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The discrete Fourier transform for computation of symmetrical components harmonics

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***Abstract*—The present paper describes a procedure for the on-line computation of the harmonics of symmetrical components based on the discrete Fourier transform (DFT) that uses all the information contained in the line-to-line voltages and line current. The proposed method has been tested experimentally to measure the harmonics of symmetrical components of a working three-phase induction motor for a wide interval of voltage source dissymmetry levels and for different load power levels.**

***Index Terms* — Power system faults – Power system harmonics - Discrete Fourier transform – Induction machines.**

I. INTRODUCTION

THE symmetrical component technique is a powerful tool for analyzing power networks under unbalanced operation in either the system load or the system components [1]. The estimation of symmetrical components can be used for efficient control and protection in electrical power systems. In fact, a power network is neither balanced nor free of harmonics and this leads to the fact that modern signal processing techniques are key-points to perform the measurements for fault detection. The usage of modern signal processing techniques in power systems is not new and lot of papers have been written in this domain [2], [3], [4], contributing to the development of specific digital instruments and permitting to take into account the real shape of the waveforms present in power systems. On the other hand, new textbooks give the most interesting algorithms to perform digital signal processing and to implement them on standard hardware [5], [6].

The analysis of power networks under unbalanced conditions has traditionally been performed using the method of symmetrical components applied to the main signal harmonic. The difficulty of measuring the phase-shift between the system variables (ie voltage and current) has led to the development of complex algorithms [7], [8], [9], limiting only the analysis to the fundamental components of line currents and line-to-line voltages and eliminating many important information coming from other harmonic components.

The aim of this paper is to describe a method to compute the symmetrical components of a system based on the discrete Fourier transform (DFT) that uses all the information contained in the line-to-line voltages and line current. In this sense, the information given by time harmonics in the power supply can be used to analyze voltage unbalance starting from current, voltage and impedance symmetrical components, completing the classical observation obtained by the study of the main harmonic components.

The first part of present paper is related to the theory of the symmetrical components in presence of harmonics. The second one describes a digital spectral method for the computation of the harmonics of symmetrical components which is applied to voltages and currents of a three-phase induction motor used as power system load. The proposed method has been tested experimentally to measure the harmonics of symmetrical components of a working three-phase induction motor for periodic or continuous monitoring in order to detect electrical faults. The stability of the results has been shown for a wide interval of voltage source dissymmetry levels and for different load levels. This has been done to test the robustness of the algorithm and its implementation on standard digital hardware.

II. SYMMETRICAL COMPONENTS THEORY

Considering the complex vectors of line-to-neutral voltages $[\underline{V}_a\ \underline{V}_b\ \underline{V}_c]^T$ and line currents $[\underline{I}_a\ \underline{I}_b\ \underline{I}_c]^T$ associated to the same load, the symmetrical components of voltages and currents are defined by the vectors $[\underline{V}_1\ \underline{V}_2\ \underline{V}_0]^T$ and $[\underline{I}_1\ \underline{I}_2\ \underline{I}_0]^T$ respectively. The subscripts *1-2-0* refer to positive, negative and zero sequence respectively. In the case of an unbalanced load, each sequence is seeing a different impedance from all others. This means that the transformation from *a-b-c* coordinates to *1-2-0* coordinates completely decouples the sequences. The impedances seen are usually noted as $\underline{Z}_1$, $\underline{Z}_2$ and $\underline{Z}_0$ for the positive, negative and zero sequences respectively.

The complex symmetrical components of voltages and currents are related by the following matrix equation :

$$\begin{bmatrix} \underline{V}_{1,h} \\ \underline{V}_{2,h} \\ \underline{V}_{0,h} \end{bmatrix} = \begin{bmatrix} \underline{Z}_{1,h} & 0 & 0 \\ 0 & \underline{Z}_{2,h} & 0 \\ 0 & 0 & \underline{Z}_{0,h} \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_{1,h} \\ \underline{I}_{2,h} \\ \underline{I}_{0,h} \end{bmatrix} \tag{1}$$

Industrial power distribution systems usually contain a great number of harmonic components. These harmonics are largely produced by the static power converters. In strictly balanced six-pulse based converter, only $6j\pm 1$ (with j=0,1,2,3,…) harmonic components are present. These

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harmonics are principally low frequency harmonics such as 1^{st}, 5^{th}, 7^{th}, 11^{th}, 13^{th}, … and the effect in the load is a sequence of phasors associated to the radian frequencies ω, -5ω, 7ω, -11ω, 13ω, …., for each harmonic component respectively. So, the direct components of harmonics 5^{th}, 11^{th}, …, of both voltages and currents can be located in the reverse direction with respect to the direct component of the 1^{st} harmonic ω. The corresponding inverse components are then located in the opposite direction of the 1^{st} harmonic ω. The direct components of harmonics 7^{th}, 13^{th}, …, of both voltages and currents can be located in the same direction as for the direct component of the 1^{st} harmonic ω and the inverse ones in the reverse direction. The zero sequence phasors have zero-phase displacement and thus are identical.

Positive, negative and zero harmonic sequence impedances can be expressed in their complex form by :

$$\underline{\boldsymbol{Z}}_{1,\mathrm{h}} = \frac{\underline{\boldsymbol{V}}_{1,\mathrm{h}}}{\underline{\boldsymbol{I}}_{1,\mathrm{h}}} \tag{2}$$

$$\underline{\boldsymbol{Z}}_{2,\mathrm{h}} = \frac{\underline{\boldsymbol{V}}_{2,\mathrm{h}}}{\underline{\boldsymbol{I}}_{2,\mathrm{h}}} \tag{3}$$

$$\underline{\boldsymbol{Z}}_{0,\mathrm{h}} = \frac{\underline{\boldsymbol{V}}_{0,\mathrm{h}}}{\underline{\boldsymbol{I}}_{0,\mathrm{h}}} \tag{4}$$

with h=1, 5, 7, 11, 13, ….

In order to determine the different harmonic components of both voltage and current with non-sinusoidal conditions, a signal processing has to be carefully designed to match the signal characteristics with respect to the fundamental harmonic. In the steady-state conditions, it is suspected that the voltage $v(t)$ and the current $i(t)$ are periodic over the interval T_1 given by the power system frequency f_1 ($T_1=1/f_1$). Although not purely sinusoidal, they are assumed to contain a finite number $(M-1)$ of harmonics. Then, the sampling period may be chosen to respect exactly the Shannon condition as :

$$\boldsymbol{T}_{\mathrm{s}} = \frac{\boldsymbol{T}_1}{2(M-1)} \tag{5}$$

III. DFT for Harmonics of Symmetrical Components

The DFT can be carried out with either real or complex sequences. The N samples time-domain signal $X_s[n]$ with the DFT given by $S[k]$ is decomposed into a set of $N-1$ cosine waves and $N-1$ sine waves with frequencies given by the index k. The magnitudes of the cosine waves are contained in the real part of the sequence $Re\{S[k]\}$ while the magnitudes of the sine waves are contained in the imaginary part $Im\{S[k]\}$. Sine and cosine waves can be described as having a "positive" frequency or a "negative" frequency. Since in a real sequence, the two views are identical, the Fourier transform ignores the "negative" frequencies.

In the complex Fourier transform, both $X_s[n]$ and $S[k]$ are arrays of complex numbers. The complex Fourier transform includes both positive and negative frequencies that means that $k=0, \ldots , N-1$ where N is the total number of samples. The reduced frequencies between 0 and $(N/2)-1$ are "positive", while the reduced frequencies between $(N/2)+1$ and $N-1$ are "negative", where $k=N/2$ corresponds with the *Nyquist* frequency and k=0 corresponds with the DC component.

With a three-phase set of sampled voltages $v_a[n]$, $v_b[n]$, $v_c[n]$ and a three-phase set of sampled currents $i_a[n]$, $i_b[n]$, $i_c[n]$, each one of the signals is obtained by using digital signal processing. The associated sampled complex voltage vector $\underline{\boldsymbol{V}}[n]$ and current vector $\underline{\boldsymbol{I}}[n]$ are given by (bold for vectors) :

$$\begin{aligned} \underline{V}[n] &= \frac{2}{3}\left[v_a[n] + v_b[n]\, e^{j\frac{2}{3}\pi} + v_c[n]\, e^{-j\frac{2}{3}\pi} \right] \\ \underline{I}[n] &= \frac{2}{3}\left[i_a[n] + i_b[n]\, e^{j\frac{2\pi}{3}} + i_c[n]\, e^{-j\frac{2\pi}{3}} \right] \end{aligned} \tag{6}$$

The coefficient 2/3 is chosen to make the vector magnitudes $|\underline{\boldsymbol{V}}(t)|$ and $|\underline{\boldsymbol{I}}(t)|$ equal to the peak value of the phase voltage and the line current respectively for the symmetrical sinusoidal case.

In fact, the voltage and current harmonic sequence components can be obtained directly by applying DFT to complex sequences $\underline{V}[n]$ and $\underline{I}[n]$ respectively (fig. 1). The finite complex sequences $\underline{V}_w[n]$ and $\underline{I}_w[n]$, that are digitally windowed values of $\underline{V}[n]$ and $\underline{I}[n]$, give the following frequency spectrum [10], [11] :

$$\begin{aligned} \underline{V}_w[k] &= \frac{1}{N}\sum_{k=0}^{N-1} \boldsymbol{V}_w[n] e^{-j\frac{2\pi k}{N}n} \\ \underline{I}_w[k] &= \frac{1}{N}\sum_{k=0}^{N-1} \boldsymbol{I}_w[n] e^{-j\frac{2\pi k}{N}n} \end{aligned} \tag{7}$$

The frequency resolution Δf depends clearly on the sample frequency T_s and the number of samples put in memory N and is given by:

$$\Delta \boldsymbol{f} = \frac{1}{T_S\, N} \tag{8}$$

It can be also expressed by the reverse of the acquisition time T_a which is nothing else that the product $N.T_s$:

$$\Delta \boldsymbol{f} = \frac{1}{T_a} \tag{9}$$

Voltage and current positive harmonic sequences $\underline{V}_{1,1}$, $\underline{I}_{1,1}$, $\underline{V}_{1,7}$, $\underline{I}_{1,7}$, $\underline{V}_{1,13}$, $\underline{I}_{1,13}$, …. are given by "positive" frequencies and the negative ones by "negative" frequencies as follows (fig.2):

$$
\begin{aligned}
&\underline{V}_{1,1} = \underline{V}_w\left[k_{f1}\right] && \underline{I}_{1,1} = \underline{I}_w\left[k_{f1}\right]\\
&\underline{V}_{1,7} = \underline{V}_w\left[7k_{f1}\right] && \underline{I}_{1,7} = \underline{I}_w\left[7k_{f1}\right]\\
&\underline{V}_{1,13} = \underline{V}_w\left[13k_{f1}\right] && \underline{I}_{1,13} = \underline{I}_w\left[13k_{f1}\right]\\
&\qquad\vdots && \qquad\vdots
\end{aligned}
$$

$$
\begin{aligned}
&\underline{V}_{2,1} = \underline{V}_w\left[N-k_{f1}\right] && \underline{I}_{2,1} = \underline{I}_w\left[N-k_{f1}\right]\\
&\underline{V}_{2,7} = \underline{V}_w\left[N-7k_{f1}\right] && \underline{I}_{2,7} = \underline{I}_w\left[N-7k_{f1}\right]\\
&\underline{V}_{2,13} = \underline{V}_w\left[N-13k_{f1}\right] && \underline{I}_{2,13} = \underline{I}_w\left[N-13k_{f1}\right]\\
&\qquad\vdots && \qquad\vdots
\end{aligned}
\tag{10}
$$

with

$$\boldsymbol{k_{f1}} = \frac{N}{2(M-1)}$$

Voltage and current positive harmonic sequences $\underline{V}_{1,5}$, $\underline{I}_{1,5}$, $\underline{V}_{1,11}$, $\underline{I}_{1,11}$, …. are given by negative frequencies and the negative ones by positive frequencies as follows :

$$
\begin{aligned}
&\underline{V}_{1,5} = \underline{V}_w\left[N-5k_{f1}\right] && \underline{I}_{1,5} = \underline{I}_w\left[N-5k_{f1}\right]\\
&\underline{V}_{1,11} = \underline{V}_w\left[N-11k_{f1}\right] && \underline{I}_{1,11} = \underline{I}_w\left[N-11k_{f1}\right]\\
&\qquad\vdots && \qquad\vdots
\end{aligned}
\tag{11}
$$

$$
\begin{aligned}
&\underline{V}_{2,5} = \underline{V}_w\left[5k_{f1}\right] && \underline{I}_{2,5} = \underline{I}_w\left[5k_{f1}\right]\\
&\underline{V}_{2,11} = \underline{V}_w\left[11k_{f1}\right] && \underline{I}_{2,11} = \underline{I}_w\left[11k_{f1}\right]\\
&\qquad\vdots && \qquad\vdots
\end{aligned}
$$

Then, with values obtained by (9) and (10), positive, negative and zero harmonic sequence impedances can be computed using the expressions (2), (3) and (4).

It is clear that the magnitude resolution depends closely of the experimental conditions in which the data acquisition is performed and mostly of the number of bits *b* the different analog to digital converters. It depends also of the sensor accuracy which is also a tricky point since for voltages and currents, they cannot be homogeneous. The, the magnitude resolution limits also the frequency bandwidth for which both positive and negative sequences harmonic components are evaluated. In the example presented (fig. 2), the magnitude resolution is around 100dB for the voltage and only 80dB for the current. For the current harmonic analysis, the reverse component of rank 11 is already less than –60dB which set the limitation.

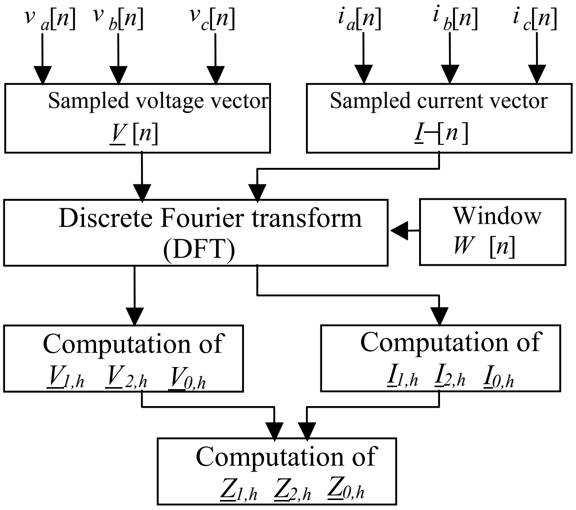

Fig. 1. Positive and negative sequence impedances computation using complex DFT.

IV. EXPERIMENTAL RESULTS

A. *Test-bed description*

A specific experimental set-up has been designed in order to perform the algorithm implementation (fig. 3). It is based on a three-phase voltage source that facilitates the simulation of a set of unbalanced voltages. Three voltage sensors and three current sensors with galvanic insulation are used to monitor the power system opreration. A magnetic brake, which can be tuned by means of a control unit, has been used to simulate the shaft load. A 0.12kW, 50Hz, 220V/380V, 2-pole three-phase induction machine is used, as a machine under test (MUT), to observe the behavior of the symmetrical components (voltage, current and impedance) under the effect of a voltage source dissymmetry.

The power system voltages and currents are measured by means of the sensors connected to the motor terminals. The six signals are used as inputs of the signal conditioning and the data acquisition board integrated into a personal computer (PC). The current probes are realized with Rogowski coils with a typical frequency bandwith of 50kHz. The voltage sensors are special transformers with large frequency bandwith of 5kHz. The algorithm for the symmetrical components evaluation and all the digital operations have been implemented by using the MATLAB™ environment.

B. *Computation of the symmetrical components and their harmonics*

The first stage in the experimental study consists in the analysis of the time-domain evolution for the power system voltages and currents with four levels of unbalanced voltage source that affects only one phase voltage magnitude with 0%, -5%, -10% and -20% of the rated phase voltage.

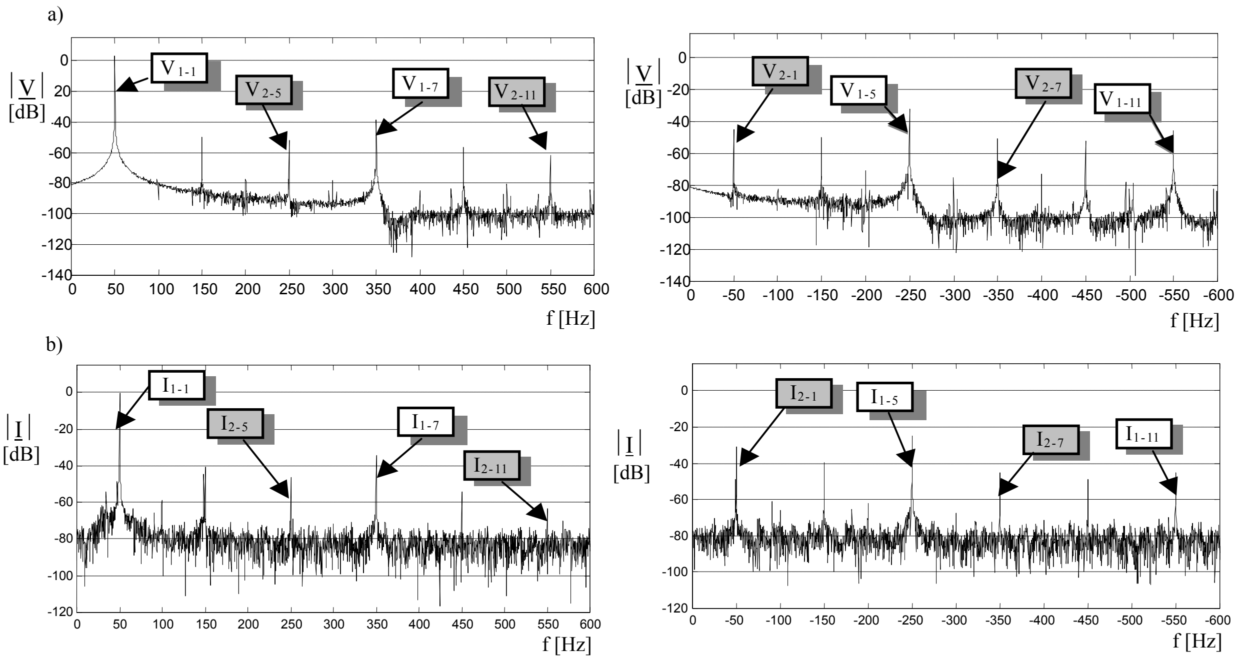

Fig. 2. Localization of the harmonics of both positive and negative components of voltages and currents into the spectrum of : a) voltage b) current

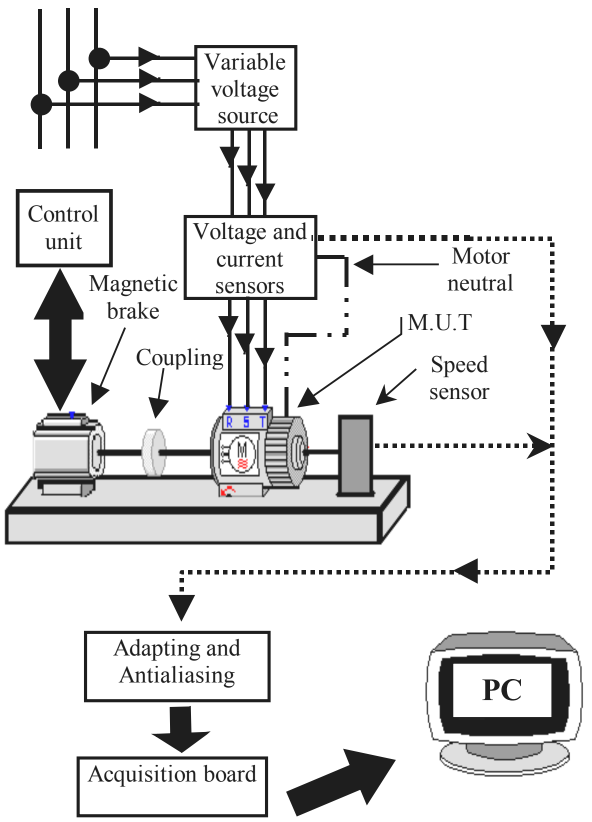

Fig. 3. Configuration of the test-bed.

Thus, each one of the previous cases has been performed with the induction motor operating at five levels of mechanical load : from 0 to 100% of the rated value by steps of 25%. For each case, the stator voltages and currents have been collected within a time period large enough (3.5s i.e. 175 periods) to perform averaging. For these cases of unbalanced operation, only the negative sequences are analyzed.

The modulus of the fundamental negative components ($\underline{\boldsymbol{V}}_{2,1}$, $\underline{\boldsymbol{I}}_{2,1}$ and $\underline{\boldsymbol{Z}}_{2,1}$) for the induction motor in test and their harmonics ($\underline{\boldsymbol{V}}_{2,h}$, $\underline{\boldsymbol{I}}_{2,h}$ and $\underline{\boldsymbol{Z}}_{2,h}$) have been computed by means of the proposed method. Thus, the experimental results to study the component evolution have been analyzed as function of the induction motor load level and the unbalance level applied to one phase of the power supply. The effect of voltage source dissymmetry on the inverse sequence of voltage and current of both the first harmonic (fig. 4) and the fifth one (fig. 5) is clearly indicated looking to the evolution of their magnitude with respect to the power supply dissymmetry level. The equivalent parameters are given in *pu* with references to the rated values of both stator voltage and line current. The 3D representations show clearly that the numerical results are quite stable since the surfaces have no singularities. On the contrary, $\underline{\boldsymbol{Z}}_{2,5}$, $\underline{\boldsymbol{V}}_{2,5}$, $\underline{\boldsymbol{I}}_{2,5}$ show a small dispersion which corresponds with small numerical values related to no-load operation with symmetrical supply voltages case, knowing that in theory the equivalent circuit of negative sequence is not excited. In this case, it is suspected that both natural unbalance of the machine windings are superposed with the small unbalance of the power supply without permitting to separate the two phenomena.

It is obvious that the inverse voltage magnitude is directly proportional to the unbalance level as expected. The coefficient of proportionality is corrupted for high-level load torque without large difference. For 20% of voltage unbalance, the magnitude of the voltage $\underline{V}_{2,1}$ reaches a value around 0.08*pu*. The magnitude of the inverse sequence current $\underline{I}_{2,1}$ has the same shape compared to the voltage but the level reached is closed to 0.4*pu* for this load. Then, as expected from the previous operations, the module of the inverse complex impedance $\underline{Z}_{2,1}$ is around 0.2*pu* except some differences for low levels of both voltage and current.

Concerning the negative components $\underline{V}_{2,5}$, $\underline{I}_{2,5}$ and $\underline{Z}_{2,5}$ of the fifth harmonic, it can be noted from fig. 6 that they have the same general tendency, and compared to the gravity of level of unbalance, that those of the first harmonic have less significant values. In this case, the machine continues to develop an inverse impedance nearly stable around 0.53pu. On the contrary to negative components of voltage and current of 1st and 5th harmonics, those of 7th and 11th harmonics show an insensitivity to unbalance level and respond in a random way. However, the machine still continues to develop a nearly constant value of negative impedance as it is shown in (fig. 6).

With the proposed algorithm implementation, it has been verified that for the induction machine, the magnitude of the inverse sequence impedance is completely independent of the load both for the fundamental but also for the time harmonics. Of course, this is more clear for the fundamental since when the rank of the harmonics increases, the magnitude resolution decreases and the computation are less accurate.

V. Conclusion

A spectral method for on-line computation of the harmonic symmetrical components has been proposed. This method is based on the DFT computation of complex sequences which, in the case of voltage and current vectors, facilitates the extraction of the information given by power supply harmonics to characterize system load operation. The proposed method can be used to detect electrical faults in the load or in the power grid on the base of the comparison with respect to the normal operation. The obtained results show the efficiency of the method that can be implemented in a simple hardware with low-cost voltage and current sensors.

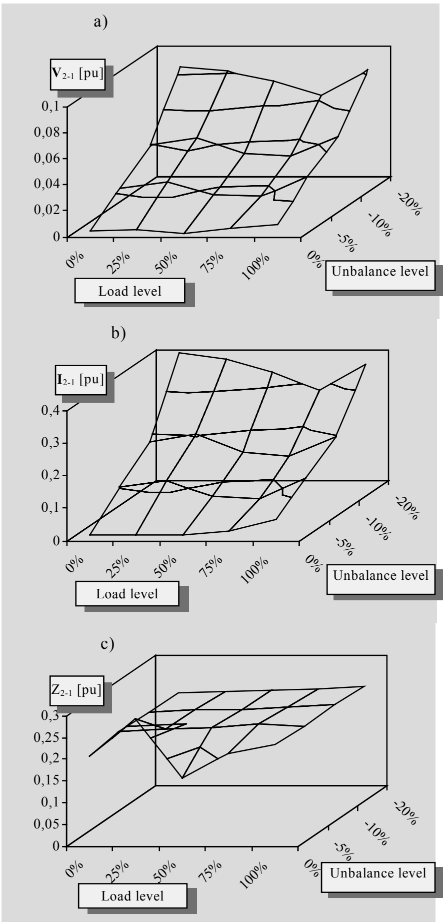

Fig. 4. Inverse sequence fundamental components : Voltage – b) Current – c) Impedance

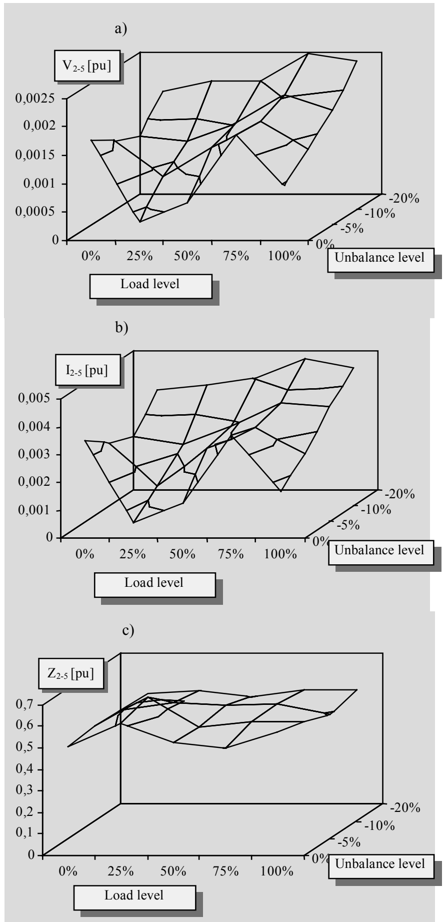

Fig. 5. Inverse sequence components for the fifth harmonic :
a) Voltage – b) Current – c) Impedance

The proposed methodology can be completed by decision tools which permit to select automatically the harmonic selection and to evaluate the influence of their magnitude evolution to decided if there is a fault or not. This is also critical since it is important to decide clearly if the unbalance is due a power grid fault, a load fault or both. This will be one of the evolution of the proposed method in the near future.

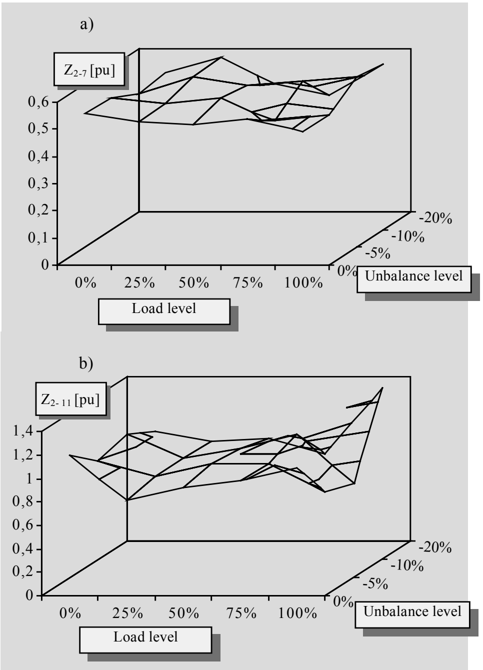

Fig. 6. Inverse sequence impedance for harmonics :
a) 7th – b) 11th

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VII. Biographies

H.Henao received the M.S. degree in electrical engineering from *Universidad Tecnologica de Pereira*, Colombia in 1983, the M.S. degree in power system planning from *Universidad de los Andes*, Bogota (Colombia) in 1986, the Ph.D degree in electrical engineering from *Institut National Polytechnique de Grenoble* in 1990.
From 1987 to 1994, he was consultant for companies as *Schneider Industries* and *GEC Alsthom* in the Modeling and Control Systems Laboratory, *Mediterranean Institute of Technology*, Marseille. In 1994, he joined the *Ecole Supérieure d'Ingénieurs en Electrotechnique et Electronique*, Amiens as Associate Professor. In 1995, he joined the *University of Picardie "Jules Verne"* as an Associate Professor in the Department of Electrical Engineering. He is currently the Department representative for the international programs and exchanges (SOCRATES).
Dr. Henao's main research interests are the modelling, simulation monitoring and diagnosis of electrical machines and electrical drives.

T. Assaf received the M.S. degree in electrical engineering from the *University of Sciences and Techniques of Lille* in 1999. Since then, he is preparing his PhD in the Department of Electrical Engineering of the *University of Picardie "Jules Verne"*, Amiens under the supervision of Prof. G.A. Capolino and Dr. H. Henao. He is a granted by the Syrian government. His research interest are electrical machines and drives for which he developed methods to detect electrical faults using voltage, current and flux sensors.

G.-A. Capolino received the B.S. degree in electrical engineering from *Ecole Supérieure d'Ingénieurs de Marseille* in 1974, the M.S. degree in electrical engineering from *Ecole Supérieure d'Electricité*, Paris in 1975, the Ph.D. degree in electrical engineering and computer science from University Aix-Marseille I in 1978 and the D.Sc. degree in engineering sciences from *Institut National Polytechnique de Grenoble* in 1987.
In 1978, he joined the *University of Yaoundé*, Cameroon as an Associate Professor and Head of the Department of Electrical Engineering. From 1981 to 1994, he has been Associate Professor in *University of Dijon* and the *Mediterranean Institute of Technology*, Marseille where he was founder and Director of the Modelling and Control Systems Laboratory. From 1983 to 1985, he was visiting Professor at University of Tunis, Tunisia. From 1987 to 1989, he was the scientific advisor of *Technicatome SA* in the field of electrical drives for nuclear propulsion. In 1994, he joined the *University of Picardie "Jules Verne"* as a Full Professor, Head of the Department of Electrical Engineering from 1995 to 1998 and Director of the Energy Conversion & Intelligent Systems Laboratory from 1995 to 1999. He is currently the Director of Graduate Studies in electrical engineering for the *University of Picardie "Jules Verne"*.
Prof. Capolino's research interests are electrical machines, power electronics and electrical drives for which he has introduced new techniques of modelling, control and simulation. He has developed new courses in power electrical engineering based on computer assistance. He has published more than 200 papers in scientific journals and conference proceedings and he has co-authored the book *Simulation & CAD for Electrical Machines, Power Electronics and Drives* (ERASMUS Program Edition, Brussels, 1991).
Prof. Capolino is Fellow of the IEEE and he is currently an Associate Editor of the IEEE Transactions on Industrial Electronics.