REFERENCE CURRENTS DETERMINATION TECHNIQUES FOR LOAD UNBALANCE COMPENSATION

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***Abstract* – It's large the concern with the power quality from the consumer's point of view as well as from the concessionaire. One of the problems is the unbalanced three-phase currents due to the use of single-phase loads, two-phase loads or unbalanced three-phase loads in three-phase power systems. To eliminate this unbalance it is necessary to identify the portion of negative sequence current present in the system and eliminate it. Several methods are presented here, accompanied by simulation results in order to provide an initial reference for the researchers and engineers .**

KEYWORDS

Unbalanced Loads ; negative sequence ; unbalance compensators

I. INTRODUCTION

The existence of distorted or unbalanced current causes several negative effects in AC mains. Electronic equipment supplied by rectifiers (electronic house appliances, motor drives, electronic ballast for illumination, induction furnaces, etc), metallurgy process , coal mines, sawmills and furnace arcs , for example, have non-linear behavior , causing disturbances in the AC mains even when fed by perfectly sinusoidal voltages. The negative effects of these current harmonics are noticed in the overheating of electric devices (rotate machines, transformers and capacitors for power factor correction) and distortion on the supply voltage, which can disturb the operation of sensitive circuits.

Unbalanced loads causes unbalanced voltages. Undesirable effects appear as additional losses in motors and generation units, increase of ripple in rectifier output voltage and transformers saturation. Beside this, phase and neutral cables will overheat due to excessive currents ([3], [5] and [16]). This article concentrates in the negative current sequence determination [19] in three-phase power systems in the presence of harmonics. This paper presents an overview about relevant papers , followed by simulations results obtained by using the Matlab software (Power System Blockset – Simulink) . All strategies were simulated considering the power converter as an ideal controlled current source and the mains voltage were considered as balanced and symmetrical .

II. METHODS FOR COMPENSATING THE NEGATIVE SEQUENCE CURRENT

A) PASSIVE ELEMENTS INSERTION

A traditional solution, proposed by Steinmetz for compensating an one-phase resistive load (figures 1a, 1b) is the insertion of passive elements, composed by inductors and capacitors [1], [4], [9], [13], [14] and [17].

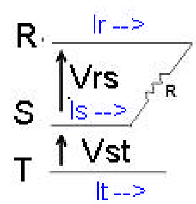

Figure 1a: Resistive one-phase load

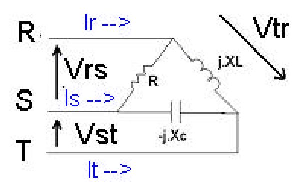

Figure 1b: Unbalance compensation by L C insertion

If, in fig. 1b, $X_c = X_L = \sqrt{3}.R$, and the positive voltage sequence is given by $\dot{V}_{rs} = V\angle 0^{\circ}$; $\dot{V}_{st} = V\angle\ 120^{\circ}$; $\dot{V}_{tr} = V\angle 120^{\circ}$, we have $\dot{i}_{rs} = \frac{\dot{V}_{rs}}{R} = \frac{V}{R}\angle 0^{\circ}$; $\dot{i}_{st} = \frac{\dot{V}_{st}}{j.Xc} = \frac{V}{\sqrt{3}.R}\angle\ 30^{\circ}$; $\dot{i}_{tr} = \frac{\dot{V}_{tr}}{j.XL} = \frac{V}{\sqrt{3}.R}\angle 30^{\circ}$ so: $\dot{i}_r = \dot{irs} - \dot{itr} = \frac{V}{R}.\frac{1}{\sqrt{3}}\angle\ 30^{\circ}$; $\dot{i}_s = \dot{ist} - \dot{irs} = \frac{V}{R}.\frac{1}{\sqrt{3}}\angle\ 150^{\circ}$; and $\dot{i}_t = \dot{itr} - \dot{ist} = \frac{V}{R}.\frac{1}{\sqrt{3}}\angle 90^{\circ}$.

So, the new system composed by the load and the compensating reactance is balanced. The line currents are equally displaced, have the same amplitude, and present unity power factor.

If the one-phase load is not a pure resistance, its reactive power must be previously compensated, so as to be able to use the above method. For arbitrary unbalanced loads, the above method can be applied together with the superposition theorem, as stated by [1] [4] and [18]. For a delta connected load whose individual loads drains active power

$(P_{rs} / P_{st} / P_{tr})$ and reactive power $(Q_{rs} / Q_{st} / Q_{tr})$: from the mains, the compensating reactive power $(Q_{rs\_C} / Q_{st\_C} / Q_{tr\_C})$, considering an resulting power factor of cos( ) are given by:

$$\begin{matrix} Q_{rs\_C} \\ Q_{stc\_C} \\ Q_{trc\_C} \end{matrix} = C. \begin{matrix} P_{rs} & Q_{rs} \\ P_{st} & Q_{st} \\ P_{tr} & Q_{tr} \end{matrix} \quad \text{where:}$$

$$C = \frac{1}{3} \begin{matrix} \tan(\ ) & \sqrt{3}\ \ \tan(\ ) & \sqrt{3}\ \ \tan(\ ) \\ \sqrt{3}\ \ \tan(\ ) & \tan(\ ) & \sqrt{3}\ \ \tan(\ ) \\ \sqrt{3}\ \ \tan(\ ) & \sqrt{3}\ \ \tan(\ ) & \tan(\ ) \end{matrix}$$

The total amount of reactive power for the individual compensating elements as a function of the desired value of the resulting power factor is considered in detail by [18]. For unit power factor, the compensated load is seen by the mains as three balanced resistive loads. For delta (star) connections the individual resistances have the value of 3R (R).

Simulation results, for off-line calculated reactances are present in figure 2.a and 2.b (One-phase Pure Resistive Load: 1 Ohms – Voltage Peak Value 1 V – connected like fig.1a) :

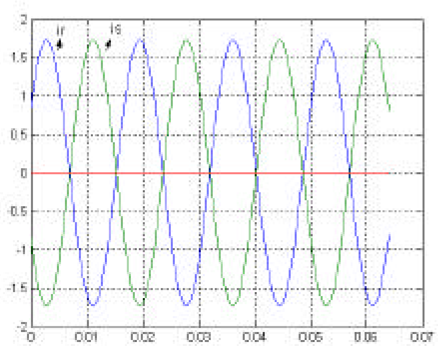

Figure 2.a- Unbalanced Line Currents

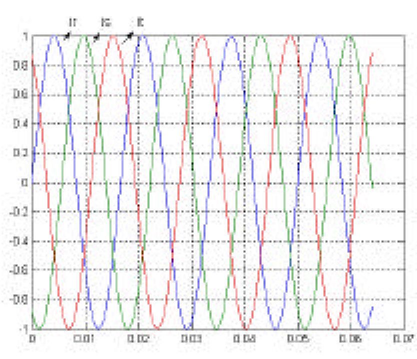

Figure 2.b-Compensated Line Currents

This method characteristics are:

The compensating reactance present great volume and weight. Also, their values depends on the load impedances. For variable loads the reactance values are changed by the use of "thyristor controlled reactors" (TCR) and "thyristor switched capacitors" (TSC).

The above method is suitable for the control of TCR and TSC compensators. [4] [8]

This compensation circuit is sensitive to the phases sequence .

It is difficult to obtain the reference current for PWM based compensator in real time .

Harmonics where neglected in the above solution. The inserted reactance, together with the transformer series reactance can present series resonance, representing a low impedance path for harmonic currents generated by loads located in the neighborhood. [27]

B) NEGATIVE SEQUENCE CURRENT INJECTION

Another solution for the compensation of unbalances is the active compensation done by negative sequence current injection through self-commutated PWM converters [5], [6], [7], [9], [10], [15], [17], [20], [21], [22], [23]and [24]. This strategy has the following advantages:

Smaller volume and weight when compared to the impedance insertion method presented in the previous item.

Fast compensation for varying loads;

Small harmonics injection and possibility of harmonics compensation;

Possibility of choosing full compensation (reactive power, harmonics and unbalance) or partial compensation, including any combination of unbalance, reactive power and harmonics. [2][5].

This last feature will be emphasized along the presentation of the existing methods in the next items. Usually, the levels of apparent power associated to reactive power and unbalances are higher than the ones associated to the harmonics. Full compensation requires high power converters with high switching frequencies, to cope with the harmonic components synthesis. The compensation of low frequency disturbances (reactive power and unbalances) can be done by bulky low switching frequency converters . The harmonics can be dealt with smaller power, higher switching frequency converter. All the following methods were simulated considering that the unbalanced load (identical to the one employed in item II.A , fig.2a) is switched on at "t=0" .

1) SPACE VECTOR REAL TIME DETECTING METHOD

Based on the Space Vectors Theory through Park transform [12] , this method [7] proposes to convert the three-phase instantaneous measured values to space vectors eq. (1), in a fixed reference frame. The components i (t) (real part) and i (t) (imaginary part) are instantaneous projections of the resulting current vector (Fig.3). Real and imaginary parts are filtered by two independent low pass filters (with unity gain and ( ) phase shift at fundamental frequency) eliminating the current harmonics . After filtering, two components, $i_{\ f}$(t) (real part) and $i_{\ f}$(t) (imaginary part), are obtained. They contain the components of the positive

($i_{f+}(t)$; $i_{f+}(t)$) and negative ($i_{f-}(t)$;$i_{f-}(t)$) sequence (at fundamental frequency). To extract the values of the filtered positive and negative sequence components ($i_{f+}(t)$; $i_{f+}(t)$; $i_{f-}(t)$; $i_{f-}(t)$) from $i_f(t)$ and $i_f(t)$, [7] proposes to create a new vector ($i_{f90}(t)$; $i_{f90}(t)$), obtained from the original vector ($i_f(t)$; $i_f(t)$), by rotating this vector by -90º. The desired components ($i_{f+}(t)$; $i_{f+}(t)$; $i_{f-}(t)$; $i_{f-}(t)$) are obtained from measured ones (($i_f(t)$; $i_f(t)$; $i_{f90}(t)$; $i_{f90}(t)$), by eq. (3), without proof due to space limitation.

To correct the phase shift caused by the filter ( ), it is necessary to rotate the vectors in agreement with the phase displacement ( ), obtaining the value of positive and negative sequence components ($i_{+}(t)$; $i_{+}(t)$; $i_{-}(t)$; $i_{-}(t)$) eqs. (4),(5) and (6). The compensating currents, are obtained by eq. (2) , and the results simulated line currents are shown in fig. 4.

$$\begin{bmatrix} i \\ i \end{bmatrix} = \frac{2}{3}\cdot\begin{bmatrix} 1 & 1/2 & 1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}\cdot\begin{bmatrix} ir \\ is \\ it \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} ir \\ is \\ it \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/2 & \sqrt{3}/2 \\ 1/2 & \sqrt{3}/2 \end{bmatrix}\cdot\begin{bmatrix} i \\ i \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_{f+} \\ i_{f+} \\ i_{f} \\ i_{f} \end{bmatrix} = \frac{1}{2}\cdot\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}\cdot\begin{bmatrix} i_{f90} \\ i_{f90} \\ i_{f} \\ i_{f} \end{bmatrix} \quad (3)$$

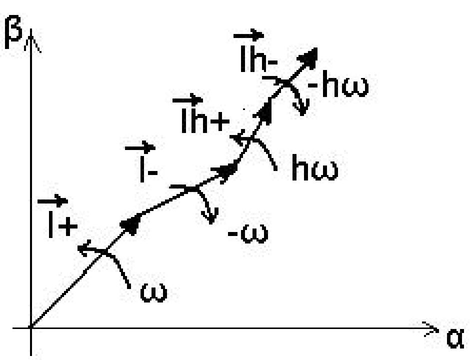

Figure 3 – Vector Projection in a fixed reference frame

(I_+(I) positive (negative) sequence vectors of fundamental

frequency / I_{h+} (I_h) positive (negative) sequence vectors of harmonics frequencies)

$$C = \begin{bmatrix} \cos & \sin \\ \sin & \cos \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} i_{+} \\ i_{+} \end{bmatrix} = C\cdot\begin{bmatrix} i_{f+} \\ i_{f+} \end{bmatrix} \quad (5)\ ; \qquad \begin{bmatrix} i \\ i \end{bmatrix} = C^t\cdot\begin{bmatrix} i_{f} \\ i_{f} \end{bmatrix} \quad (6)$$

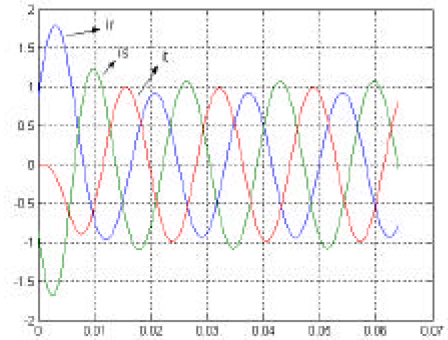

Figure 4 – Compensated Line Currents By Space Vector Real Time Detecting Method

2) POSITIVE SYNCHRONOUS REFERENCE FRAME

The load current is transformed into rotating frame dq using eqs. (1) and (7) , where (t) is a time variant angle that represents the angular position of the reference frame . The current is rotating at constant speed in synchronism with the AC voltages . A PLL (Phase-Locked Loop) circuit is necessary for synchronizing the rotating frame system . The positive sequence of the fundamental current in dq components is a dc value that can be isolated by a low pass filter. The oscillatory part is formed by harmonics and negative sequence components , and corresponds to the compensating current vector. The compensating currents (in R,S,T frame) , are obtained by eqs. (8) and (2) , and the results simulated line currents are shown in fig. 5.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\ t) & \mathrm{sen}(\ t) \\ \mathrm{sen}(\ t) & \cos(\ t) \end{bmatrix}\cdot\begin{bmatrix} i \\ i \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} i \\ i \end{bmatrix} = \begin{bmatrix} \cos(\ t) & \mathrm{sen}(\ t) \\ \mathrm{sen}(\ t) & \cos(\ t) \end{bmatrix}\cdot\begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (8)$$

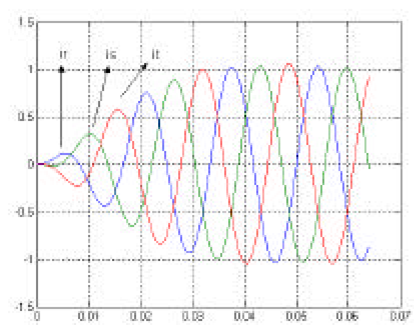

Figure 5 .- Compensated Line Currents by Positive Synchronous Reference Frame Method

3) MODIFIED SYNCHRONOUS REFERENCE FRAME

The reference rotation angle is computed using the AC voltages so there are no need of a synchronizing circuit . A comparison between positive synchronous reference frame and modified synchronous reference frame can be seen in [28] .

4) NEGATIVE SYNCHRONOUS REFERENCE FRAME

By the method presented in item B-2, the load current is transformed into rotating frame dq using eqs. (1) and (7) , where (t) is a time variant angle that represents the angular position of the reference frame . The current is rotating at constant speed in synchronism with Ac voltages . So the positive sequence of the fundamental current is a dc value . It is difficult to separate by a low pass filter only the negative sequence because its represents a 120 Hz oscillation (for a 60Hz mains) . The negative sequence is smaller than positive sequence and close to fundamental positive frequency. Also, the presence of a positive sequence, third harmonic current, will result a 120Hz signal. So, both negative sequence and third harmonic contributes to the 120Hz signal. In references [6] and [21], using a strategy similar to the one in item B-2 , the negative sequence is extracted by a composition of two vectors. The first one, obtained by using a positive rotating synchronous reference frame and the second, using a negative one. The load current is transformed into rotating frame dq using eqs. (1) and (7) , where (t) is a time variant angle that represents the angular position of the reference frame . The positive sequence of the fundamental current in dq components is a dc value that can be isolated by a low pass filter. The residual is formed by harmonics and negative sequences. The residual vector can be represented in a clockwise rotating frame (at -2 t speed).The negative sequence of the fundamental current in this frame is a dc value that can be isolated by a low pass filter .and corresponds to the compensating current vector. The harmonics elimination can be done by using as reference the oscillatory part of the negative reference frame.

The compensating currents are obtained by eqs. (8)and (2) , and the results simulated line currents are shown in fig. 6.

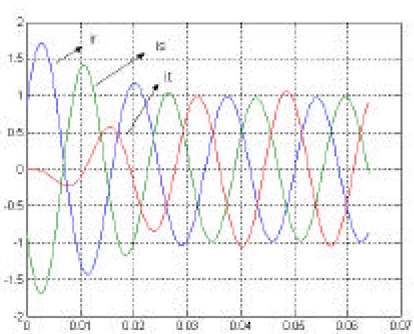

Figure 6 .- Compensated Line Currents by Negative Synchronous Reference Frame

To show the separation of negative sequence and harmonics , a current source , with 0.5 A amplitude , 180 Hz , is connected in parallel to the original resistive load (item II.A). The non-compensated and compensated line currents are shown in figures 7a and 7b respectively .

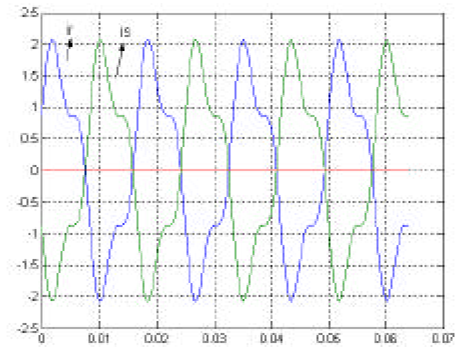

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Figure 7a .- Line Currents with harmonics and negative sequence

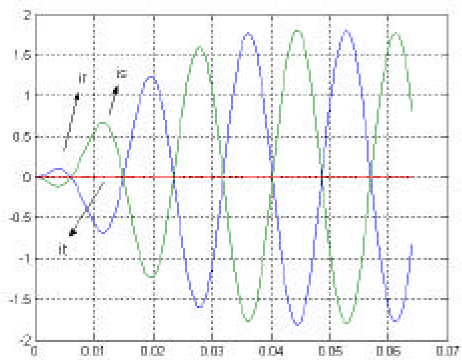

Figure 7b.- Line Currents without harmonics but still with negative sequence after only harmonics elimination

5) PQ METHOD

Another solution [11], studied in detail by [5], defines the instantaneous active and reactive power (p and q).

The instantaneous components of the voltage and current vectors in a fixed reference frame, are obtained by eq. (1). By eq. (9) the instantaneous power components , that are composed by a constant ($\bar{p};\bar{q}$) and a oscillatory part $\tilde{p};\tilde{q}$, are defined:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v & v \\ v & v \end{bmatrix} \cdot \begin{bmatrix} i \\ i \end{bmatrix} \qquad (9)$$

$$\begin{bmatrix} i \\ i \end{bmatrix} = \begin{bmatrix} v & v \\ v & v \end{bmatrix}^{1} \cdot \begin{bmatrix} p_c \\ q_c \end{bmatrix} \qquad (10)$$

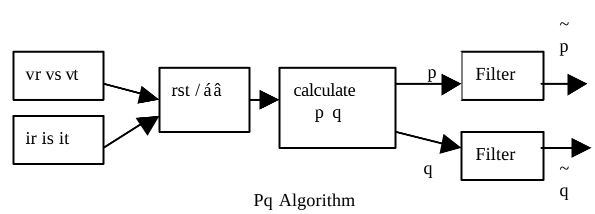

Figure 8 – pq Algorithm

Where p and q eq. (9) are define by Akagi [11] as real and imaginary instantaneous power. The compensating powers $p_c; q_c$ are defined as a combination of $\tilde{p}$, $\bar{q}$ and $\tilde{q}$, according to the user needs, and injected to the mains by using a converter. The components $\bar{p}, \tilde{p}$, $\bar{q}$ and $\tilde{q}$, are obtained by low and high pass filters (figure 8). The compensating currents are obtained from $p_c; q_c$, and eqs. (10) and (2). In this method it is difficult to separate the harmonics and unbalance. Also, distorted voltages will affect the compensation. There are problems, that must be observed like the influence of distorted voltage waveforms at PCC (point of common coupling) , they are analyzed and solutions are propose in [26].

PQ Method results simulated line currents are shown in fig. 9.

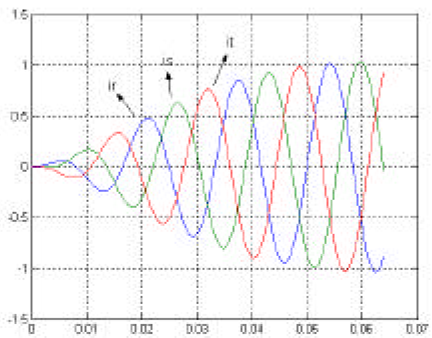

Figure 9 .- Compensated Line Currents by PQ Method

6) POWER BALANCE CONTROL METHOD

The real power supplied from the mains is equal to the real power demanded by the load plus losses in inverter . To maintain power balance , the dc capacitor must supply the power difference between the mains and the load under transient operation . The output of the dc voltage controller indicates the eventual changes in power balances and permits to impose directly the amplitude of desired sinusoidal line current. This amplitude is multiplied by the in phase sinusoids generated by a PLL (Phase-Locked Loop) system , leading to an estimation of the instantaneous fundamental active component of the load current . The advantages is that the load currents parameters were not required and the numbers of sensors is reduced .[29] . Full compensation is accomplished. Its impossible to separate unbalance and harmonics.

7) DIRECT NEGATIVE SEQUENCE INJECTION-DNSI

The use of this method to generate on line references for a PWM based compensator is presented , by the authors , based on results of [25] and the theory of symmetrical components [3]. In this solution method harmonics where neglected but the elimination of the negative sequence is done without any transformation method , using only algebraic calculations .

The necessary negative sequence current compensation can be calculated from the load currents phasors (Ir,Is,It) by eq. (11) , without proof due to space limitation . The complex matrix can be separated into two sub-matrices : one with real terms and other with imaginary terms multiply by j eq. (12) . The j of imaginary term has the same means of shift the waveform by 90º . So measuring the load currents and shifting them by 90º , we multiple the currents by the matrix terms that are now only constant values . The result of the sum of these multiplications is the reference current that will be injected , results simulated line currents are shown in fig. 10. This method will be better explained , including the operation with harmonics in a coming paper .

$$\begin{bmatrix} Ir \\ Is \\ It \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1\angle 60 & 1\angle -60 \\ 1\angle -60 & 1 & 1\angle 60 \\ 1\angle 60 & 1\angle -60 & 1 \end{bmatrix} \cdot \begin{bmatrix} Ir \\ Is \\ It \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} Ir \\ Is \\ It \end{bmatrix} = \frac{1}{3} \cdot \left(\begin{bmatrix} 1 & -1/2 & -1/2 \\ -1/2 & 1 & -1/2 \\ -1/2 & -1/2 & 1 \end{bmatrix} + j \begin{bmatrix} 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} & 0 & \frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \end{bmatrix} \right) \cdot \begin{bmatrix} Ir \\ Is \\ It \end{bmatrix} \quad (12)$$

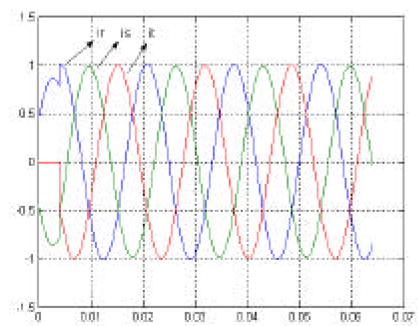

Figure 10 .- Compensated Line Currents by DNSI Method

C) OTHERS METHODS

There are others methods that can't be presented here because of lack of space but the references and details are indicated. They are: [17] synchronous detection method , [22] and [30] p-q-r theory, [24] based in time-domain analysis of the load currents ; [15] and [20] Average Power Method ; [28] Modified pq- method and [8] Detection Negative Power .

A comparison between Pq Method , Modified Pq Method Positive Synchronous Reference Frame and Modified Synchronous Reference Frame for active calculation of negative sequence under sinusoidal and non-sinusoidal conditions is done by [28] .

III. CONCLUSION

This paper gives an overview about techniques used for determining the compensation current for unbalanced loads. Each method is presented, including simulated results to show their performance. The absence of space forced the author to reduce the explanations about each method, eliminate some simulated results and present a concise comparison between the methods. Considering the necessity of extracting the negative sequence from harmonic corrupted currents, the methods shown in items B-1 and B-4 seems the more attractive ones.

The initial transient depends on the low-pass filter response and can be further improved .

IV. ACKNOWLEDGEMENT

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