IMPROVING THE DYNAMIC RESPONSE OF ACTIVE POWER FILTERS BASED ON THE SYNCHRONOUS REFERENCE FRAME METHOD

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Abstract – **This paper presents a new strategy for improving the dynamic response of active power filters that use the synchronous reference frame method (i_d-i_q method). This strategy is based on the substitution of conventional filtering by a process so efficient as that, faster, simpler and requesting a less computational burden. Such modification produces a transient time in the compensation process that lasts 1/6 of the mains fundamental voltage period (or 1/3, if there is even order harmonics in the currents). Due to its fast response, the proposed modification makes it possible the application of the i_d-i_q method to a single phase. With such a feature, this method becomes suitable for the harmonic compensation of unbalanced loads, still keeping a fast dynamic response. The paper presents the strategy, the simulations and the experimental results.**

I. INTRODUCTION

The performance of a shunt active power filter depends on many factors. Among them, the reference template generation method is a very important one. The reference template generation method is responsible for the generation of the reference currents that must be followed by an inverter to produce the compensation currents that will "eliminate" the harmonic currents generated by non-linear loads.

Many methods for generating the reference template were proposed in the literature [1]-[5], among them, three methods can be highlighted: the method proposed by Akagi et al [1], the method proposed by Bhattacharya et al [2] and the method proposed by Zhou et al [3].

The method proposed by Akagi (p-q method) uses the "Instantaneous Active and Reactive Power Theory". In that technique the real and imaginary powers are calculated, both of them with dc and ac components. The dc components that are related to the fundamental frequency are extracted by means of conventional filters. The ac components resting are related to the harmonic content of the load currents and they are used to generate the reference template of the compensation currents. This method presents the disadvantages of being affected by the presence of harmonics in the mains voltage and of making use of conventional filtering, decreasing its dynamic response. This method is very efficient for balanced three-phase loads.

The method proposed by Bhattacharya (i_d-i_q method) is based on the calculation of the i_d-i_q components of the instantaneous three-phase currents. This method creates a reference frame system with two orthogonal axes that rotate at the synchronous speed of the mains voltage (d-q system), that is, a synchronous reference frame. This synchronous reference comes from a phase locked loop (PLL) [6]-[7]. In this rotating reference, the current fundamental components become dc levels in the i_d-i_q currents, which are filtered by conventional filters. The method is immune to the presence of harmonics in the mains voltages, once the PLL presents a strong characteristic of noise rejection. Because it uses conventional filters, it is also a slow method (in [2] a transient time of 2 cycles is reported). As the Akagi's method, this one was proposed for balanced three-phase loads.

The method proposed by Zhou is a very fast one and is based on the least compensation current principle, not using conventional filters. The least compensation current principle establishes that the RMS value of the compensation current I_c is minimum when the fundamental current is completely extracted. The fundamental current can be written as: I_1=A_1 sin(ù t). The factor sin(ù t) is known from the PLL, but A_1 must be determined. The determination of A_1 can be performed by a control mechanism that increases A_1 by a value ÄA proportional to the modulus of ÄI_c. If this change in A_1 increases I_c, the signal of ÄA is wrong and must be changed, in the other case the signal of ÄA is correct and A_1 is converging to the fundamental amplitude. This is a very fast algorithm; in [3] it is reported a transient time of 1/2 cycle. As a major drawback, this method needs a trial-and-error adjust of a proportional gain used for generating ÄA. This method was proposed for single-phase systems and, therefore can be applied to each phase individually. This characteristic makes this method efficient for unbalanced three-phase loads.

This paper proposes a modification in the i_d-i_q method, eliminating the cause of its slow dynamic response: the use of conventional filters. The reference template generation method achieved with such modification presents the following advantages:

- It is extremely fast, presenting a transient time equal to 1/6 of cycle (or 1/3 of cycle, if there is even order harmonics in the current) for balanced three-phase loads;

- It is immune to the presence of harmonics in the voltage mains;

- It does not need any adjusts;

- It does not represent a big computational burden, once it does not use conventional filters, but the calculation of moving averages over small periods;

- It is suitable for harmonic compensation of unbalanced loads, once it can be applied to a single phase, still keeping a good dynamic response.

The fundamentals of using moving averages will be presented as well as simulations and experimental results demonstrating the dynamic response. Comparisons with the conventional method will also be performed.

II. Moving Average Process Fundamentals

In Fig.1, the block diagram represents the traditional technique for extracting the fundamental currents in the synchronous reference frame method.

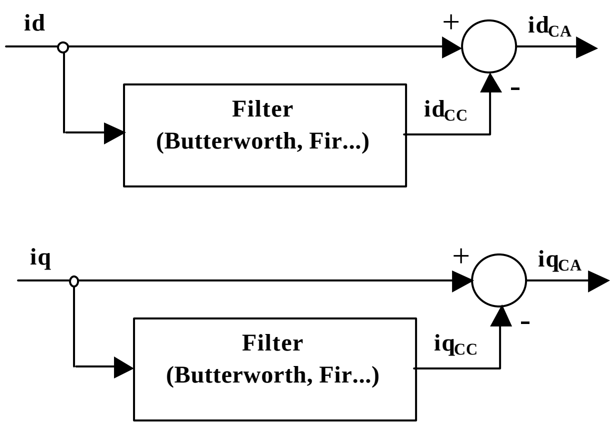

Figure 1 – Block diagram representing the DC component extraction process used in the conventional i_d-i_q method

In this block diagram, the three-phase currents a, b and c have already been transformed to the stationary reference frame (a-b-c to á-â-0 transformation) and later to the synchronous reference frame (á-â to d-q transformation). A filter (Butterworth, FIR etc.) is used to extract the DC components that represent the fundamental frequency of the currents. A PLL produces the unity vectors (sin (è) and cos (è)) needed in the stationary to synchronous transformation. The transformations are shown in the matrixes below:

a. a-b-c to α-β-0 Transformation (Invariant Power Clark Transformation [8]):

$$T_1 = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}; \qquad (1)$$

b. α-β to d-q Transformation (Park Transformation [5]):

$$T_2 = \begin{bmatrix} \cos q & \sin q \\ -\sin q & \cos q \end{bmatrix}. \qquad (2)$$

The dc component extraction process with the proposed modification is represented in Fig.2. It is assumed that even harmonics are not present in the load currents (in that case, some parameters would change). The filters are substituted by blocks that calculate the moving average, that is: an integration block, a transport delay block, a subtract block and a division block. The transport delay block output is the current integral value delayed by 1/6 of the fundamental period. The integrator block output minus the transport delay block output represents the current integration over the interval [t-T/6,t], where T is the fundamental period and it comes from the PLL. Finally, the division block divides the current integral by the integration interval width, that is, T/6. Therefore, the product block outputs are the moving averages of id and iq calculated over 1/6 of the fundamental period:

$$Moving_{average,id} = \frac{6}{T} \cdot \int_{t-\frac{T}{6}}^{t} id \cdot dt \quad \text{and} \quad (3.1)$$

$$Moving_{average,iq} = \frac{6}{T} \cdot \int_{t-\frac{T}{6}}^{t} iq \cdot dt. \qquad (3.2)$$

This procedure can be performed because every odd order harmonic component is multiple of six when it is transformed to the d-q reference frame.

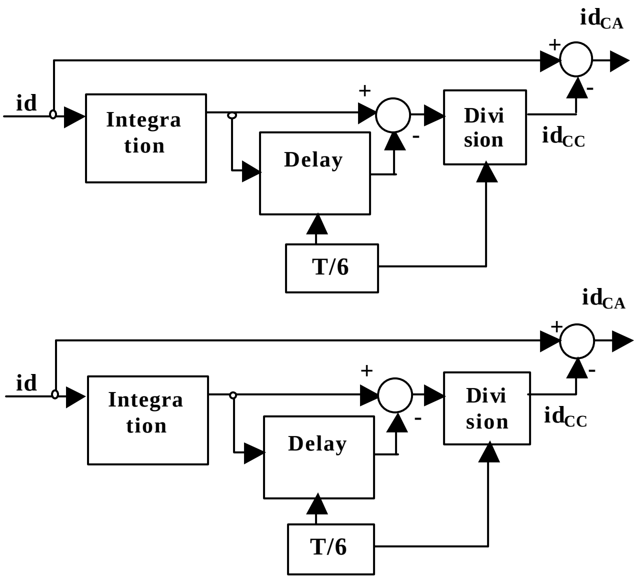

Figure 2 - Block diagram representing the DC component extraction process used in the modified id-iq method

Thus, every transformed odd order harmonic has a null average value over 1/6 of the fundamental period. The exception is the fundamental current that becomes dc levels determined by the moving averages.

The following paragraphs describe in depth how the odd order harmonics become multiple of six when they are transformed to the d-q reference frame. After that, the presence of even order harmonics is considered.

First, it is important to know the type of phase sequence presented by each harmonic component. Let us consider a balanced three-phase load. The three-phase currents will present a phase difference of 2.ð/3 rad, that is, the phases will be: φa = 0, φb = -2.π/3 and φc=+2.π/3. Therefore, the phases presented by a n order harmonic component will be:

$$j_{an} = 0 \cdot n \tag{4.1}$$

$$j_{bn} = -2 \cdot \frac{p}{3} \cdot n \tag{4.2}$$

$$j_{cn} = +2 \cdot \frac{p}{3} \cdot n \tag{4.3}$$

The triplen harmonics will be that with order equal to 3.i, with i=0,1,2,3…. If n is substituted by 3.i in equations (4.1), (4.2) and (4.3): φa=φb=φc, that is, triplen harmonics presents zero phase sequence. Therefore, those harmonics will be closed in the i_0 current. Of course, this analysis is not necessary when the considered system does not present neutral wire.

The 6.i+5 order harmonics, with i=0,1,2,3…(that is, 5th, 11th, 17th, 23th…) presents negative phase sequence. Substituting n by 6.i+5 in equations (4.1), (4.2) and (4.3), the phases will be: φa = 0, φb = +2.π/3 and φc=-2.π/3, in other words, the phase sequence will be a-c-b.

The 6.i+1 order harmonics, with i=0,1,2,3…(that is, 1th, 13th, 19th, 25th…) presents positive phase sequence. Substituting n by 6.i+1 in equations (4.1), (4.2) and (4.3), the phases will be: φa = 0, φb = -2.π/3 and φc=+2.π/3, in other words, the phase sequence will be a-b-c.

After the synchronous transformation, positive sequence harmonics will have their order decreased by one and negative sequence harmonics will have theirs increased by one. Therefore, 6.n+1 and 6.n+5 order harmonics will have their orders transformed to 6.n and 6.n+6 (=6.(n+1)), respectively, after the synchronous transformation. In other words, they will be multiples of six and, therefore, the unique component that will present a non-null average value over 1/6 of the period will be the zero order harmonic components corresponding to the fundamental.

When the positive and negative parts of the load current wave are not symmetric, there will be even order harmonics in the current. After the synchronous transformation, those harmonics will be multiple of three by the reasons below:

1. The even order harmonics that are also multiples of three will be isolated in the zero phase current i0;

2. The 6.i+2 order harmonics, with i=0,1,2,3…(that is, 2th, 8th, 14th, 20th…), will present negative phase sequence.

3. The 6.i+4 order harmonics, with i=0,1,2,3…(that is, 4th, 10th, 16th, 22th…), will present positive phase sequence.

By the reasons that have been already exposed, the 6.i+2 and the 6.i+4 order harmonics will become 6.i+3 (=3.(2.i+1)) order harmonics after the synchronous transformation, in other words, they will become triplen harmonics.

Therefore, if there is even order harmonics in the currents, the moving averages must be taken over the interval [t-T/3,t] (over this interval the moving average value of the transformed odd order harmonics will still be null, except the transformed fundamental, of course). It is important to note that the previous knowledge of the integration interval is not needed, once it is simple to construct an even order harmonic detector by analysis and comparison of some signals such as: i_d, i_q and their variations in time.

III. SIMULATIONS

The Fig. 3.a and the Fig. 3.b present the simulation results for the conventional and modified i_d-i_q method, respectively. In both cases, the load current is a three level square current.

In the conventional method simulation, it was adopted the low-pass filter reported in [2], that is, a 5^{th} order Butterworth filter with a 30Hz cut-off frequency. The transient time reported is greater than 2 cycles.

The Fig. 3.b shows a perfectly sinusoidal source current and the exact 1/6 of cycle transient time, as expected. Fig. 3.c and Fig. 3.d show the compensation current for the a phase and the i_d-i_q currents, respectively. The i_d-i_q currents are oscillating at 360Hz (6.60Hz), as expected too.

It is important to note that the result presented in Fig. 3.a could be improved if the cut-off frequency and the filter order were increased. Nevertheless, such modifications would not produce a better result than that of Fig. 3.b, besides that, the complexity of the filters would have to be increased with the order.

The Figs. 4.a, 4.b and 4.c show the simulation of the modified method applied over a three-level square current plus 44% of 2^{nd} order harmonic component. In Fig. 4.c, it can be noted that the currents oscillate at 180Hz (3*60Hz), as expected.

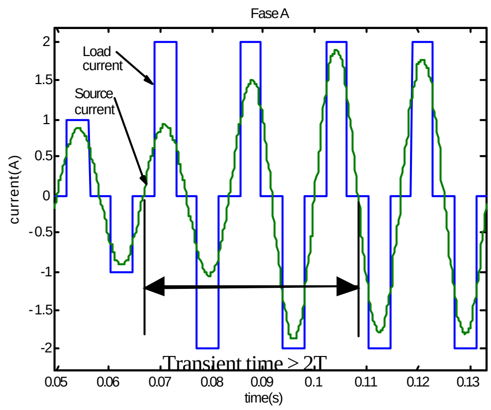

Figure 3.a – Result presented by the conventional i_d-i_q method using a 5^{th} order Butterworth filter with a 30Hz cut-off frequency.

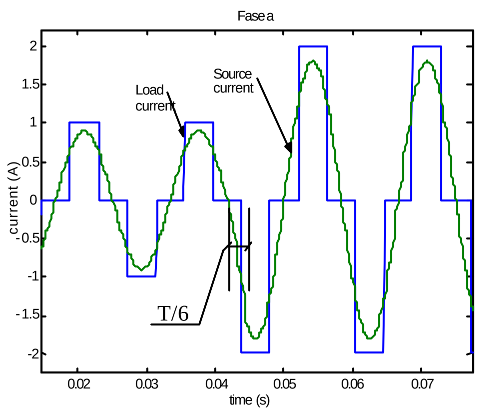

Figure 3.b – Result presented by the modified i_d-i_q method.

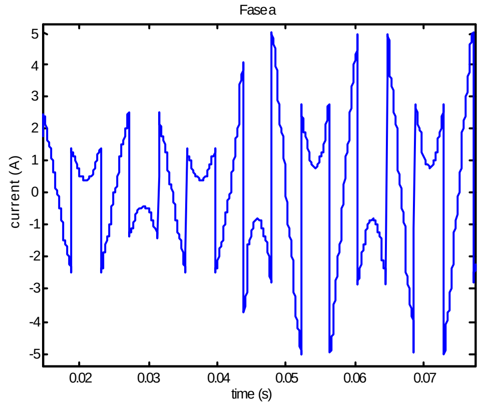

Figure 3.c – Compensation current presented by the modified i_d-i_q method.

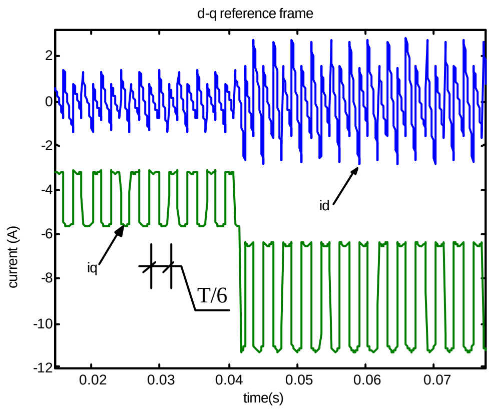

Figure 3.d – Load currents related to Fig. 3.b in the d-q system.

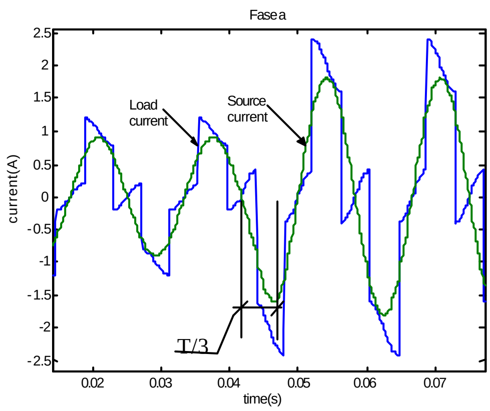

Figure 4.a – Result presented by the modified method for a three level square current plus 44% of 2^{nd} order harmonic component.

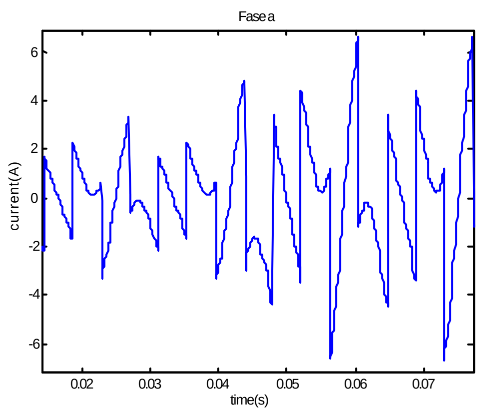

Figure 4.b – Compensation current for the current shown in Fig. 4.a.

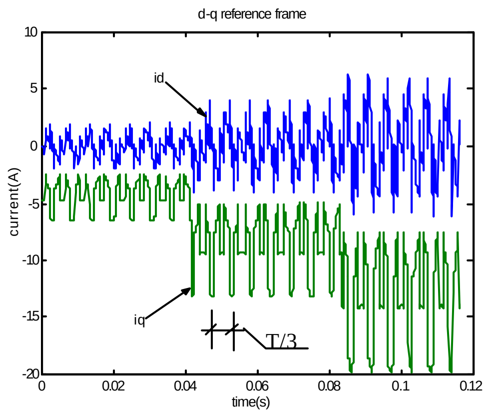

Figure 4.c – Load currents related to Fig. 4.a in the d-q system.

IV. Synchronous Reference Frame Method Application to Unbalanced Loads

The synchronous reference frame method, in its basic form, is based on the consideration of balanced three-phase loads. Such a drawback can be overcome by applying the method in each phase separately.

The Fig. 5 shows how it is possible to apply this single-phase strategy to the a phase.

The strategy is to get the three load currents through the acquisition of only one. The other two currents can be produced by 120 and 240° phase delays, easily implemented by software.

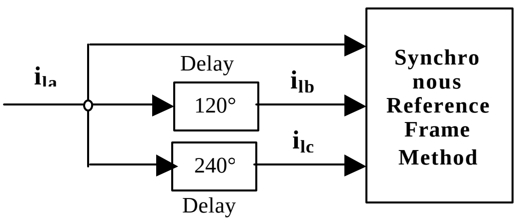

Figure 5 – Synchronous reference frame method application to the a phase only.

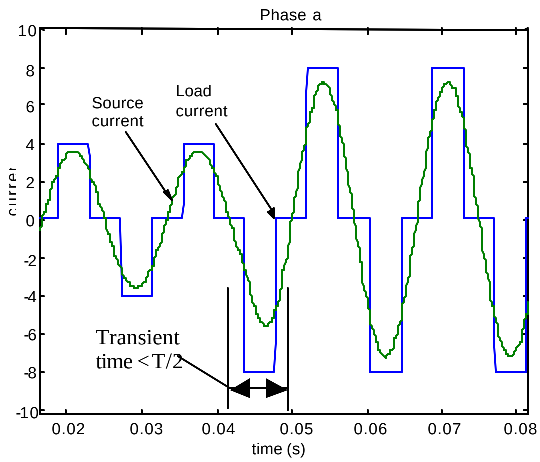

Figure 6 – Modified method performance, when applied to a single phase.

This strategy, however, increases the transient time due to the phase delays. From Fig. 5, it is possible to conclude that every change in current i_{la} will be present in all the currents only after 240°, that is, 2/3 of cycle. Therefore, when the modified method is applied to a single phase, the transient times will be 1 and 5/6 of cycle, for currents with and without even order harmonics, respectively.

Fig. 6 shows the modified method performance, when applied to a single phase. It can be noted that the transient time is less than 5/6 of cycle due to the particular current waveform.

V. Experimental Results

The modified method was implemented in real-time in the Simulink® application using the Real-Time Workshop® Toolbox. The load current acquisition was performed by Hall effect sensors and Advantech®'s PCL-812 acquisition board. The nonlinear load was a three-phase non-controlled rectifier with resistive load at the dc link (no capacitor was used). The sample frequency adopted was 5KHz. No current control strategy was implemented, once the aim of the implementation was to validate only the proposed modification in the reference template generation control method. Therefore, what is shown in Fig. 7 and Fig. 8 is the acquired signal and the acquired signal minus the reference template generated.

Fig. 7 shows the step response of the modified method applied to the three phases of the load at once. The current step effect was implemented by a gain step in the acquisition. In Fig. 8, it is shown the performance of the modified method applied to the a phase only. The transient times are very similar to those of the simulation.

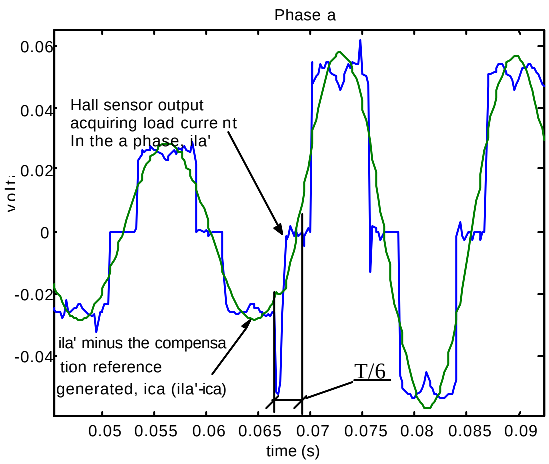

Figure 7 – Modified method current step response when applied to the three-phases of a non-controlled rectifier at once.

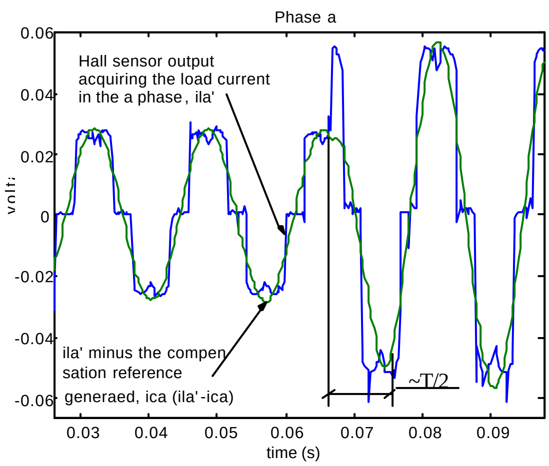

Figure 8 – Modified method current step response when applied to the a-phase only.

VI. Conclusions

The proposed modification to the id-iq method brings to this method the following new advantages: transient time reduction (the worst case is 1/3 of cycle, for balanced loads), simplicity in the digital implementation and computational burden reduction. Those new benefits allied to the old one, that is, immunity to voltage harmonics in the mains, make this method very attractive.

A very interesting point is the extremely fast dynamic response presented by the method when there is not even order harmonics. Therefore, plants with non-linear loads that present only odd order harmonics can have their current harmonics compensated with an almost ideal transient time.

The application of the method to a single phase, allowing the harmonic current compensation in unbalanced loads is an important feature that comes from the proposed modification, once the single phase strategy allied to the conventional method would produce a very long transient time.

VII. References

[1] Akagi, H., Kanazawa, Y., Nabae, A., "Instantaneous reactive power compensation comprising switching devices without energy storage components", IEEE Trans. Ind. Appl., vol. IA-20, pp 625-630, 1984;

[2] Bhattacharya, S., Divan, D., "Synchronous frame based controller implementation for a hybrid series active filter system", IEEE/IAS Annual Meeting, pp 2531-2540, 1995;

[3] Zhou, L., Li, Zicheng, "A novel active power filter based on the least compensation current control method", IEEE Trans. On Power Electron., vol. 15, pp 655-659, 2000;

[4] Dixon, J. W., García, J. J., and Móran, L., "Control system for three-phase active power filter which simultaneously compensates power factor and unbalanced loads", IEEE Trans. Ind. Elect., vol. 42, pp 636-641, 1995;

[5] Soares, V., Verdelho, P., and Marques, G. D., "An instantaneous active and reactive current component method for active filters", IEEE Trans. On Power Electron., vol. 15, pp 660-669, 2000;

[6] Best, R. E., "Phase Locked Loops – Theory, Design and Applications", McGraw-Hill Book, USA, 1984;

[7] Kaura, V., Blasko, V., "Operation of a phase locked loop system under distorted utility conditions", IEEE Trans. Ind. Appl., vol. 33, pp 58-63, 1997;

[8] Oliveira, C.C.B.de, Schmidt,H.P., Kagan, N., Robba, E.J., "Introdução a sistemas elétricos de potência – Componentes simétricas", Editora Edgard Blücher LTDA,.2a edição, São Paulo, 1996;