Electric Power Systems Research 141 (2016) 487–499

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Practical evaluation of unbalance and harmonic distortion in power conditioning

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ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form 6 June 2016
Accepted 9 August 2016

Keywords:
Power quality
Harmonics
Unbalance
Measurement
Active power filter
Series–shunt active compensation

ABSTRACT

This paper presents a method for assessing the quality improvement of the electric power obtained by using compensation equipment based in active power filters, APF. Power quality indicators that allow to separate the contribution to unbalance of each harmonic and interharmonic of voltages and currents are introduced, calculated with an enhanced procedure. To characterize the behavior of these indices, a parallel active compensator, and a series–parallel active compensator have been used for the compensation in a system with unbalance and distortion. The results obtained with an experimental platform designed for the purpose have allowed to verify the validity of the proposed procedure and they have shed new light on the interpretation of the indices of unbalance and harmonic distortion.

1. Introduction

The standard IEEE Std. 1459–2010 represents nowadays the most extended model for the decomposition of the apparent power terms, in conditions of asymmetry and distortion [1]. However, this model does not include an adequate assessment of the unbalance caused by the load [2]. This is particularly significant in relation to the contribution to the unbalance produced by the set of harmonics different from the fundamental. This shortcoming is accentuated when modern compensation equipment is used, like active power filters with parallel connection; or combined series–parallel compensation equipment [3–8]. In the latter case, using an adequate compensation strategy, it can eliminate the harmonics and unbalance of the current and to obtain a conditioned voltage at the load terminals. On the other hand, the use of active compensation equipment based on power inverters involves the appearance of time-variant waveforms of voltage and current. The analysis of these waveforms in the frequency domain results in the occurrence of harmonics and interharmonics. Specifically, Std IEC 61000-4-7 establishes a resolution of 5 Hz for spectral analysis in the measurement of voltage and current. Fourier analysis of the waveforms at the PCC and the load terminals provide results for the frequency of 5 Hz and all integer multiples. The need to provide the power terms and associated indexes to characterize the resulting mitigation require a model decomposition of the apparent power that makes explicit the contribution of harmonics to unbalance [9–11]. The works [9,10] established a new model of decomposition of the apparent power that can separate it into four components, and from there, to define three indices to characterize the unbalance and distortion. However, this model does not include the contribution of interharmonics to each power component. In Ref. [11], a transformation matrix is introduced that allows to obtain the balanced, first unbalanced, and second unbalanced components for waveforms that include interharmonics. This work relies on these previous proposals to develop an efficient method of computation of the balanced and unbalanced components in the measured waveforms of voltage and current in systems with load active conditioning.

This new procedure has been applied to an unbalanced and distorted system, both in load and supply; before and after the connection of a shunt active compensator, and with combined series–parallel compensation. The description of the experimental setup and the obtained results will be presented, to evaluate the performance of the proposed procedure and the characterization of the power indices in these applied cases.

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http://dx.doi.org/10.1016/j.epsr.2016.08.012

2. Power components and Power Quality indices in unbalanced and nonsinusoidal situations

In balanced nonsinusoidal three-phase systems, where the waveforms are repeated every one-third of a cycle in the corresponding phase, the voltage and current harmonics can be divided in three groups with different phase sequences. The harmonics set of order $3h+1$ (for $h=0,1,2,\ldots$) that have a positive sequence of phases, the set of order $3h+2$ that have a negative phase sequence, and the set of order $3h+3$ that are in phase with each other (zero sequence). However, in an unbalanced and nonsinusoidal system, that rule no longer holds. The determination of the balanced and unbalanced harmonic components is important, among other reasons, because some solutions against harmonic distortion are based in that assumption. For instance, the Δ connection of the transformer windings to block the 3rd order harmonics, or the change in the behavior of the nonlinear loads against unbalance.

A recent proposal to set the balanced and unbalanced components of each signal is the transformation defined in Ref. [11]. It calculates a balanced component and two unbalanced components, defined through the following relation:

$$\begin{bmatrix} X_{br} \\ X_{u'r} \\ X_{u''r} \end{bmatrix} = T_r \cdot \begin{bmatrix} X_{Ar} \\ X_{Br} \\ X_{Cr} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha_k & \alpha_{2k} \\ 1 & \alpha_{k+1} & \alpha_{2k+2} \\ 1 & \alpha_{k+2} & \alpha_{2k+1} \end{bmatrix} \cdot \begin{bmatrix} X_{Ar} \\ X_{Br} \\ X_{Cr} \end{bmatrix} \quad (1)$$

where X_{Ar}, X_{Br} and X_{Cr} are the phasors of the voltages or currents of each phase, at the angular frequency $r{\cdot}\omega_F$, obtained from the Fourier transform of the instantaneous values in a measuring window of period $T_F = 2\pi/\omega_F$ (where ω_F defines the frequency resolution of the Fourier transform); and X_{br}, $X_{u'r}$, $X_{u''r}$ are the corresponding balanced, first unbalanced and second unbalanced components. The transformation matrix T_r is defined using the complex exponential expressions $\alpha_{(\cdot)} = e^{j(\cdot)2\pi/3}$, with $k = r\ \omega_F/\omega_1$; where $r = 1,2,\ldots N$ is the harmonic order respect to the fundamental frequency of the measuring window. k is the relative harmonic order, referred to the fundamental frequency of the system, ω_1; and it takes integer values for the harmonics of ω_1 and noninteger values for the remaining interharmonics. The transformation matrix T_r satisfies, for all possible values of k, the orthogonality property

$$T_r{}^* \cdot T_r{}^T = T_r{}^T \cdot T_r{}^* = \frac{1}{3} I \quad (2)$$

where the superscript * represents the conjugate, ^{T} the transpose, and I is the identity matrix. This property allows to establish the following relation between the magnitudes of the phasors of the phase values and those of the phasors of the unbalance components:

$$X_{Ar}^2 + X_{Br}^2 + X_{Cr}^2 = 3\left(X_{br}^2 + X_{u'r}^2 + X_{u''r}^2\right) \quad (3)$$

This relation is very useful to define the balanced and unbalanced components of voltages and currents, because the definition of the effective values V_e and I_e in the IEEE Standard 1459 [1] is based in quadratic expressions of the magnitudes.

However, before exposing the development of the different terms, it is convenient to explain the relation between the balance/unbalance components and the Fortescue symmetrical components. First of all, because the symmetrical components of the harmonic spectrum can be obtained more efficiently using the FFT Transform over the Park vector of the three-phase signals [12], saving computational cost. And secondly because the explicit relationship helps to understand how symmetrical components are transformed into balanced or unbalanced components.

When the inverse Fortescue transform is used to substitute the phase components by the symmetrical components in Eq. (1), the resultant relationship is:

$$\begin{bmatrix} X_{br} \\ X_{u'r} \\ X_{u''r} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} b_1 & b_2 & b_3 \\ b_3 & b_1 & b_2 \\ b_2 & b_3 & b_1 \end{bmatrix} \cdot \begin{bmatrix} X_{Pr} \\ X_{Nr} \\ X_{Zr} \end{bmatrix} \quad (4)$$

where X_{Pr}, X_{Nr} and X_{Zr} are the positive, negative and zero sequence phasors at this frequency, and the coefficients b_1, b_2, b_3 have the expressions

$$\begin{aligned} b_1 &= 1 + \alpha_{k+2} + \alpha_{2(k+2)} \\ b_2 &= 1 + \alpha_{k+1} + \alpha_{2(k+1)} \\ b_3 &= 1 + \alpha_k + \alpha_{2k} \end{aligned} \quad (5)$$

The three coefficients have the same functional structure and are periodicals for k, with period 3. For instance, the expression for b_3 can be represented as:

$$b_3 = 1 + \alpha_k + \alpha_{2k} = \left(1 + 2\cos\frac{2\pi k}{3}\right) e^{j\frac{2\pi k}{3}} \quad (6)$$

Fig. 1a shows the polar plot of Eq. (6) and Fig. 1b presents the magnitudes of the complex coefficients b_1, b_2, b_3 as a function of k. The three values evolve cyclically, changing the position of the symmetrical components into the balance/unbalance components. For instance, when $k=1$, the transformation matrix of Eq. (4) is the identity matrix; identifying the positive-sequence component, X_{Pr}, with the balanced component, X_{br}, and the negative and zero sequence components with the first and second unbalanced components respectively. When $k=2$ the balanced component is the negative-sequence component, X_{Nr}; and when $k=3$ the balanced component is the zero-sequence component, X_{Zr}. This figures allow also to estimate the weight of each symmetrical component at the balance/unbalance components when k has noninteger values. For instance, for interharmonics very near the fundamental frequency, the major contribution to the balanced component X_{br} is from the positive-sequence X_{Pr}.

On the other side, the calculation of the equivalent voltages and currents according to IEEE Std. 1459 can be formulated with the Fortescue symmetrical components [1],

$$\begin{aligned} V_e^2 &= \sum_{\forall k} V_{ek}^2 = \sum_{\forall k}\left[V_{Pk}^2 + V_{Nk}^2 + \frac{V_{Zk}^2}{1+\xi}\right] \\ I_e^2 &= \sum_{\forall k} I_{ek}^2 = \sum_{\forall k}\left[I_{Pk}^2 + I_{Nk}^2 + (1+3\rho) I_{Zk}^2\right] \end{aligned} \quad (7)$$

where ξ is the ratio between the Y and Δ equivalent load active powers, and use to be taken as 1.0 as the general case; and ρ is the ratio between the resistance of the neutral conductor and of the phase conductors, also usually considered as 1.0 [1]. If the symmetrical component magnitudes are formulated into balanced and unbalanced components, the values of the equivalent voltages and currents can be separated in both components at each frequency,

$$\begin{aligned} V_{er}^2 &= \left[V_{Pbk}^2 + V_{Puk}^2 + V_{Nbk}^2 + V_{Nuk}^2 + \frac{V_{Zbk}^2 + V_{Zuk}^2}{1+\xi}\right] \\ V_{ek}^2 &= V_{ebk}^2 + V_{euk}^2 \end{aligned} \quad (8)$$

$$\begin{aligned} I_{ek}^2 &= I_{Pbk}^2 + I_{Puk}^2 + I_{Nbk}^2 + I_{Nuk}^2 + (1+3\rho)(I_{Zbk}^2 + I_{Zuk}^2) \\ I_{ek}^2 &= I_{ebk}^2 + I_{euk}^2 \end{aligned} \quad (9)$$