ISTANBUL UNIVERSITY –
JOURNAL OF ELECTRICAL & ELECTRONICS ENGINEERING

YEAR : 2008 (759-767)
VOLUME : 8
NUMBER : 2

A NOVEL THEORY OF REFERENCE REACTIVE CURRENT IDENTIFICATION BASED ON THE PER UNIT SYSTEM USED FOR THE ACTIVE FILTERS

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ABSTRACT

This paper, presents a new method of reactive current identification. The principle is based on the transformation of the voltage and current of the electrical supply network to the per unit system. The fundamental of the current is then obtained by extraction. This new method is compared to that of the theory pq. Interesting results were obtained with a satisfactory power factor correction.

Keyword: *Active Filter, identification, Per Unit, Power factor, reactive current.*

1. INTRODUCTION

Reactive power is a concept used by engineers to describe the background energy movement in an Alternating Current (AC) system arising from the production of electric and magnetic fields. These fields store energy which changes through each AC cycle. Devices storing energy by virtue of a magnetic field produced by a flow of current are named to reactive power consumers; those storing energy by virtue of electric fields are named reactive power generators.

Power flows, both active and reactive, must be carefully controlled for a power system to operate within acceptable voltage limits. Reactive power flows can give rise to substantial voltage changes across the system, which means that it is necessary to maintain reactive power balances between sources of and load on a 'zonal basis'. Unlike system frequency, which is consistent throughout an interconnected system, voltages experienced at points across the system form a "voltage profile" which is uniquely related to generation and demand at that instant, and is also affected by the prevailing system network arrangements. National Grid is obliged to secure the transmission network to closely defined voltage and stability criteria. This is predominantly achieved through circuit arrangements, transformers and shunt or static compensation.

Most equipments connected to the electric power supply generate or absorb reactive power, but not all can be used economically to control voltage. Principally synchronous generators and specialized compensation equipments are used to set the voltage at particular points in the system, which is realized by control of the reactive power flows.

Received Date: 04.03.2008
Accepted Date: 01.07.2008

2. REACTIVE POWER COMPENSATION PRINCIPLES

In a linear circuit, the reactive power is defined as the ac component of the

instantaneous power, with a frequency equal to 100 / 120 Hz in a 50 or 60 Hz system. The reactive power generated by the ac power source is stored in a capacitor or a reactor during a quarter of a cycle, and in the next quarter cycle is sent back to the power source.
In other words, the reactive power oscillates between the ac source and the capacitor or reactor at a frequency equals to two times the rated value (50 or 60 Hz). For this reason it can be compensated using active power filter (APF), avoiding its flow from the load (inductive or capacitive) to the source, and thus improving voltage stability of the power system. Reactive power compensation can be implemented with parallel or series APF generators.

3. PRESENTATION OF THE THEORY SUGGESTED

The supply voltage, supposed sinusoidal, is considered in per unit system and it represents the image of the fundamental current signal. Calculation of per unit values of voltage and current consists in the determination of the basic voltage V_{base} [5, 6, 7] and the basic current (peak value of current fundamental component) I_{1base}. The voltage and the current instantaneous values are divided respectively by the peak values V_{base} and I_{1base}.
The per unit current, containing harmonic and reactive components, is calculated by adding, with different signs, per unit voltage to per unit current. Multiplication of this current by I_{1base} yields the harmonic and reactive current as it shows figure 1.

3.1. Effective value

A sinusoidal voltage signal is written as:. $v(t) = V_{\max}\sin(\omega t + \varphi)$ where $V_{\max}$ is the signal amplitude, ω is the signal pulsation; $\omega = 2\pi f = 2\pi / T$. φ is the phase angle.
The effective value of a sinusoidal voltage can be expressed like follow:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T V^2(t)dt} = \frac{V_{\max}}{\sqrt{2}} \qquad (01)$$

Such as $V_{\max}$ is the peak value.

The effective value of a not-sinusoidal current is given according to the Budeanu definition [9] by:

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T I^2(t)dt} = \sqrt{\sum_h I_{hRMS}^2} \qquad (02)$$

I_h: the effective value corresponding to the h harmonic.
T: the period of the fundamental component.

3.2. Total harmonic distortion

The THD block measures the total harmonic distortion of a periodic distorted signal. The THD block input can be a measured voltage or current signal. The THD is defined as the root mean square (RMS) value of the signal total harmonics, divided by the RMS value of its fundamental signal. For example, the THD of a measured current is defined as:

$$\text{Total Harmonic Distortion} = \frac{I_H}{I_F}$$

Where

$$I_H = \sqrt{I_2^2 + I_3^2 + ... + I_n^2} \qquad (03)$$

I_n: RMS value of the n harmonic component.

I_F: RMS value of the fundamental current component.

The total harmonic distortion (THD) is given according to IEEE-519 standard [8] like follow:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_{hRMS}^2}}{I_{1RMS}} \qquad (04)$$

I_{1RMS}: the effective value corresponding to current fundamental component.

4. PROPOSED THEORY DESCRIPTION

The proposed method is based on the fundamental component extraction of the polluted current according to the following synoptic scheme:

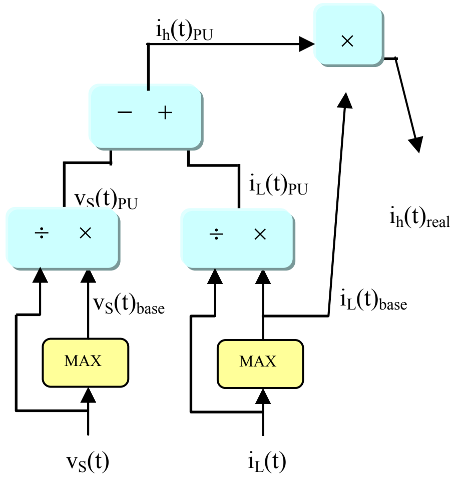

Figure 1. Synoptic diagram of the suggested method

Where
$i_L(t)$: Nonlinear load current [A].
$v_S(t)$: Voltage source [V].
$i_L(t)_{base}$: Amplitude of nonlinear load current [A].
$v_S(t)_{base}$: Amplitude of the voltage source [V].
$i_L(t)_{PU}$: Nonlinear load current [pu].
$v_S(t)_{PU}$: Voltage source [pu].
$I_h(t)_{PU}$: Harmonics load current [pu].
$I_h(t)$: Harmonics load current [A].

The voltage basic value or the maximal value is easily measured admitting that the voltage is sinusoidal according to the equation (01).
We transform our system in Per Unit:
Such as:

$$V_S(t) = V_{\max}\sin(\omega t)[Volt] \quad (05)$$

$$V_{base} = V_{\max} = \sqrt{2}V_{RMS}\,[Volt] \quad (06)$$

One divides the equation (05) by the equation (06), [5, 6,7]:

$$V_S(t) = 1.\sin(\omega t)[pu] \quad (07)$$

The load current is non-sinusoidal in other words it contains fundamental component plus harmonics components. The basic current $i_L(t)_{base}$ used in this theory is measured starting from the effective value of fundamental current is calculated like following:
From equations (02) and (04):

$$I_{RMS}^2 = I_{1RMS}^2 + THD^2.I_{1RMS}^2 \quad (08)$$

Thus:

$$I_{1RMS} = \sqrt{\frac{I_{RMS}^2}{(1+THD^2)}} \quad (09)$$

Using equation (09), we can calculate directly the current fundamental effective value.

Thus:

$$I_{1\max} = I_{1base} = \sqrt{2}I_{1RMS}\,[A] \quad (10)$$

$$i_L(t) = I_{1\max}\sin(\omega t + \varphi)\,[A] \quad (11)$$

Where φ is the phase angle between the supply voltage *v(t)* and the load current *i(t)*

By dividing equation (11) by I_{1base}, we get:

$$i_L(t) = 1.\sin(\omega t + \varphi)[pu] \quad (12)$$

4.1. Calculation of the non active current

One proposes the function *f(t)* expressed like follow:

$$f(t) = i_{Lpu}(t) - V_{Spu}(t) \quad (13)$$

Knowing that

$$\sin(\alpha+\beta) = \sin(\alpha).\cos(\beta) + \cos(\alpha).\sin(\beta) \quad (14)$$

$$f(t) = \sin(\varphi).\cos(\omega t) + [\cos(\varphi) - 1]\sin(\omega t) \quad (15)$$

f(t) is a trigonometric function and it can be written as :

$$f(t) = g(t) = A\cos(\omega t + \phi) \quad (16)$$

Where:

A is the amplitude of the *f(t)* function.
ϕ is the phase angle of the *f(t)* function.

The *g(t)* function represents the load reactive current or non active load current.

Calculation of amplitude *A*

$$A = \sqrt{2}\sqrt{\left|\frac{1}{T}\int_{t}^{t+T} f(t)^2\right|} \qquad (17)$$

Calculation of the angle ϕ

$$\phi = ar\cos\left(\frac{1}{A}f(t)\right) - \omega t \qquad (18)$$

5. COMPARISON BETWEEN THE P-Q THEORY AND THE PROPOSED SOLUTION

5.1. PQ theory description

The p-q theory, or "Instantaneous Power Theory", was developed by Akagi et al in 1983, with the objective of applying it to the control of active power filters [10]. Initially, it was developed only for three-phase systems without neutral wire, being later worked by Watanabe and Aredes, [11] for three-phase four wires power systems.

This theory is based on time-domain, what makes it valid for operation in steady-state or transitory regime, as well as for generic voltage and current power system waveforms, allowing to control the active power filters in real-time. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation (exception done to the need of separating the mean and alternated values of the calculated power components).

The p-q theory performs a transformation (known as "Clarke Transformation") of a stationary reference system of coordinates a – b – c to a reference system of coordinates α – β – 0, also stationary.

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 $\alpha-\beta$ coordinates [2].

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (19)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (20)$$

In equation (19) and (20), 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 real and imaginary powers are calculated as follows

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (21)$$

In equation (21), $e_\alpha i_\alpha$ 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 has not conventional electric unit like W or Var. q is instantaneous imaginary power.

Equation (21) can be written as equation (22).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1}\begin{bmatrix} p \\ q \end{bmatrix} \qquad (22)$$

From equation (22), instantaneous compensating currents in α and β coordinates, are given by,

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1}\begin{bmatrix} \tilde{p} \\ -q \end{bmatrix} \qquad (23)$$

The compensated currents in the standard three-phase form are derived as follow:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \qquad (24)$$

5.2. Case study

In this study, and to simplify calculation, we will not take into account the part of the harmonic current but only the reactivate energy compensation and we supposes that the load is linear but it absorbs a reactive energy variable in time.

A three-phase energy system is proposed supplying a linear load such as:

In this case, the line-to-neutral voltages are as follow:

$$V_a(t) = \sqrt{2}\sin(\omega t) \quad (25)$$

$$V_b(t) = \sqrt{2}\sin(\omega t - 120°) \quad (26)$$

$$V_b(t) = \sqrt{2}\sin(\omega t + 120°) \quad (27)$$

Where

$\omega = 2\pi f$, $V = 230V$, $f = 50Hz$

The line currents have similar expressions. They are as follow:

$$i_a(t) = \sqrt{2I_1}\sin(\omega t + \varphi(t)) \quad (28)$$

$$i_b(t) = \sqrt{2I_1}\sin(\omega t + \varphi(t) - 120°) \quad (29)$$

$$i_c(t) = \sqrt{2I_1}\sin(\omega t + \varphi(t) + 120°) \quad (30)$$

Such as:

V : is the rms value of the voltage (V)
I : is the rms value of the current (A).
ω : is the angular frequency (rad/s)
f : is the frequency (Hz)
t: is the time (s)
$\varphi(t)$: Angle phase

The phase angle is a time function (figure 2) :

$$\varphi(t) = \frac{8}{\sqrt{10^4 t^4 - 199t^2 + 1}} \quad (31)$$

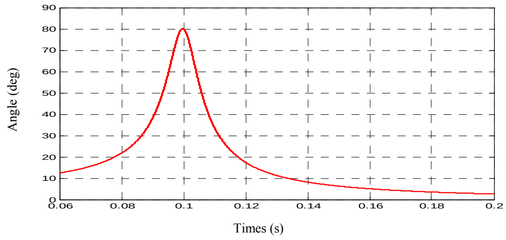

Figure 2. Angle (φ)

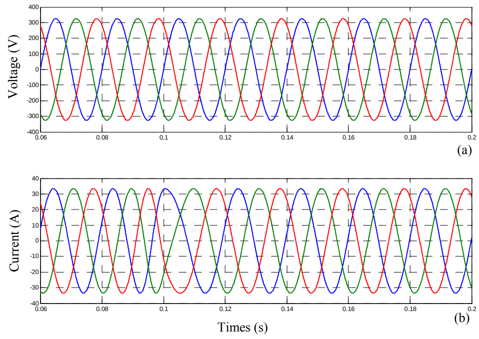

Figure 3.
a- Tree phase voltage supply waveforms
b- Three phases Load current waveforms

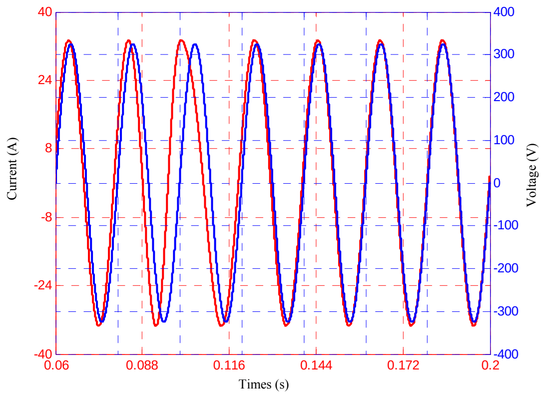

Figure 4. First phase load current and supply voltage waveforms

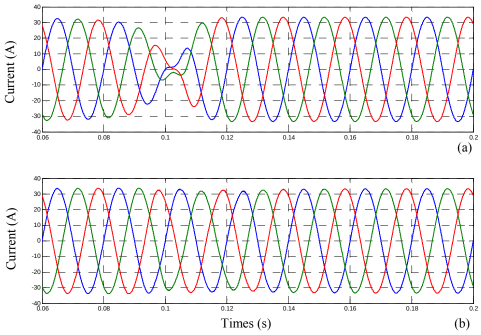

Figure 5.
a- Source current waveform after compensation by pq theory
b- Source current waveform after compensation by proposed solution

Figure 5, shows the source current waveform after compensation using the two theories. At t = 0.1 sec, it is noticed, for the pq theory, the current deformation. For the proposed theory, the source current keeps the same forms in spite of the strong call of reactive energy at time (t = 0.1 sec).

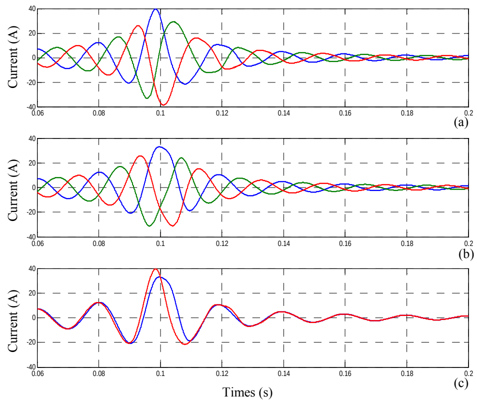

Figure 6. Identified reactive current
a- By proposed theory
b- By pq theory
c- First phase comparison

Figure 6, shows the waveform of the current injected into the network to compensate the load reactivate current. At t = 0.1 sec, the reactive current identified by the proposed method is equal to 40 A while that of the pq method is approximately equal to 33 A. Further the difference in the amplitudes level, the figure 6-c shows also difference in the phase angle level.

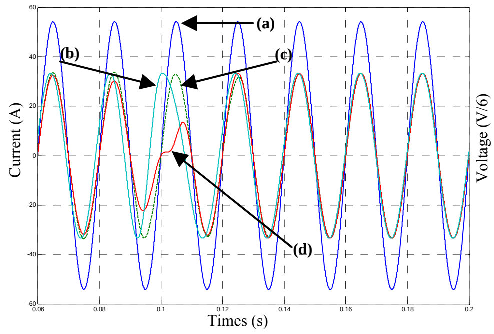

Figure 7. Comparison first phase current and voltage
a- First phase source voltage (*Va / 6*)
b- First phase load current
c- First phase source current (Proposed solution)
d- First phase source current (pq theory)

In figure 7, it clearly appears the elimination of phase angle between the source current and the supply voltage. Both of source currents obtained by the two methods are in phase with the supply voltage (*Vmax* value is divided by 6 in figure 7). The first phase source current obtained by the proposed theory guard almost the same amplitude as the load current. On the other hand at the moment of strong call of reactive power, the source current obtained by pq theory waste their initial amplitude.

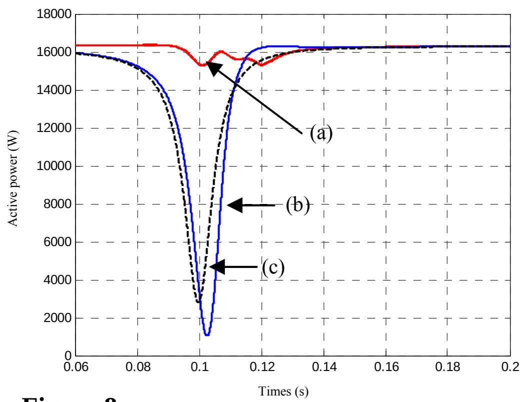

Figure 8.
(a) Active power after compensation by proposed theory
(b) Active power after compensation by pq theory
(c) Active power before compensation

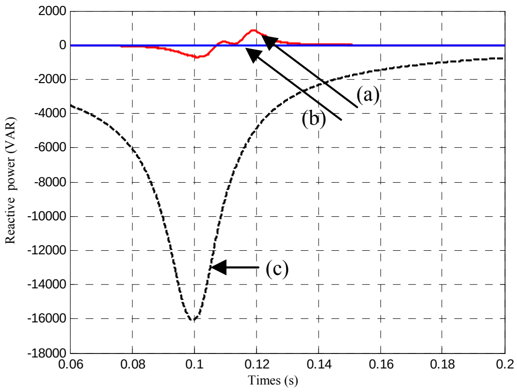

Figure 9.
(a) Reactive power after compensation by proposed theory
(b) Reactive power after compensation by pq theory
(c) Reactive power before compensation

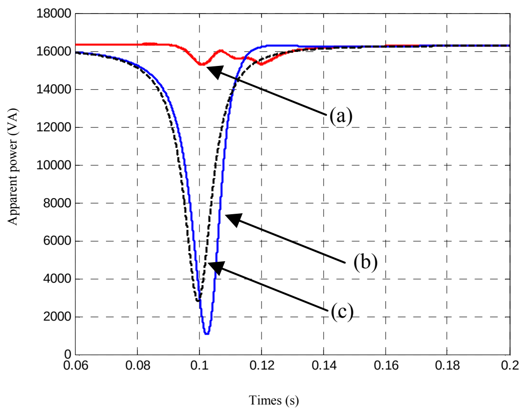

Figure 10.
(a) Apparent power after compensation by proposed theory
(b) Apparent power after compensation by pq theory
(c) Apparent power before compensation

Figure 8 and figure 9, show the evolution of the active and reactive instantaneous power. The increase in the reactive demand causes a call of the active and reactive power. This latter is well compensated by the theory pq. The proposed theory compensates reactive energy and even active energy consumed by the load which is clear on the waveform of the apparent power in figure 10.

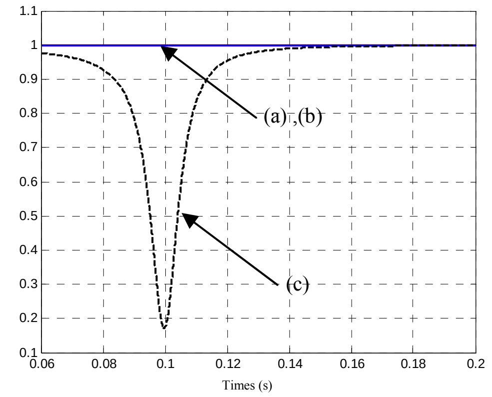

Figure 11.
(a) Power factor after compensation by proposed theory
(b) Power factor after compensation by pq theory
(c) Power factor before compensation

Figure 11 shows that the two methods give a unit power factor.

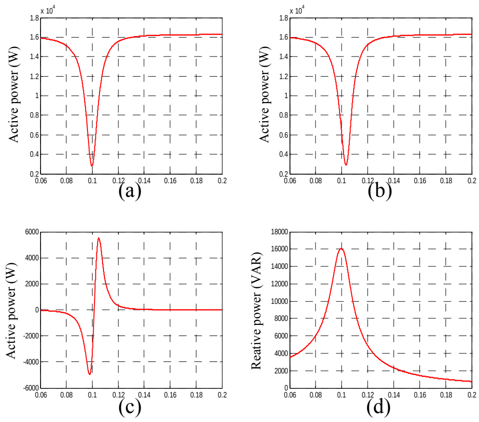

Figure 12. pq theory instantaneous power
(a) Instantaneous active power p
(b) Instantaneous average power $\overline{p}$
(c) Instantaneous fluctuate power $\tilde{p}$
(d) Instantaneous non active power q

Figure 12, shows the waveforms of the instantaneous powers obtained by the pq theory. The figures (12a) and (12d) respectively represent the active power p and the reactive power q (non active power) which are time variable like shown at t = 0.1 sec. On the other hand the average power $\overline{p}$ is not instantaneous. The delay in (figure 12b) is a result of the used high-pass filter (HPF). This delay also influences on the fluctuating power $\tilde{p}$ injected into the network. According to equations 23 and 24, when the fluctuating power pass by zero value (Figure 12c), it causes the deformation of current (figure 5a). Since this power is delayed regarding to average power $\bar{p}$, it causes a delay in the injected current obtained by the pq theory (figure 6c)

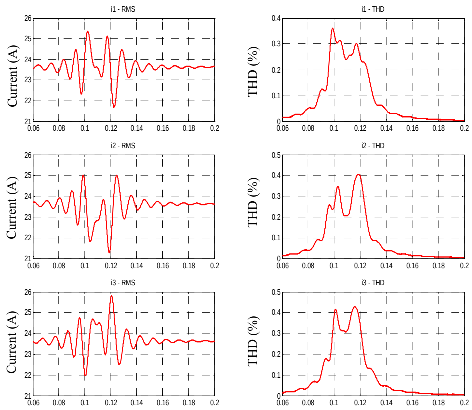

Figure 13. Proposed theory measured values

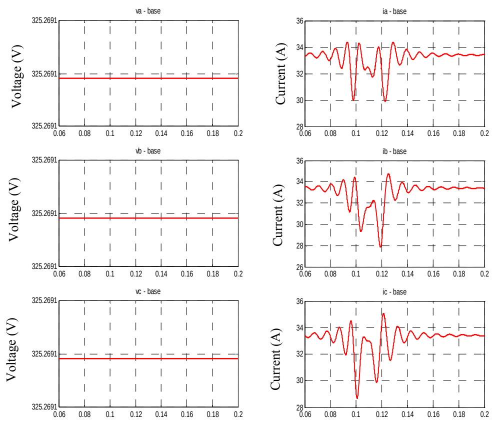

Figure 14. Proposed theory based values

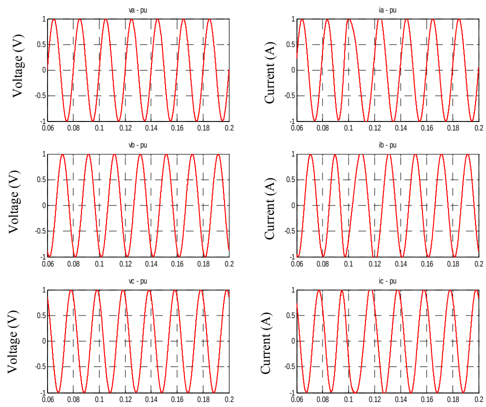

Figure 15. Proposed theory unit values

In figure 13, the increase in reactive energy, influences on the two measuring systems of the effective value (RMS) and of the THD and consequently it influences the basic currents (figure 14). But, it is slightly influences on the unit values of the current (figure 15).

6. CONCLUSION

This paper presents a new method of identification used for the extraction of the load reactive current. It is easy to be implemented with a very short execution time. These characteristics allowed us to obtain results more satisfactory than those obtained using the pq theory. This method is applicable for the three-phase systems and even the single-phase systems. The good precision of this theory is proved by the good power factor value measured when reactive current is identified using the suggested method and which is closer to the ideal value. We call this new method “the Extraction Theory”.

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BIOGRAPHIE

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