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Effective apparent power definition based on sequence components for non-sinusoidal electric power quantities

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A B S T R A C T

In the present paper, effective apparent power based sequence components for non-sinusoidal electric quantities is proposed. The effective voltages and currents based sequence components contained in the old and new versions of the IEEE Std 1459 are given, only, at the fundamental frequency. These effective quantities are derived for the non-sinusoidal situations by means of the symmetrical harmonic components. The latter are obtained by the use of three transformation matrices. Two tests systems are used for the validation process. The resulted effective quantities based on symmetrical harmonic components are very similar to those based on the phase reference frame. The new alternative expressions can be considered as a new vision of power quality research and update, as well as, for diagnosis purposes in distorted and unbalanced power systems.

1. Introduction

The definition of apparent power for unbalanced or non-sinusoidal three-phase systems is still a controversial issue [1–6]. In the literature, one can find few suggested methods they can be used for unbalanced and non-sinusoidal electric quantities [5,7,8]. In the IEEE approach, effective voltages and currents have been presented as convenient quantities which give more realistic energy flow in distorted and unbalanced circuits. The effective quantities are given for three or four wire systems in phase reference frame. The alternative expressions in sequence reference frame have been given only at the fundamental frequency. This limitation calls for a better method that can give symmetrical harmonic components for overall range of integer harmonic orders. Recently, it has been proven that generalized application of the Fortescue method to harmonic components is not possible. Additional components have been proposed to overcome the limitation of the Fortescue method for non-sinusoidal situations [9]. To the authors' knowledge, the work in reference [10] related to Girgis et al. was the first who proposed three transformation matrices giving symmetrical harmonic components similar to that of the Fortescue method. Each matrix is applied to a sub-set of harmonic orders of which the corresponding balanced three phase quantities have positive rotating sequence or negative rotating sequence or without rotating sequence corresponding to the zero sequence. The unbalanced voltages and currents phasors abc at hth harmonic order is then transformed to new three phasors called balanced, first unbalanced and second unbalanced. This new method has been presented as a powerful tool for the diagnosis purposes and the resonance occurrence evaluation as well as for modern power theory in distorted and unbalanced power systems [10–12].

More recently, Langella et al. proposes 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 [13]. This method uses a same designation as Girgis method and its transformation matrix has a generic property for all harmonic and interharmonic components and conserves some similarities with the Girgis method.

In the present paper, effective voltages and currents contained in the old and new versions of the IEEE Std 1459 are extended to sequence harmonic components by means of the Girgis method. The great merit of the extended formulas to non-sinusoidal situations is that it offers

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the assessment of unbalance in the presence of harmonics which can interest some power quality objectives by considering new indices. Two examples are used to verify the validity of the proposed formulas.

2. Symmetrical harmonic components

It is known that for the perfectly balanced and distorted three-phase electric circuits, the voltages (or currents) of order 1, 4, 7, 10, 13,... correspond to a positive sequence. The voltages (or currents) of order 2, 5, 8, 11, 14,... correspond to a negative sequence. The voltages (or currents) of order h = 3, 6, 9, 12, 15,... correspond to a zero sequence. They are designed as subsets G_1, G_2 and G_0, respectively. A new decomposition method has been proposed which gives the symmetrical harmonic components corresponding to the overall range of harmonic orders [10]. A new more coherent designation takes place defining, at each harmonic order, the balanced components (*bn*), the first unbalanced components (*fu*) and the second unbalanced components (*su*) resulting from the application of the matrices (1)–(3):

$$T_{G_1} = 1/3 \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}; \quad h = 3m - 2 \tag{1}$$

$$T_{G_2} = 1/3 \begin{bmatrix} 1 & a^2 & a \\ 1 & a & a^2 \\ 1 & 1 & 1 \end{bmatrix}; \quad h = 3m - 1 \tag{2}$$

$$T_{G_0} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & \dfrac{-1-\sqrt{3}}{2} & \dfrac{-1+\sqrt{3}}{2} \\ 1 & \dfrac{-1+\sqrt{3}}{2} & \dfrac{-1-\sqrt{3}}{2} \end{bmatrix}; \quad h = 3m \tag{3}$$

where h corresponds to the hth harmonic order, the integer number $m \in N^*$ and the complex operator $a = e^{(j2\pi)/3}$. T_{G_1} corresponds to a sub-set G_1. T_{G_2} corresponds to a sub-set G_2. T_{G_0} corresponds to a sub-set G_0. The matrices show evidence of the presence of the unbalance at each harmonic order including the fundamental one. The phasors of three-phase voltages (or currents) for each harmonic order can be found by:

$$\begin{bmatrix} \bar{V}_{bn}^h \\ \bar{V}_{fu}^h \\ \bar{V}_{su}^h \end{bmatrix} = [M] \begin{bmatrix} \bar{V}_a^h \\ \bar{V}_b^h \\ \bar{V}_c^h \end{bmatrix} \tag{4}$$

$[M]$ corresponds to one of the three matrices T_{G_1}, T_{G_2} and T_{G_0} according to the harmonic order.

3. Effective electric power quantities based sequence components

3.1. IEEE approach

Recent proposals of effective electric quantities have been given as more realistic physical meaning of energy flow in three-phase power systems. According to the reference [14], the expression of effective voltage (V_e) is given for four wires systems as follows:

$$V_e = \sqrt{V_{e1}^2 + V_{eH}^2} \tag{5}$$

where V_{e1} and V_{eH} the fundamental and the non-fundamental effective voltages, respectively:

$$V_{e1} = \sqrt{\frac{\left(V_{ab}^1\right)^2 + \left(V_{bc}^1\right)^2 + \left(V_{ca}^1\right)^2 + 3\left[\left(V_a^1\right)^2 + \left(V_b^1\right)^2 + \left(V_c^1\right)^2\right]}{18}} \tag{6}$$

$$V_{eH} = \sqrt{\frac{\sum_{h=2}^{H}\left\{\left(V_{ab}^h\right)^2 + \left(V_{bc}^h\right)^2 + \left(V_{ca}^h\right)^2 + 3\left[\left(V_a^h\right)^2 + \left(V_b^h\right)^2 + \left(V_c^h\right)^2\right]\right\}}{18}} \tag{7}$$

V_a^1, V_b^1 and V_c^1 are the rms fundamental line to neutral voltages and V_{ab}^1, V_{bc}^1 and V_{ca}^1 characterize the rms fundamental line to line voltages. Whereas, V_a^h, V_b^h and V_c^h represent the rms line to neutral voltages and V_{ab}^h, V_{bc}^h and V_{ca}^h denote the rms line to line voltages, both at the hth harmonic order. The dc component is, generally, neglected in practical electric systems and the range of harmonic orders has a finite number noted H which, generally, does not exceed 100 [15].

The corresponding effective current:

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2 + I_n^2}{3}} \tag{8}$$

I_a, I_b, I_c and I_n are the rms value of the distorted phase and neutral currents, respectively.