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Assessment of unbalance and distortion components in three-phase systems with harmonics and interharmonics

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ABSTRACT

This paper deals with the identification of balance, unbalance and distortion components in unbalanced three-phase systems with distorted waveforms containing harmonics and interharmonics. The analysis starts from the harmonic distortion and unbalance components found through the symmetrical component-based (SCB) approach previously defined by the authors. The SCB approach is extended in this paper by introducing an auxiliary reference frequency and identifying its consistency condition with respect to the fundamental system frequency. After defining the auxiliary reference frequency, the proposed approach directly uses the classical symmetrical component transformation matrix at any harmonic or interharmonic. Various results are presented, for conventional test cases and for measurements gathered from real systems with variable unbalanced and distorted loads. These results show that the extended SCB approach is particularly useful to analyze three-phase systems in unbalanced and distorted conditions with harmonics and interharmonics, because of its simplicity and intuitiveness compared to other approaches.

1. Introduction

A three-phase system with periodic phase current waveforms (period T) is defined as *balanced* if the phase current waveforms are equal in shape, are regularly shifted in time of $T/3$ and the sequence of phase rotation is conventional (i.e., counterclockwise). Otherwise, the three-phase system is *unbalanced*. The definition of balance works regardless of the possible waveform distortion with respect to the sinusoid at the fundamental frequency. The classical definition of unbalance, i.e., the ratio between the negative and the positive sequence components, takes into account only the components at the fundamental frequency. Likewise, the classical definition of the total harmonic distortion (*THD*) refers to balanced three-phase systems only. However, in practice, unbalance, harmonics and interharmonics [1] are simultaneously present in actual systems.

The extraction of information concerning the levels of unbalance and distortion in three-phase systems with neutral has been addressed recently. First and second unbalance components have been determined in [2] by considering harmonic distortion, resorting to different transformation matrices applied at different harmonic orders; however, these two components have no individual physical meaning and are combined together to represent the system unbalance. The symmetrical component transformation has been applied in [3] to study the harmonic distortion due to fluorescent lamps, by considering only odd harmonics and providing a simple formulation of the neutral-to-phase current ratio in a particular case. Furthermore, the approach of [2] has been applied in [4] to extend the definition of apparent power based on symmetrical components to the case of non-sinusoidal waveforms.

In [5] the symmetrical component-based (SCB) approach has been introduced to exploit the same transformation matrix from phase quantities into symmetrical components to separate balance, unbalance and distortion components. The rationale for this separation is based on the fact that a balanced waveform may contain components at different harmonics, and the balance components are obtained by picking up selected entries of the transformed voltage and current vectors at different harmonic orders. The unbalance components are directly taken from the complementary entries calculated by using the same transformation matrix, without the need to create the first and second unbalance components. The SCB balance, unbalance and distortion components are defined as sums of squared RMS values of the transformed components at

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each harmonic order [6]. The SCB approach has been applied in [7] to characterize the harmonic distortion in photovoltaic systems with different types of unbalance (that is, structural unbalance, unbalance from partial shading, and mixed unbalance).

Recently, the approach used in [2] has been extended in [8] and [9] to take into account interharmonics, again using different versions of the transformation matrices. An application of this method of evaluation of unbalanced and distorted components has been presented in [10] to characterize the disturbance compensation obtained by active power filters. Furthermore, in [11] the use of the Discrete-Wavelet transform has been proposed to evaluate the symmetrical components. This approach has shown to be adequate also for studying non-stationary distorted and unbalanced waveforms. The effects of unbalance, harmonics, and interharmonics on phase-locked loop systems (PLL) have been analyzed in [12], resulting in the proposal of analytical formulas that characterize the PLL phase angle and frequency errors in the presence of disturbances.

Following the same rationale used in [8], the main contribution of this paper is to extend the SCB approach to take into account interharmonics, providing a simple identification of the balance, unbalance and distortion components. This extension is presented for the general case of distorted waveforms with harmonics and interharmonics, when the output from the measurement system is gathered by using a proper sampling rate in the frequency domain. The consistency conditions for proper sampling are established in this paper by introducing an auxiliary reference frequency in the general case. The sampling rate is then chosen in a way consistent with current standards, in particular with Standard IEC 61000-4-7 [13] defining the harmonic and interharmonic groups and subgroups. Finally, the balance, unbalance and distortion indicators are calculated with the extended SCB approach on the basis of their corresponding components.

The rest of the paper is organized as follows. Section 2 introduces the general hypotheses used in the approach presented in this paper to deal with harmonics and interharmonics in balanced systems. Section 3 illustrates the extension of the SCB indicators to interharmonics for a general unbalanced system with distorted waveforms. Section 4 shows some examples of application to test cases and real-case measurements, highlighting the calculation of the various components and indicators. The last section contains the concluding remarks.

2. Assessment of the sequences in a balanced system

Let us first consider a balanced three-phase system, in which the waveforms gathered in the time domain are subject to the Fast Fourier Transform (FFT) in order to obtain the related components in the frequency domain.

Let us formulate the frequency axis partitioning in two different ways:

1. partitioning according to the nominal system frequency $f_1 = 50$ Hz (or 60 Hz), associated to the variable f_h for the harmonic order $h = 1, \ldots H$, with frequency variation step Δf_h;
2. partitioning depending on the rate used for sampling the waveform in the harmonics domain, that is, 5 Hz for $f_1 = 50$ Hz (i.e., 10 periods for a total of 200 ms, while 12 periods are used for $f_1 = 60$ Hz) as indicated in the Standard IEC 61000-4-7, associated to the auxiliary variable $\hat{f}_z$ for $z = 1, \ldots, N_Z$, with frequency variation step $\Delta\hat{f}_z$.

Let us now assume that the following *consistency conditions* are satisfied for any integer $k = 0, 1, 2, \ldots$:

$$H = 10^{-k} N_Z \tag{1}$$

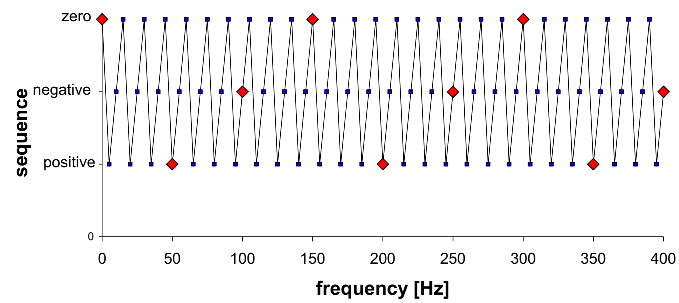

Fig. 1. Identification of the positive, negative and zero sequences for a balanced system at 5-Hz fundamental frequency (small points) and at 50-Hz fundamental frequency (large points).

$$\Delta f_h = 10^k \Delta\hat{f}_z \tag{2}$$

By using the FFT to process the waveform measured for a duration $T = 10^k/f_1$ with $k > 0$, the waveform components at frequency multiple of $1/T$ are seen as harmonics resulting from the FFT, but are interharmonics for the system operating at fundamental frequency f_1 [8]. Because of this, in the sequel the variable z will be denoted as interharmonic order. In particular, starting from this general condition, the case $k = 0$ corresponds to the calculation carried out by considering only the harmonic orders defined at frequency f_1, while the case $k = 1$ is the one considered in the Standard IEC 61000-4-7.

The maximum interharmonic order N_Z can be linked to the maximum harmonic order considered in the classical harmonic analysis, for which $H = 40$ or $H = 50$ are used, by applying (1). If $k = 1$ the resulting values are $N_Z = 400$ or $N_Z = 500$, respectively.

By applying the SCB approach to the FFT results with auxiliary fundamental frequency $\hat{f}_1 = 5$ Hz, if the three-phase system is balanced, the components associated with positive, negative and zero sequences are illustrated in Fig. 1. In the figure, the small points represent the frequencies drawn with the frequency variation step $\Delta\hat{f}_z$, and the large points represent the frequencies multiple of f_1. From Fig. 1, if the consistency conditions are satisfied, the positive, negative and zero sequences assigned to the components at the frequency variation step Δf_h are fully consistent with the sequences assigned to the components at the frequency variation step $\Delta\hat{f}_z$.

The same concept is represented in Table 1, showing the sequences referring to the various harmonic orders and to the interharmonic bands defined in the standard IEC 61000-4-7 (zero frequency included).

3. Extension of the SCB indicators

3.1. Interharmonics-based balance, unbalance and distortion components

Let us now consider a general unbalanced three-phase system, in which the three phase currents at the interharmonic order $z = 1, \ldots, N_Z$ are identified by the phasors $\mathbf{i}^z = \left[\bar{I}_a^z \bar{I}_b^z \bar{I}_c^z\right]^{\mathrm{T}}$, where the superscript T denotes vector transposition. Applying the symmetrical component transformation matrix [14] with the operator $\alpha = e^{\mathrm{j}\frac{2\pi}{3}}$, at each interharmonic order the triplet of phase current phasors is transformed into the new triplet $\mathbf{i}_{\mathrm{T}}^z = \left[\bar{I}_{\mathrm{T1}}^z \bar{I}_{\mathrm{T2}}^z \bar{I}_{\mathrm{T3}}^z\right]^{\mathrm{T}}$, as follows:

$$\begin{vmatrix} \bar{I}_{\mathrm{T1}}^z \\ \bar{I}_{\mathrm{T2}}^z \\ \bar{I}_{\mathrm{T3}}^z \end{vmatrix} = \frac{1}{3} \begin{vmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{vmatrix} \begin{vmatrix} \bar{I}_a^z \\ \bar{I}_b^z \\ \bar{I}_c^z \end{vmatrix} \tag{3}$$

The interharmonics-based components are defined here as in [5], by using the superscripts b for balance, u for unbalance, and d for distortion. The notion of positive, negative and zero sequences