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Effective electric power quantities and the sequence reference frame: A comparison study

O. Boudebbouz*, A. Boukadoum, A. Medoued

Department of Electrical Engineering, Laboratoire d'électrotechnique de Skikda «LES», Université du 20 Août 1955, Skikda 21000, Algeria

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ABSTRACT

More recently, unbalanced and distorted electric three phase quantities have been analyzed in the sequence reference frame, successively, by two elegant decomposition techniques referred to Girgis and Langella. Some comparisons regarding the matrices structures of the two methods have been drawn out in the Langella work. The latter also, makes it possible to evaluate the quantities defined in the IEEE Standard 1459-2010 by means of harmonic sequence components. Some previous author's works have focused on the Girgis method in which they analyzed the harmonic resonance phenomena and evaluated the quantities defined in the IEEE Standard 1459-2010 in the sequence reference frame. In the present work, the authors follow up with the Langella method and they present more explicit sequence effective electric quantities based on the two methods. Some substantial comparisons between the aforementioned works are presented as well.

1. Introduction

For a long ninety years ago, the sequence reference frame initiated by Fortescue has, only, been adopted for linear unbalanced three-phase power systems [1]. It sets down the theory of symmetrical components as well as the methods to be used in the steady state analysis of AC circuits. It is used daily by modern power engineers who deal with three-phase circuits. Analysis of three-phase circuits in an efficient and comprehensible way is the key importance of the Fortescue paper [2]. Some recent works have focused on the Fortescue method in nonlinear electric power systems [3–5]. In [3], the instantaneous approach has been applied to IEEE Standard 1459 power terms and quality indices. In this work, the sequence reference frame has been only considered for fundamental electric quantities. In [4], non-fundamental effective apparent power defined through an instantaneous power approach has been, only, proposed for balanced harmonics. In [5], forward generalization to harmonic domain of effective voltage expression contained in Section 3.2.2.8 of the IEEE Standard 1459-2010 [6], has been noted without showing any matrix used for obtaining the sequence harmonic components. Implicitly, we understand that the Fortescue transformation has been considered as an analysis tool in the harmonic domain.

The Fortescue transformation has some limitations for nonlinear systems and more recently, two new methods have been proposed to the study the unbalance in the presence of harmonics or interharmonics [7,8].

The first one related to Girgis et al. proposed three matrices' transformations [7]. Each matrix is applied to a sub-set of integer harmonic orders of which the corresponding balanced three-phase quantities have the same sequence. Unbalanced and distorted systems of related three-phase phasors at each harmonic order can be resolved into three symmetrical phasors called balanced, first unbalanced, and second unbalanced. They represent the sequence harmonic components of the original phasors. This new designation has some similarities with the classical one related to the Fortescue method but with more extent to the harmonic domain.

The second one related to Langella et al. proposed a new unique transformation matrix that is capable of suitably extracting the balanced, first unbalanced, and second unbalanced components suitable for all of the harmonic and interharmonic orders [8]. This method uses a same designation as Girgis method but introduces sequence interharmonic components as well. A used transformation matrix has a generic property for all harmonic and interharmonic components and conserves some similarities with the Girgis method.

* Corresponding author. Tel.: +213 771 785796.
E-mail address: boudebouz7@yahoo.fr (O. Boudebbouz).

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Some comparisons regarding the matrices structures of the two methods have been drawn out in the Langella work. The latter also, makes it possible to evaluate the quantities defined in the IEEE Standard 1459-2010 by means of harmonic sequence components.

Some previous author's works have focused on the Girgis method in which they analyzed the harmonic resonance phenomena and evaluated the quantities defined in the IEEE Standard 1459-2010 in the sequence reference frame [9,10].

In the present work, the authors follow up with the Langella method and present more explicit sequence electric quantities based on the two methods. Some substantial comparisons between the aforementioned works are presented as well.

2. Unbalance decomposition techniques

More recently, new decomposition techniques related to Girgis et al. and Langella et all have been proposed to give harmonic sequence components corresponding to the overall range of harmonic orders [7,8]. They allow us to define, at each harmonic order, the balanced components (bn), the first unbalanced components (fu) and the second unbalanced components (su). Each method uses three matrices' transformations which present some differences. However, they are able to separate a frequency domain which falls in same sub-sets of harmonic orders of which the corresponding balanced three-phase quantities have the same sequence. For perfectly balanced and distorted systems, the harmonics of order $h = 1, 4, 7, 10, 13, \ldots$, are purely positive – sequence and are designed as subset S_1. The harmonics of order $h = 2, 5, 8, 11, \ldots$, are purely negative – sequence and are designed as subset S_2. The harmonics of order $h = 3, 6, 9, \ldots$, are purely zero – sequence and are designed as subset S_0.

It is known that DC components are present in non-negligible proportions in AC circuits near traction and HVDC lines, in LV networks where inverters or compensators operate incorrectly, and as quasi-DC when currents are induced geomagnetically in transmission systems. In [7], the DC components have been considered as zero sequence components whereas in [8] they have not been mentioned. In the present paper, the DC components are ignored.

2.1. Girgis method (GM)

For any range of harmonic orders of interest, the HSCs proposed by GM are found by the application of the three matrices, $\bar{T}_{G1}$, $\bar{T}_{G2}$ and $\bar{T}_{G0}$ as follow:

$$\bar{T}_{G1} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \tag{1}$$

$$\bar{T}_{G2} = \frac{1}{3}\begin{bmatrix} 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \\ 1 & 1 & 1 \end{bmatrix} \tag{2}$$

$$\bar{T}_{G0} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \dfrac{-1-\sqrt{3}}{2} & \dfrac{-1+\sqrt{3}}{2} \\ 1 & \dfrac{-1+\sqrt{3}}{2} & \dfrac{-1-\sqrt{3}}{2} \end{bmatrix} \tag{3}$$

$\alpha = e^{j(2\pi/3)}$ the rotational operator. The application of the matrices (1)–(3) show evidence of the presence of the imbalance at each harmonic order, including the fundamental one.

For each harmonic order, the phasors of the voltages (currents) in the sequence reference frame can be found using:

$$\begin{bmatrix} \bar{V}^h_{\text{bn}} \\ \bar{V}^h_{\text{fu}} \\ \bar{V}^h_{\text{su}} \end{bmatrix} = \bar{G}^h \begin{bmatrix} \bar{V}^h_a \\ \bar{V}^h_b \\ \bar{V}^h_c \end{bmatrix} \tag{4}$$

$\bar{G}^h$ represents one of the three matrices, $\bar{T}_{G1}$, $\bar{T}_{G2}$ and $\bar{T}_{G0}$ according to the harmonic order. $\bar{T}_{G1}$ is applied to harmonics of subsets S_1 in which the harmonics orders are $h = 3m - 2$. $\bar{T}_{G2}$ is applied to harmonics of subsets S_2 in which the harmonics orders are $h = 3m - 1$. $\bar{T}_{G0}$ is applied to harmonics of subsets S_0 in which the harmonics orders are $h = 3m$. m is a nonzero integer number.

2.2. Langella method (LM)

The LM represents a generic process with a unique transformation matrix according to the harmonic or interharmonic orders. In the compact form, we have:

$$\bar{T}_{Lr} = \frac{1}{3}\begin{bmatrix} 1 & \alpha_k & \alpha_{2k} \\ 1 & \alpha_{k+1} & \alpha_{2k+2} \\ 1 & \alpha_{k+2} & \alpha_{2k+1} \end{bmatrix} \tag{5}$$

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