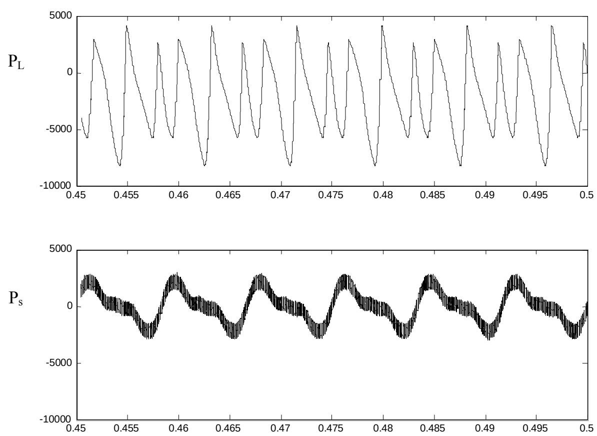

Fig. 16. Load and sources instantaneous active power variations with instantaneous power theory for distorted mains voltages.

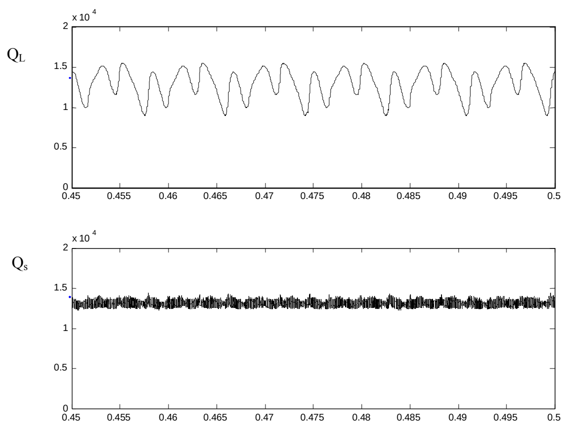

Fig. 17. Load and sources instantaneous reactive power variations with proposed method for distorted mains voltages.

Above figures show that the actual currents are almost agree with the reference currents. In an unsymmetrical or distorted voltage system, the results obtained by the *pq* theory are not good. However, the proposed theory gives good results for both a non-ideal voltage system and a distorted voltage system. In the proposed method, the distorted mains voltages do not affect the compensated mains current.

When this new approach is used the simulation results can be summarized as follows:

- the phase supply currents become sinusoidal, balanced, and in phase with the fundamental voltages;
- the neutral current is made nearly equal to zero;
- the total instantaneous active power supplied is not made constant, but it presents only a small ripple.
- the total instantaneous reactive power is almost zero and has only a small ripple.

VI. CONCLUSION

In this paper, a new APF control scheme has been proposed to improve the performance of APF under non-ideal mains voltage scenarios. The computer simulation has verified the effectiveness of the proposed control scheme. Experimental results in a scaled-down laboratory prototype will be done and reported in future paper. From the simulation results, the proposed approach was very successful and easily implemented. Active power filters, based on the proposed theory, give satisfactory operation even when the system phase voltages are unsymmetrical and distorted, because no distortion appears in the line currents. The APF is found effective to meet IEEE 519 standard recommendations on harmonics levels in all of the non-ideal voltage conditions. The switching frequency and also switching losses are reduced %23 in proposed method. The total instantaneous active power supplied is not made constant, but it presents only a small ripple. The total instantaneous reactive power is almost zero and has only a small ripple.

VII. ACKNOWLEDGEMENT

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