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A NOVEL THEORY OF REFERENCE HARMONIC 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 the harmonic currents reference identification. The principle is based on the transformation of the voltage and current of the electrical supply network in the per unit system. For this proposed solution we suppose that the voltage supply is sinusoidal and the load current is polluted. The harmonic current of nonlinear load is then obtained by the difference between both signals; per unit current and voltage where per unit voltage signal represent the fundamental of the load current. This new method is compared with that of named pq theory. Interesting results were obtained with a very satisfactory filtered current THD.

Keyword: *Active Filter, Per Unit, RMS, THD, current harmonic.*

1. INTRODUCTION

The appearance of new semiconductor components, like the thyristors GTO and transistors IGBT made it possible to consider new solutions of the disturbances electrical supply networks compensation. The active filters constitute an interesting alternative to the traditional solutions. Self-adapting flexible devices because, they come to be added to already existing structures of converters. They can also be used as complement with the traditional solutions of depollution. The role of an active filter is to compensate the nonlinear loads currents disturbances in real time, in all or in partly, to protect the electrical networks supply.

The control strategy is based on harmonic currents detection in the temporal field. Three possibilities of the harmonic currents identification were previously proposed [1]:

- Identification starting from the load current polluted detection.
- Identification starting from the source current detection.
- Identification starting from the voltage source detection.

The various methods of current reference identification can be gathered in two approach families.

The first uses the Fourier fast transform (FFT) in the frequencies field, to extract the current harmonics. This method is well adapted to the loads where the harmonic contents vary slowly. It also gives the advantage of selecting

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the harmonics individually, and of choosing to only compensate most dominating.

It should be noted that this method requires a great computing power in order to realize, in real time, all the transformations necessary to extract the harmonic current [3].

The second family is based on the instantaneous powers calculation in the temporal field. Some of these methods are based on the harmonic powers calculation of nonlinear load [4]. Others can be used to compensate at the same time the harmonic currents and the reactive power, while being based on the subtraction of the active fundamental part of the total current [4].

2. PRESENTATION OF THE THEORY SUGGESTED

The voltage of the electrical supply network is obtained using a PLL system. With nil phase angle, the voltage represents the image of the current fundamental component in per unit system. Calculation of per unit current and voltage of our system consists in the determination of peak values of voltage V_{base} [5, 6, 7] and the nonlinear load fundamental component I_{1base}. The instantaneous values of voltage and current are divided respectively by the peak values V_{base} and I_{1base}.

V_{base} considered as fundamental component of current I_{1base}. Difference between V_{base} and I_{1base} results in harmonic current component in per unit system. Finally, one multiplies this per unit harmonic component by I_{1base} to get the required harmonic current as it shows figure 1.

3. PERIODIC SIGNAL DECOMPOSITION

Fourier showed that any periodic no-sinusoidal function *y(t)* of frequency *f* can be represented according to the sum form harmonic decomposition in the made up:

- Of a sinusoidal term at the frequency *f* of effective value Y_1. This term is called fundamental.
- Of sinusoidal terms whose frequencies are equal to N multiple the fundamental frequency and of effective values Y_n. These other multiples frequencies of fundamental are called harmonics.
- Of a possible continuous component of the amplitude Y_0.

The expression of this waveform is given by the function Fourier development of the voltage or current *y(t):*

$$y(t) = Y_0 + \sqrt{2}Y_1 \sin(\omega t - \varphi_1) + \sqrt{2}Y_2 \sin(2\omega t - \varphi_2) + \ldots + \sqrt{2}Y_n \sin(n\omega t - \varphi_n). \quad (01)$$

$$y(t) = Y_0 + \sqrt{2}Y_1 \sin(\omega t - \varphi_1) + \sum_{n \neq 1}^{\infty} \sqrt{2}Y_n \sin(n\omega t - \varphi_n) \quad (02)$$

3.1. EFFECTIVE VALUE

A sinusoidal waveform can be written as: $s(t) = S_{\max} \sin(\omega t + \varphi)$. $S_{\max}$ is the signal amplitude, $\omega = 2\pi f = 2\pi / T$ is the instantaneous phase, φ is the phase at the time origin or as conventionally called “the phase angle”.

For a sinusoidal signal, effective value is always considered to be the significant value that commonly used when speaking about sinusoidal voltage or current (RMS) [2].

The effective value of a sinusoidal voltage is given by:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} = \frac{V_{MAX}}{\sqrt{2}} \quad (03)$$

Such as V_{MAX} is the peak value.

The effective value of a non-sinusoidal current is given according to the Budeanu definition as follow [9]:

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = \sqrt{\sum_h I_{hRMS}^2} \quad (04)$$

I_h: the effective value corresponding to the *h* harmonic.

T: the period of the fundamental component.

3.2. THE TOTAL HARMONIC DISTORTION

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

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

Where

$$I_H = \sqrt{I_2^2 + I_3^2 + \ldots + I_n^2} \qquad (05)$$

I_n: RMS value of the n harmonic

I_F: RMS value of the fundamental current.

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

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_{hRMS}^2}}{I_{1RMS}} \qquad (06)$$

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

4. PROPOSED THEORY DESCRIPTION

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

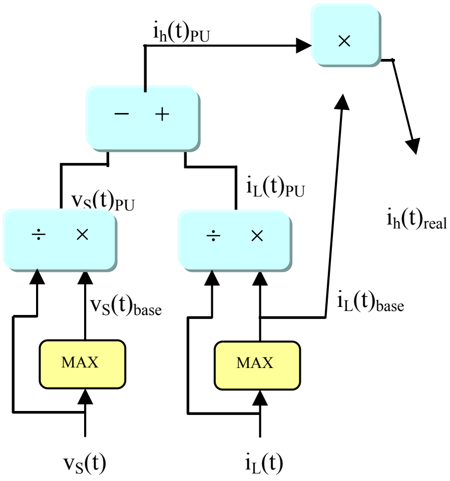

Figure 1. Synoptic diagram of the suggested method

The basic voltage value or the max value is easily measured admitting that the voltage is sinusoidal according to the equation (03).

One expresses our system (real) in Per Unit:

Such as:

$v_S(t)$ is the voltage source.

$$v_S(t) = V_{MAX}\sin(\omega t)$$

$$V_{base} = V_{MAX} = V_{RMS}.\sqrt{2} \qquad (08)$$

One divides the equation (07) by V_{MAX} [5, 6,7], to get:

$$v_S(t) = 1.\sin(\omega t)\ [pu] \qquad (09)$$

The load current is non-sinusoidal. In other words, it includes fundamental besides harmonic 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 equation (04) and equation (06) and considering $i_L^*(t)$ as nonlinear load current:

$$I_{RMS}^2 = I_{1RMS}^2 + THD^2.I_{1RMS}^2 \qquad (10)$$

Thus:

$$I_{1RMS} = \sqrt{\frac{I_{RMS}^2}{(1+THD^2)}} \qquad (11)$$

Using equation (11), one can calculate directly the current fundamental effective value.

Thus:

$$I_{1MAX} = I_{1base} = I_{1RMS}.\sqrt{2} \qquad (12)$$

$$i_L(t) = I_{1MAX}\sin(wt) + I_{3MAX}\sin(3\omega t) + \ldots \qquad (13)$$

Dividing equation (13) by I_{1base} yields to:

$$i''_L(t) = 1.\sin(wt) + \frac{I_{3MAX}}{I_{1base}}\sin(3\omega t) + \ldots \qquad (14)$$

$i''_L(t)$: The nonlinear load current in per unit.

Using equation (09) and (14):

$$i''_L(t) - v_S(t) = i''_h(t) = \frac{I_{3MAX}}{I_{1base}}\sin(3\omega t) + \ldots \qquad (15)$$

Then, one multiplies this equation by I_{1base} :

$$i_h(t) = I_{3MAX}\sin(3\omega t) + I_{5MAX}\sin(5\omega t)\ldots \qquad (16)$$

The $i_h(t)$ current is the identified harmonic current.

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

5.1. P-Q 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.

5.2. Case study

A three-phase energy system is supposed supplying a nonlinear load. The line-to-neutral voltages are as follow:

$$v_a = \sqrt{2}V\sin(\omega t) \tag{17}$$

$$v_b = \sqrt{2}V\sin(\omega t - 120°) \tag{18}$$

$$v_b = \sqrt{2}V\sin(\omega t + 120°) \tag{19}$$

Where

$\omega = 2\pi f$;*V= 230 V* ; *f = 50 Hz* ;

The line currents have a similar expression. They are as follows:

$$i_a = i_{Fa} + i_{Ha} \tag{20}$$

$$i_b = i_{Fb} + i_{Hb} \tag{21}$$

$$i_c = i_{Fc} + i_{Hc} \tag{22}$$

Whose fundamental component currents are given by:

$$i_{Fa} = \sqrt{2}I_1\sin(\omega t) \tag{23}$$

$$i_{Fb} = \sqrt{2}I_1\sin(\omega t - 120°) \tag{24}$$

$$i_{Fc} = \sqrt{2}I_1\sin(\omega t + 120°) \tag{25}$$

The harmonic currents:

$$i_{Ha} = \sqrt{2}\sum_{h\neq 1} I_h \sin(h\omega t - \beta_h) \tag{26}$$

$$i_{Hb} = \sqrt{2}\sum_{h\neq 1} I_h \sin(h\omega t - \beta_h - 120°h) \tag{27}$$

$$i_{Hc} = \sqrt{2}\sum_{h\neq 1} I_h \sin(h\omega t - \beta_h + 120°h) \tag{28}$$

Where:

V : is the rms value of the voltage (V)

I_1 : is the rms value of the fundamental component current (A).

I_h : is the rms value of the of h order harmonic component current (A)

ω : is the angular frequency (rad/s)

f : is the frequency (Hz)

β_h : is the phase angle of h order harmonic component current (rad).

t: is the time (s)

Order Harmoniques (h)	I_h(A)	β_h (deg)
1	33.408	0
3	0.0016355	-177.62
5	7.5626	-160.92
7	3.7263	-154.34
9	0.0039737	96.098
11	2.974	157.34
13	2.0803	151.33
15	0.0012634	171.66
17	1.805	21.32
19	1.4051	-6.2373

Table 1. Current amplitude value and the phase angle of each harmonic.

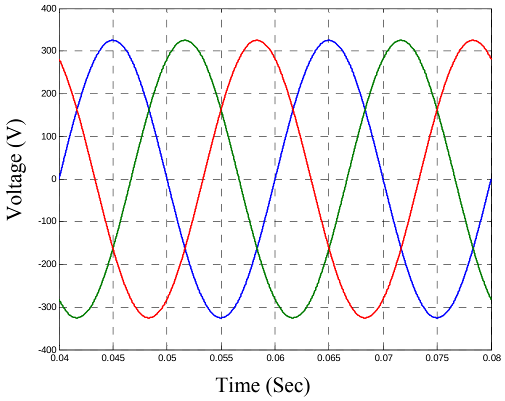

Figure 2. Power supply phases voltages

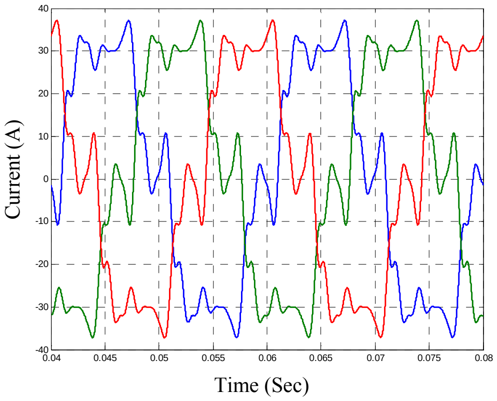

Figure 3. Load hypothesis currents

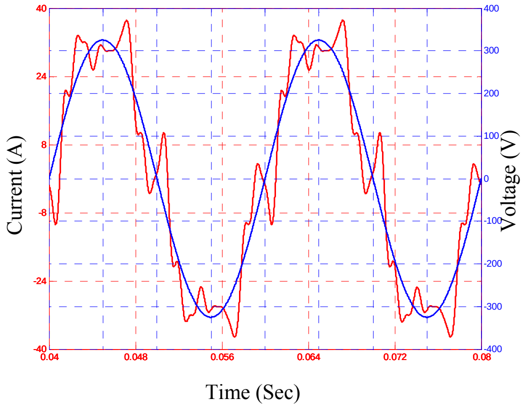

Figure 4. First phase voltage and current

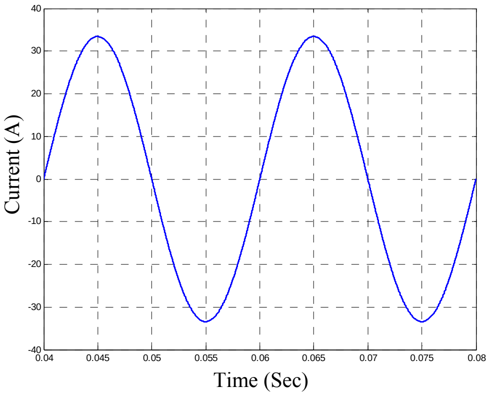

Figure 5. First phase hypothesis current fundamental component

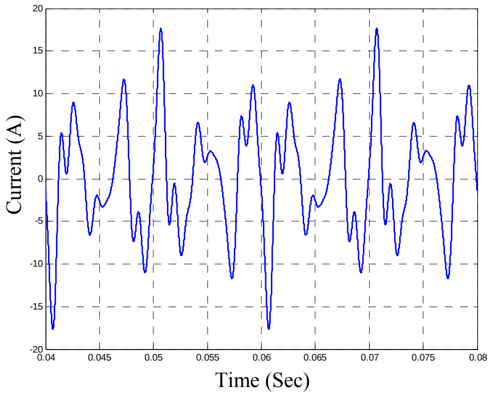

Figure 7. First phase hypothesis current harmonic component

Order harmoniques	Hypothesis polluted Current amplitude (A)	Hypothesis polluted fundamental component Current amplitude (A)	Hypothesis polluted harmonic component Current amplitude (A)
0	0	0	0
1	33.4084	33.4084	0.0002
3	0.0022	0.0004	0.0018
5	7.5636	0.0008	7.5628
7	3.7251	0.0007	3.7258
9	0.0048	0.0006	0.0046
11	2.9750	0.0014	2.9746
13	2.0797	0.0006	2.0802
15	0.0032	0.0028	0.0009
17	1.8050	0.0017	1.8053
19	1.4031	0.0043	1.4050
THD (%)	**28.3156**	**0.0172**	**4.3518e+006**

Table 2. First phase hypothesis current amplitude

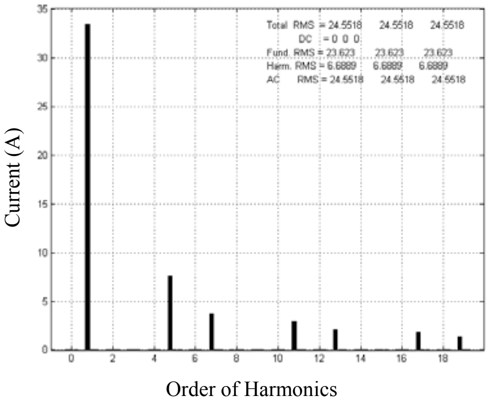

Figure 6. Amplitudes first phase hypothesis current

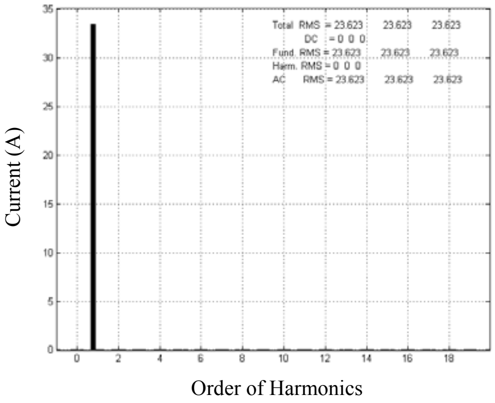

Figure 8. Amplitudes first phase hypothesis current of fundamental component

5.3. PQ theory results

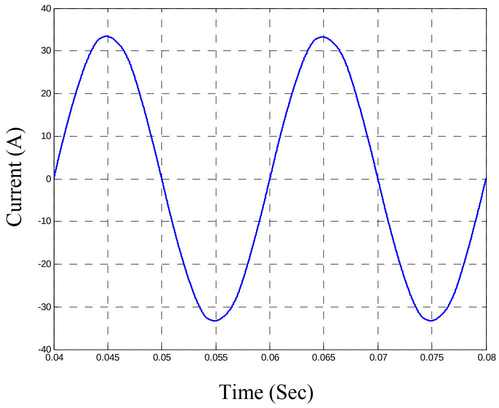

Figure 9. First phase current fundamental component identified by pq theory

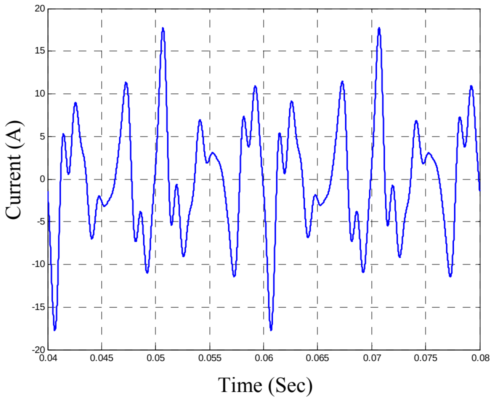

Figure 11. First phase current harmonic component identified by pq theory

Order harmoniques	Fundamental component amplitude of the current identified by pq theory (A)	Harmonic component amplitude of the current identified by pq theory (A)
0	0	0
1	33.4091	0.0008
3	0.0027	0.0006
5	0.1420	7.5081
7	0.1419	3.7684
9	0.0042	0.0007
11	0.0154	2.9698
13	0.0171	2.0865
15	0.0026	0.0008
17	0.0088	1.7975
19	0.0117	1.4147
THD (%)	**0.6067**	**1.2517e+006**

Table 3. First phase current amplitude identified by pq theory

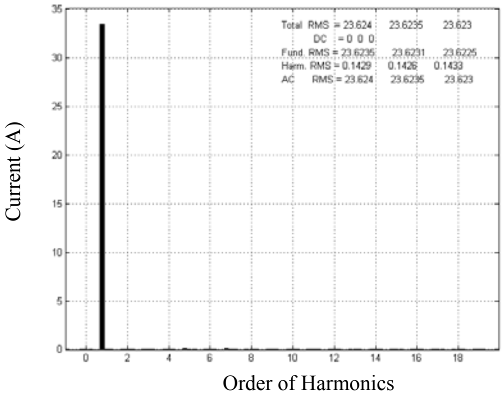

Figure 10. Amplitude first phase current fundamental component identified by pq theory

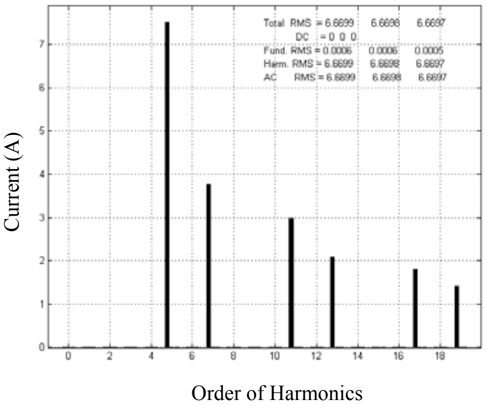

Figure 12. Amplitude first phase current harmonic component identified by pq theory

5.4. Proposed theory results

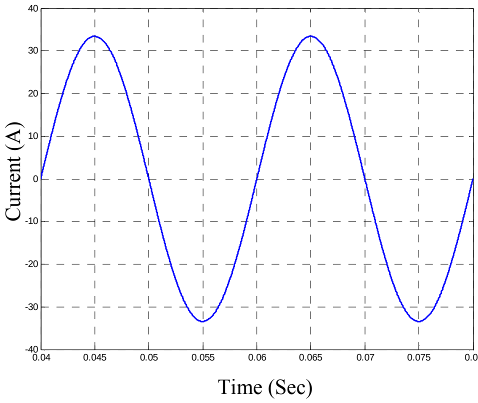

Figure 13. First phase current fundamental component identified by proposed theory

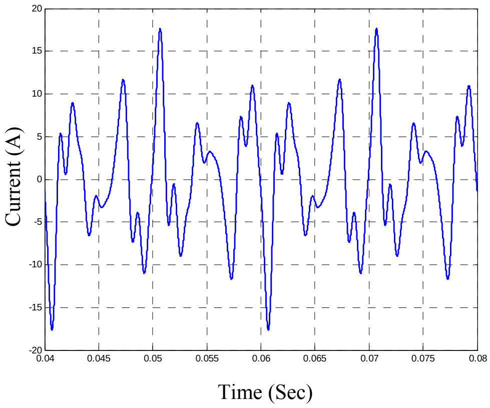

Figure 15. First phase current harmonic component identified by proposed theory

Order harmoniques	Fundamental component amplitude of the current identified by proposed theory (A)	Harmonic component amplitude of the current identified by proposed theory (A)
0	0	0
1	33.4085	0.0003
3	0.0004	0.0018
5	0.0008	7.5628
7	0.0007	3.7258
9	0.0006	0.0046
11	0.0014	2.9745
13	0.0006	2.0802
15	0.0028	0.0009
	0.0017	1.8053
19	0.0043	1.4050
THD (%)	**0.0172**	3.6726e+006

Table 4. First phase current amplitude identified by proposed theory

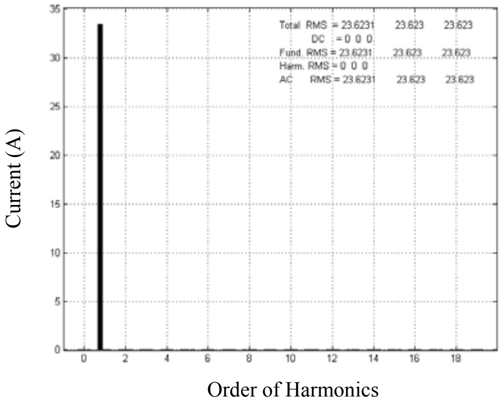

Figure 14. Amplitude first phase current fundamental component identified by proposed theory

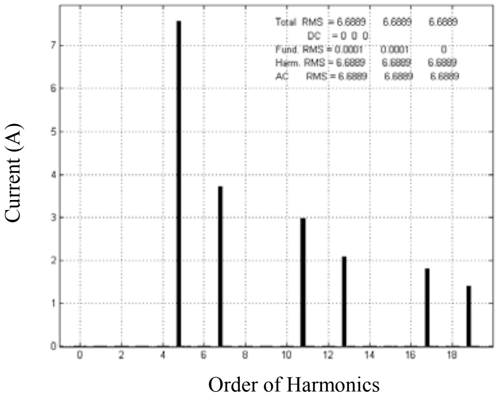

Figure 16. Amplitude first phase current harmonic component identified by proposed theory

5.6. Comparison

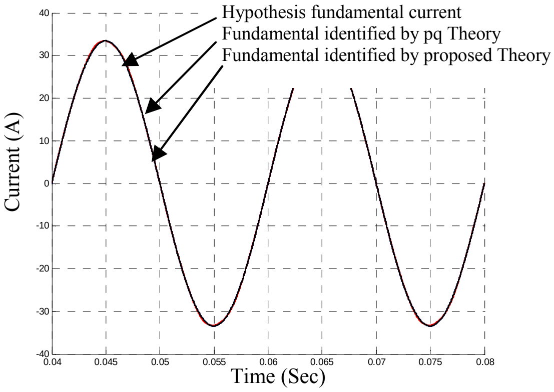

Figure 17. Comparison of the first phase fundamentals components

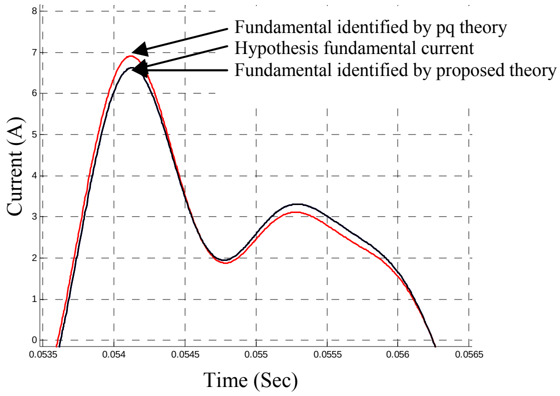

Figure 20. Zoom in the figure 19

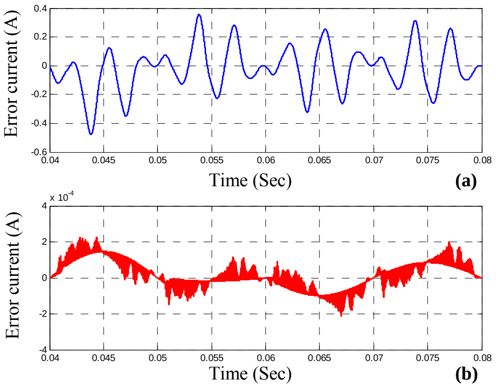

Figure 21.
(a) Error between the fundamental hypothesis current and the fundamental current identified by pq theory
(b) Error between the fundamental hypothesis current and the fundamental current identified by proposed theory

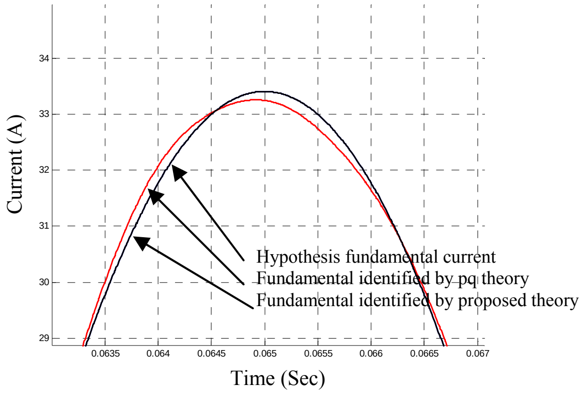

Figure 18. Zoom in the figure 17

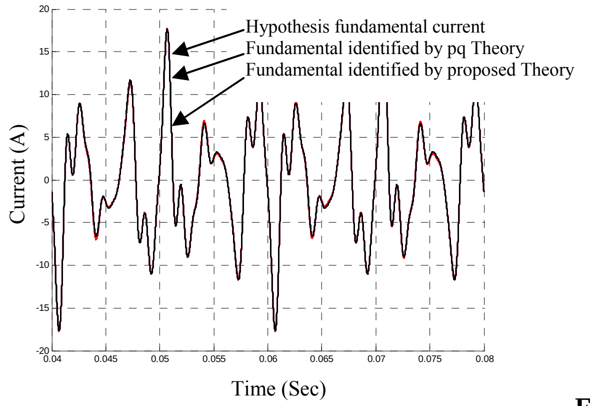

Figure 19. Comparison of the first phase harmonics components

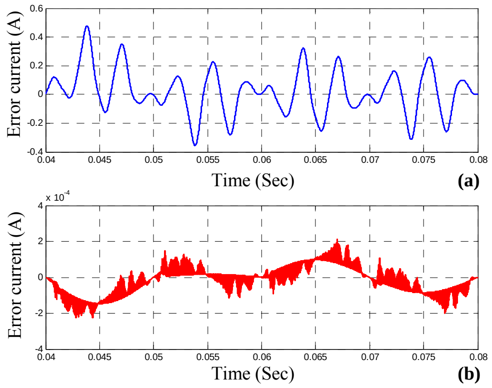

Figure 22.
(a) Error between the harmonic hypothesis current and the harmonic current identified using pq theory
(b) Error between the harmonic hypothesis current and the harmonic current identified using proposed theory

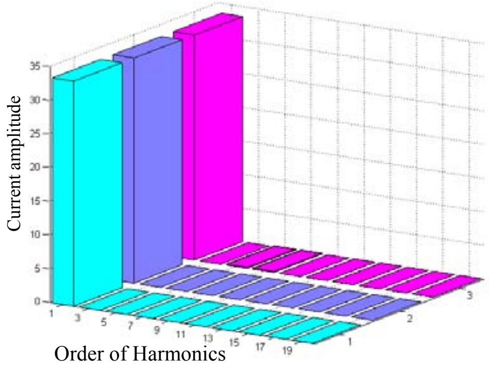

Figure 23. Fundamentals components
1 - Hypothesis current
2 - Current identified by pq theory
3 - Current identified by proposed theory

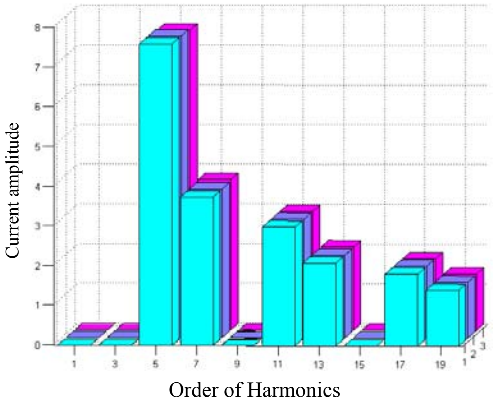

Figure 24. Harmonics components
1 - Hypothesis current
2 - Current identified by pq theory
3 - Current identified by proposed theory

6. CONCLUSION

This paper presents a new identification method used for the extraction of the harmonic reference currents, which 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 THD value measured for the harmonic current identified by the suggested method which is closer to the ideal value, which clearly appears in very small error calculated between the fundamental component of the hypothesis current and the current identified using the suggested theory (about 2.10^{-14} (A)). The only disadvantage of this method is the real time identification problem, because this technique uses two equipments, one to measure the THD and the other one to measure the RMS. These devices cause a delay equal to one period of the measured signal (current).

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BIOGRAPHIE

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