Discussion on Useless Active and Reactive Powers Contained in the IEEE Standard 1459

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***Abstract*—This paper deals with the useless active powers and the reactive powers included in the unbalance power (S_{U1}), and in the nonfundamental effective apparent power (S_{eN}) defined in IEEE Standard 1459. Only the fundamental positive-sequence active power (P_1^+) must be delivered to loads under ideal supply operating conditions. Fundamental negative- and zero-sequence active powers (P_1^- and P_1^0, respectively), and the harmonic active power (P_H) are considered useless active powers because they increase the power losses in the load and in the distribution lines, reducing the global efficiency of the electrical power systems. S_{U1} and S_{eN} are calculated in this paper for two cases, resolving the effective apparent power (S_e) by means of the product between the terms of the effective voltage (V_e) and the effective current (I_e). It yields to expressions of some useless active powers and reactive powers that differ from the definitions included in IEEE Standard 1459. New definitions of V_e, I_e, and S_e are proposed to avoid the disagreements detailed in this paper. The new definitions are compared with the IEEE Standard 1459 definitions by means of one numerical example. Magnitudes calculated by means of the IEEE Standard 1459 definitions present a general overvaluation that arrives at a maximum of 83% for S_{U1}.**

***Index Terms*—Electrical power quality, IEEE Standard 1459, nonactive powers, nonfundamental effective apparent power, reactive powers, unbalance power, useless active powers.**

I. Introduction

The IEEE Standard 1459 [1] includes definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions. The analysis of nonsinusoidal and unbalanced electrical systems is still under research, as demonstrated by works in the field [2]–[6]. It is stated in the IEEE Standard 1459 introduction that "the new definitions were developed to give guidance with respect to the quantities that should be measured or monitored for revenue purposes, engineering economic decisions, and determination of major harmonic polluters." Some works deal with instruments for the measurement of the electric power quantities defined in IEEE Standard 1459 [7]–[11]. In [12], a new perspective for the IEEE Standard 1459 definitions is introduced by using the stationary wavelet transform. The IEEE Standard 1459 power magnitudes are also used in the detection of the major sources of waveform distortion [13] or in the definition of the reference currents of shunt active power compensators [14]–[16].

Some of the definitions proposed in the IEEE Standard 1459 are still under discussion. In [17], the author disagrees with the definition of nonfundamental power. In [18], the authors propose a new definition for unbalance power following an instantaneous approach based on well-established concepts used in the IEEE Standard 1459 for the definition of active and reactive power in single-phase systems. In the approach proposed in this paper, the IEEE Standard 1459 power magnitudes are calculated using the supply voltages and the load currents. After resolving S_e, the different power terms are related to the power magnitudes defined in the IEEE Standard 1459.

The structure of this paper is as follows. After the introduction, a summary of the IEEE Standard 1459 power definitions used in this paper is presented. The analysis focuses on the study of unbalanced and nonlinear loads. In Section III, the IEEE Standard 1459 power magnitudes are calculated by means of the voltage and current components V_e and I_e for an unbalanced linear load and a nonlinear balanced load. The comparison of the IEEE Standard 1459 definitions with the power magnitudes obtained by means of the proposed approach in this paper permit highlighting some differences that raise doubts about the definitions of V_e and I_e included in the IEEE Standard 1459. Section IV includes the new expressions of V_e and I_e that overcome the presented problems. Section V includes a comparison between the existing and new definitions by means of a numerical example. This paper concludes with a summary of the main points developed in this paper.

II. Power Quantities in IEEE Standard 1459

The IEEE Standard 1459 establishes new electric power quantities for any situation of the electric power system. The new power magnitudes are obtained by means of the resolution of the effective apparent power in three-phase systems introduced by Buchholz in [19]. The symmetrical components of the supply fundamental voltages and load fundamental currents are used in the IEEE Standard 1459 to define several fundamental power magnitudes. The importance of the fundamental positive-sequence powers P_1^+ and Q_1^+ are recognized in [1] and [7].

This section details the IEEE Standard 1459 power definitions applied to some electric circuits. These power definitions will be resolved in Section III of this paper by means of a new

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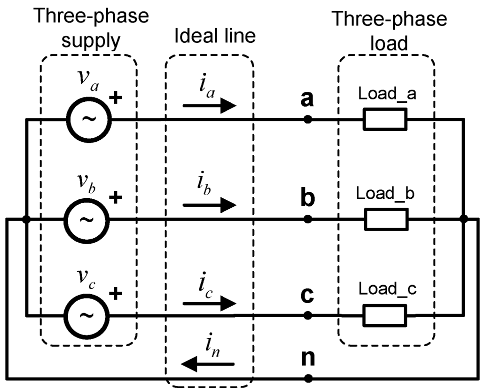

Fig. 1. Three-phase four-wire electrical system under analysis.

approach that uses the supply voltages and load current components. Fig. 1 shows the general three-phase four-wire electrical system analyzed in this paper. The instantaneous supply voltages (phase to neutral) are denoted by v_a, v_b, and v_c. The ac supply can feed the load with fundamental and harmonic symmetric or asymmetric voltage components. At the same time, the three-phase load can be balanced or unbalanced and linear or nonlinear. i_a, i_b, and i_c are the instantaneous supply currents demanded by the load, and i_n is the neutral instantaneous current. It is considered an ideal line in the analysis, but the effect of the unbalanced and nonlinear currents in the electrical system is included in the supply voltages.

The effective voltage (V_e) is defined as a function of the supply rms line-to-neutral voltages (V_a, V_b, V_c), and rms line-to-line voltages (V_{ab}, V_{bc}, V_{ca}) as follows:

$$V_e = \sqrt{\frac{3\left(V_a^2 + V_b^2 + V_c^2\right) + \left(V_{ab}^2 + V_{bc}^2 + V_{ca}^2\right)}{18}}. \quad (1)$$

The effective current (I_e) is defined as a function of the phase (I_a, I_b, I_c) and neutral (I_n) rms currents as follows:

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2 + I_n^2}{3}}. \quad (2)$$

The effective apparent power (S_e) is defined as follows:

$$S_e = 3\, V_e I_e. \quad (3)$$

As indicated in [20], several concepts of the apparent power can be found in the literature. An explanation of why V_e and I_e are defined in this way is given in [21] and [22].

Power magnitudes for unbalanced linear loads and for nonlinear loads are detailed separately in the following subsections. Section II-A summarizes power definitions for a three-phase unbalanced linear load connected to a three-phase fundamental asymmetric supply. Section II-B summarizes the IEEE Standard 1459 power definitions for a three-phase nonlinear load connected to a three-phase asymmetric supply that also includes harmonic components.

A. Power Magnitudes for a Three-Phase Unbalanced Linear Load Connected to a Three-Phase Fundamental Asymmetric Supply

For this case, the supply voltages in Fig. 1 are not equal $(V_a \neq V_b \neq V_c)$. V_e coincides with the fundamental effective voltage (V_{e1}) because the supply voltage only contains fundamental components. Subscript "1" is used to identify the fundamental components. V_{e1} is calculated in [1, p. 18, Sec. 3.2.2.8] in terms of the rms fundamental positive-, negative-, and zero-sequence voltages (V_1^+, V_1^-, and V_1^0, respectively) as follows:

$$V_e = V_{e1} = \sqrt{\left(V_1^+\right)^2 + \left(V_1^-\right)^2 + \frac{\left(V_1^0\right)^2}{2}}. \quad (4)$$

The currents through the unbalanced linear load are not equal ($I_a \neq I_b \neq I_c$ and $I_n \neq 0$). I_e coincides with the fundamental effective current (I_{e1}). I_{e1} is resolved in [1, p. 18, Sec. 3.2.2.8] in terms of the rms fundamental positive-, negative-, and zero-sequence currents (I_1^+, I_1^-, and I_1^0) as follows:

$$I_e = I_{e1} = \sqrt{\left(I_1^+\right)^2 + \left(I_1^-\right)^2 + 4\left(I_1^0\right)^2}. \quad (5)$$

According to (3)–(5), S_e corresponds to the fundamental effective apparent power (S_{e1})

$$S_e = S_{e1} = 3\, V_{e1} I_{e1}. \quad (6)$$

The fundamental positive-sequence apparent power (S_1^+) is obtained by the product of V_1^+ and I_1^+, as follows:

$$S_1^+ = 3 V_1^+ I_1^+. \quad (7)$$

S_1^+ exists in three-phase linear and balanced electrical systems. S_1^+ is resolved into the fundamental positive-sequence active power (P_1^+) and the fundamental positive-sequence reactive power (Q_1^+)

$$\begin{aligned}\left(S_1^+\right)^2 &= \left(3V_1^+ I_1^+\right)^2 \cdot \left(\left(\cos\theta_1^+\right)^2 + \left(\sin\theta_1^+\right)^2\right)\\ &= \left(P_1^+\right)^2 + \left(Q_1^+\right)^2. \end{aligned} \quad (8)$$

where θ_1^+ is the phase angle between V_1^+ and I_1^+. The unbalanced power (S_{U1}) is calculated by means of S_{e1} and S_1^+ as follows:

$$S_{U1}^2 = \left(S_{e1}\right)^2 - \left(S_1^+\right)^2. \quad (9)$$

S_{U1} is the power magnitude that quantifies the load unbalances and the voltage asymmetries, including only fundamental components of the voltages and currents.

The fundamental negative-sequence apparent power (S_1^-) and the fundamental zero-sequence apparent power (S_1^0) are resolved by means of their corresponding active and reactive parts as follows:

$$\left(S_1^-\right)^2 = \left(P_1^-\right)^2 + \left(Q_1^-\right)^2 = \left(3V_1^- I_1^-\right)^2 \quad (10)$$

$$\left(S_1^0\right)^2 = \left(P_1^0\right)^2 + \left(Q_1^0\right)^2 = \left(3V_1^0 I_1^0\right)^2. \quad (11)$$

The fundamental positive-, negative-, and zero-sequence active powers (P_1^+, P_1^-, and P_1^0, respectively) are defined in the IEEE Standard 1459 as follows:

$$P_1^+ = 3V_1^+ I_1^+ \cos\theta_1^+ \tag{12}$$
$$P_1^- = 3V_1^- I_1^- \cos\theta_1^- \tag{13}$$
$$P_1^0 = 3V_1^0 I_1^0 \cos\theta_1^0 \tag{14}$$

where θ_1^+, θ_1^-, and θ_1^0 are the phase angle between the voltage and the current of the corresponding symmetrical components. P_1^+ is the unique active power that is considered useful while P_1^- and P_1^0 are considered useless active powers due to the power losses produced in the load and line wires [6], [9], [16], [20], [22], and [23]. Instead of using the term "non-active powers" to denote the power magnitudes that are not desirable in an ideal electrical system, the authors considered the term "useless powers" to be more suitable, which includes all power magnitudes that are not P_1^+.

The fundamental active power (P_1) is obtained as the sum of the three fundamental active powers that are equal to the active power (P), in this case

$$P_1 = P_1^+ + P_1^- + P_1^0 = P. \tag{15}$$

The fundamental positive-, negative-, and zero-sequence reactive powers (Q_1^+, Q_1^-, and Q_1^0, respectively) are produced by the product of the currents that are in quadrature with their corresponding voltages and are defined as follows:

$$Q_1^+ = 3V_1^+ I_1^+ \sin\theta_1^+ \tag{16}$$
$$Q_1^- = 3V_1^- I_1^- \sin\theta_1^- \tag{17}$$
$$Q_1^0 = 3V_1^0 I_1^0 \sin\theta_1^0. \tag{18}$$

Q_1^+, Q_1^-, and Q_1^0 are considered useless power flows because they are not converted into any other kind of energy. The fundamental reactive power (Q_1) is obtained as the sum of the reactive powers that is equal to the conventional reactive power (Q) in this case

$$Q_1 = Q_1^+ + Q_1^- + Q_1^0 = Q. \tag{19}$$

B. Power Magnitudes for a Three-Phase Nonlinear Load Connected to a Three-Phase Nonsinusoidal Asymmetric Supply

In this case, the supply voltages include harmonic components produced by the harmonic current components demanded by the nonlinear load [24]. V_e is divided in [1] into V_{e1} and the nonfundamental effective voltage (V_{eH}) as follows:

$$V_e^2 = V_{e1}^2 + V_{eH}^2 \tag{20}$$

where the subscript "H" denotes the nonfundamental quantities. V_{e1} is composed by the fundamental positive-, negative-, and zero-sequence terms of the supply voltages, as in (4). V_{eH} is composed by the nonfundamental voltages.

Following the same approach for the currents, I_e is resolved into I_{e1} and the nonfundamental effective current (I_{eH}) as follows:

$$I_e^2 = I_{e1}^2 + I_{eH}^2. \tag{21}$$

I_{e1} is composed by the fundamental positive-, negative-, and zero-sequence terms of the load currents, as in (5). I_{eH} is composed by the nonfundamental currents.

The nonfundamental effective apparent power (S_{eN}) is defined as follows:

$$S_{eN}^2 = S_e^2 - S_{e1}^2 = (3\,V_{e1} I_{eH})^2 + (3\,V_{eH} I_{e1})^2 + (3\,V_{eH} I_{eH})^2. \tag{22}$$

S_{eN} is resolved in three terms. The first term is the current distortion power (D_{eI})

$$D_{eI}^2 = (3\,V_{e1} I_{eH})^2. \tag{23}$$

The second term is the voltage distortion power (D_{eV})

$$D_{eV}^2 = (3\,V_{eH} I_{e1})^2. \tag{24}$$

The third term is the harmonic apparent power (S_{eH}), as defined in (25). S_{eH} is resolved in the harmonic active power (P_H) and the harmonic distortion power (D_{eH}) as follows:

$$S_{eH}^2 = (3\,V_{eH} I_{eH})^2 = P_H^2 + D_{eH}^2. \tag{25}$$

P_H is considered a useless power since it produces losses in the load and in the electrical system [6], [9], [20], and [22]. P_H is defined by means of the harmonic voltages and currents of the same harmonic order that are in phase as follows:

$$P_H = 3 \sum_{h \neq 1} V_h I_h \cos\theta_h \tag{26}$$

where the subscript "h" is used to denote the harmonic order and θ_h is the phase angle between V_h and I_h.

The active power (P) in the electric power system is obtained as the sum (15) and (26)

$$P = P_1 + P_H. \tag{27}$$

The harmonic reactive power (Q_H) is defined as follows:

$$Q_H = 3 \sum_{h \neq 1} V_h I_h \sin\theta_h. \tag{28}$$

The conventional reactive power (Q) in the electric power system is obtained as the sum of (19) and (28)

$$Q = Q_1 + Q_H. \tag{29}$$

In the following section, some of the power magnitudes defined previously are calculated using the supply voltages and the load current components. The analysis is performed over two different circuits and yields differences with some of the definitions included in IEEE Standard 1459.

III. Effective Apparent Power Resolution by Means of the Voltage and Current Components

In this section, S_e is resolved following an approach that uses the supply voltages and load currents. The products of the different current and voltage components that appear after this resolution are related to the different power magnitudes defined in Section II. Differences appear between the definitions of some useless active powers and reactive powers included in IEEE Standard 1459 and the expressions obtained by means of the approach proposed in this paper. To highlight these disagreements, two different cases are analyzed in the following sections.

The first studied case corresponds to a three-phase unbalanced linear load connected to a three-phase asymmetric supply that only contains fundamental voltage components. The first case is focused on the fundamental active and reactive power terms that are part of S_{U1}. The second case highlights the IEEE Standard 1459 quantification error by means the calculation of the harmonic active and reactive powers that are part of S_{eN} The load of case 2 includes a balanced linear part that only demands fundamental positive-sequence active currents in parallel with a balanced nonlinear load. The supply voltages include harmonic terms of the same order than the harmonic currents, corresponding to the voltages that appear between load terminals due to nonideal distribution line impedances.

These two cases do not correspond to real situations that can appear in electrical power networks. They are selected to highlight the quantification errors included in some IEEE Standard 1459 power definitions. The quantification errors can only be demonstrated by means of the comparison between the results obtained with the approach used in this paper and the well-known active and reactive power definitions included in IEEE Standard 1459. The two cases are selected due to a reduced number of voltage and current components where the quantification errors are demonstrated. A more realistic case that includes all types of power magnitudes is presented later in this paper. It highlights the differences between IEEE Standard 1459 definitions and the proposed ones.

The subscript "_m" is used to distinguish the expressions obtained in this paper that are mistaken and disagree with the definitions included in IEEE Standard 1459. Power magnitudes calculated specifically for case 1 and case 2 are identified with subscripts "_c1" and "_c2," respectively. Expressions proposed by the authors that redefine magnitudes included in IEEE Standard 1459 are distinguished by the subscript "#."

Case 1: Three-Phase Unbalanced Linear Load Connected to an Asymmetric Fundamental Supply: In this case, the three-phase unbalanced linear load $(Z_a \neq Z_b \neq Z_c)$ demands fundamental positive-, negative-, and zero-sequence current components ($I_a \neq I_b \neq I_c$ and $I_n \neq 0$), as represented in Fig. 2. The current through the neutral wire corresponds to the sum of the currents through the three lines. The neutral current includes only the sum of the fundamental zero-sequence components because positive and negative currents are zero-sum components [25]. The three-phase supply is asymmetric, including fundamental positive-, negative-, and zero-sequence voltage components. The IEEE Standard 1459 power magnitudes for this case are detailed in Section II-A.

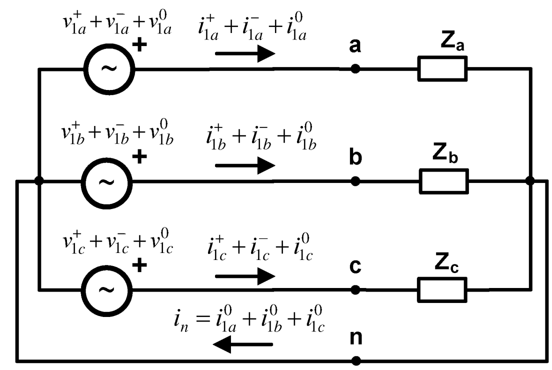

Fig. 2. Equivalent circuit of a three-phase unbalanced linear load connected to an asymmetric fundamental supply.

Replacing (4) and (5) in (6) and expanding terms [18], S_{e1} is expressed as follows:

$$\begin{aligned} S_{e1}^2 = 9 \cdot \Big[& \left(V_1^+ \cdot I_1^+\right)^2 + \left(V_1^+ \cdot I_1^-\right)^2 + 4 \cdot \left(V_1^+ \cdot I_1^0\right)^2 \\ & + \left(V_1^- \cdot I_1^+\right)^2 + \left(V_1^- \cdot I_1^-\right)^2 + 4 \cdot \left(V_1^- \cdot I_1^0\right)^2 \\ & + \frac{1}{2} \cdot \left(V_1^0 \cdot I_1^+\right)^2 + \frac{1}{2} \cdot \left(V_1^0 \cdot I_1^-\right)^2 \\ & + 2 \cdot \left(V_1^0 \cdot I_1^0\right)^2 \Big]. \end{aligned} \tag{30}$$

The first term in (30) appears in the expression of S_1^+ in (7), while the remaining terms belong to S_{U1}, which is expressed as follows:

$$\begin{aligned} S_{U1}^2 = 9 \cdot \Big[& \left(V_1^+ \cdot I_1^-\right)^2 + 4 \cdot \left(V_1^+ \cdot I_1^0\right)^2 + \left(V_1^- \cdot I_1^+\right)^2 \\ & + \left(V_1^- \cdot I_1^-\right)^2 + 4 \cdot \left(V_1^- \cdot I_1^0\right)^2 + \frac{1}{2} \cdot \left(V_1^0 \cdot I_1^+\right)^2 \\ & + \frac{1}{2} \cdot \left(V_1^0 \cdot I_1^-\right)^2 + 2 \cdot \left(V_1^0 \cdot I_1^0\right)^2 \Big]. \end{aligned} \tag{31}$$

The term $V_1^- \cdot I_1^-$ appears in the expression of S_1^- in (10) while the term $V_1^0 \cdot I_1^0$ appears in the expression of S_1^0 in (11). A different resolution of S_{U1} is reported in [26]. The fundamental zero-sequence apparent power obtained by means of (31), denoted as $S_{1\_c1}^0$, can be written as follows:

$$\left(S_{1\_c1}^0\right)^2 = \left(P_{1\_m}^0\right)^2 + \left(Q_{1\_m}^0\right)^2 = \left(3\sqrt{2} V_1^0 \cdot I_1^0\right)^2. \tag{32}$$

By means of the use of the voltage and current components in the definitions included in IEEE Standard 1459, the expressions of the zero-sequence active power $(P_{1\_m}^0)$ and the zero-sequence reactive power $(Q_{1\_m}^0)$ included in (32) are as follows:

$$P_{1\_m}^0 = \sqrt{2}\left(3 V_1^0 I_1^0 \cos\theta_1^0\right) \tag{33}$$

$$Q_{1\_m}^0 = \sqrt{2}\left(3 V_1^0 I_1^0 \sin\theta_1^0\right). \tag{34}$$

In the expressions of $P_{1\_m}^0$ and $Q_{1\_m}^0$, the factor $\sqrt{2}$ disagrees with the commonly accepted expression of P_1^0 and Q_1^0 [(14) and (18), respectively] included in IEEE Standard 1459. To obtain (14) and (18), all of the factors that multiply the power terms between brackets in (30) must be equal to one. It is stated in

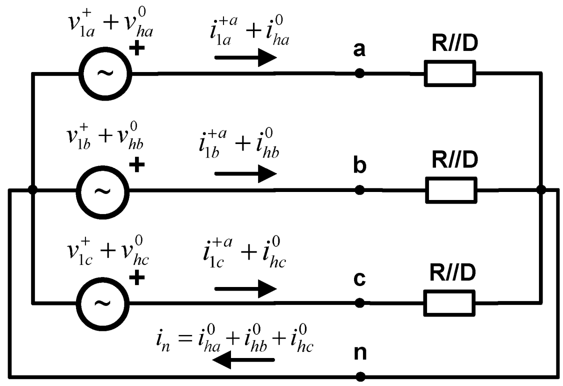

Fig. 3. Power system with zero-sequence harmonic components.

[17] that "the definition of non-fundamental power S is flawed." After the analysis was performed previously, the previous statement can be extended to include a fundamental power magnitude S_{U1}.

The remaining power magnitudes defined in IEEE Standard 1459 (P_1^+, P_1^-, Q_1^+, and Q_1^-) coincide with the expressions obtained by means of the use of the voltage and current components. Nevertheless, it is necessary to modify the definitions included in (4) and (5) as they appear in (35) and (36) to reach an agreement in the definitions included in IEEE Standard 1459 with the results obtained by means of the voltage and current components

$$V_{e1\#}=\sqrt{\left(V_1^+\right)^2+\left(V_1^-\right)^2+\left(V_1^0\right)^2} \tag{35}$$

$$I_{e1\#}=\sqrt{\left(I_1^+\right)^2+\left(I_1^-\right)^2+\left(I_1^0\right)^2}. \tag{36}$$

The expressions obtained for this case show that the fundamental zero-sequence current is over valuated in (5) by a factor of 4 while the fundamental zero-sequence voltage is under valuated in (5) by a factor of 1/2. These factors result in a value of S_{U1} that does not quantify the unbalance phenomenon correctly. The product of (35) and (36) yields the expression of the new fundamental effective apparent power $(S_{e1\#})$ that contains the same terms as (30), but with all factors equal to one.

Case 2: Three-Phase Balanced Nonlinear Load Connected to a Three-Phase Nonsinusoidal Symmetric Supply: The circuit analyzed in this case is represented in Fig. 3. The load is balanced and includes a linear part (represented by the resistance R) in parallel with a nonlinear distorting load (denoted as D). Harmonic orders of voltage and current components in balanced systems can be classified according to the rotation of the corresponding phasors [14], [27]. Harmonic current components of an order equal to $3n+3$ (with $\mathrm{n}=0,1,\ldots,\infty$) are in phase (with any rotation sequence) and are denoted as zero-sequence components. To simplify the analysis, it is assumed for this case that the nonlinear load demands only zero-sequence current components $(i_{ha}^0, i_{hb}^0, i_{hc}^0)$, with an rms value equal to I_h^0 in the three phases. The resistances demand only fundamental positive-sequence active current components $(i_{1a}^{+a}, i_{1b}^{+a}, i_{1c}^{+a})$, with an rms value equal to I_1^{+a} in the three phases. The neutral current is equal to the sum of the three line zero-sequence current components $(i_{ha}^0+i_{hb}^0+i_{hc}^0)$, with an rms value equal to $3\cdot I_h^0$.

The supply voltage includes the fundamental positive-sequence voltages $(v_{1a}^+, v_{1b}^+, v_{1c}^+)$ plus some harmonic zero-sequence components $(v_{ha}^0, v_{hb}^0, v_{hc}^0)$ that appear due to the flow of the harmonic zero-sequence current components through the distribution lines. Under this condition, the harmonic order of the current and voltage harmonic components is the same. The rms value of the fundamental positive-sequence voltages is V_1^+, while the rms value of the zero-sequence voltage components is V_h^0. For this case, V_e is calculated by means of (20) as follows:

$$V_e=\sqrt{\left(V_1^+\right)^2+\frac{1}{2}\left(V_h^0\right)^2}. \tag{37}$$

Replacing the values of the load currents in (21) defined previously, I_e is equal to

$$I_e=\sqrt{\left(I_1^{+a}\right)^2+4\left(I_h^0\right)^2}. \tag{38}$$

Substituting (37) and (38) into (3), and expanding the terms, S_e is written as follows:

$$S_e^2=9\left[\left(V_1^+I_1^{+a}\right)^2+4\left(V_1^+I_h^0\right)^2+\frac{1}{2}\left(V_h^0I_1^{+a}\right)^2+2\left(V_h^0I_h^0\right)^2\right]. \tag{39}$$

The first term in (39) corresponds to P_1^+, and is obtained by the product of the fundamental positive-sequence voltage with the fundamental positive-sequence active current. The remaining terms in (39) are part of S_{eN}

$$S_{eN}^2=9\left[4\left(V_1^+I_h^0\right)^2+\frac{1}{2}\left(V_h^0I_1^{+a}\right)^2+2\left(V_h^0I_h^0\right)^2\right]. \tag{40}$$

It is possible to identify the power magnitudes in (40) and detailed in (23)–(25). The first term in (40) includes the product of V_1^+ and I_h^0 and corresponds to D_{eI}. By rearranging the terms, D_{eI} can be expressed as follows:

$$D_{eI}^2=\left(3\,V_1^+\left(2I_h^0\right)\right)^2. \tag{41}$$

The expression of I_{eH} in (23) is equal to $2\cdot I_h^0$ in this case. The second term in (40) includes the product of V_h^0 and I_1^+ and corresponds to D_{eV}. By rearranging the terms, D_{eV} can be expressed as follows:

$$D_{eV}^2=\left(3\left(\frac{1}{\sqrt{2}}V_h^0\right)I_1^+\right)^2. \tag{42}$$

The expression of V_{eH} in (24) is equal to $((1/\sqrt{2})\cdot V_h^0)$. The last term in (40) includes the product of V_h^0 and I_h^0 and corresponds to S_{eH}. By rearranging the terms, S_{eH} can be expressed as follows:

$$S_{eH}^2=\left(3\,V_{eH}I_{eH}\right)^2=2\left(3\,V_h^0I_h^0\right)^2. \tag{43}$$

As detailed in (25), S_{eH} can be resolved by means of P_H and D_{eH}. Since (43) includes harmonic voltage and current components of the same order, S_{eH} is resolved as follows:

$$S_{eH}^2 = 2 \cdot \left(3\, V_h^0 I_h^0\right)^2 \left(\left(\cos\theta_h^0\right)^2 + \left(\sin\theta_h^0\right)^2\right). \tag{44}$$

The useless harmonic active power included in (44) is denoted as P_{H_m} and is expressed as follows:

$$P_{H\_m} = \sqrt{2}\left(3V_h^0 I_h^0 \cos\theta_h^0\right). \tag{45}$$

The other term in (44) corresponds to D_{eH} and in the case under analysis, it corresponds to a harmonic reactive power that is expressed as follows:

$$D_{eH} = Q_{H\_m} = \sqrt{2}\left(3V_h^0 I_h^0 \sin\theta_h^0\right). \tag{46}$$

Expressions (45) and (46) do not coincide with the commonly accepted expressions of P_H and Q_H written in (26) and (28), respectively. The differences are due to the factor $\sqrt{2}$ that multiplies the remaining terms that appear in P_H and Q_H. This factor is responsible for the increase in the nonfundamental power quoted in [17]. To correct these errors, it is necessary to modify (37) and (38) as follows:

$$V_{e\_c2} = \sqrt{\left(V_1^+\right)^2 + \left(V_h^0\right)^2} \tag{47}$$

$$I_{e\_c2} = \sqrt{\left(I_1^{+a}\right)^2 + \left(I_h^0\right)^2}. \tag{48}$$

These expressions yield to new expressions of the effective apparent power (S_{e_c2}) and the nonfundamental effective apparent power (S_{eN_c2})

$$S_{e\_c2}^2 = 9\left[\left(V_1^+ I_1^{+a}\right)^2 + \left(V_1^+ I_h^0\right)^2 + \left(V_h^0 I_1^{+a}\right)^2 + \left(V_h^0 I_h^0\right)^2\right] \tag{49}$$

$$S_{eN\_c2}^2 = 9\left[\left(V_1^+ I_h^0\right)^2 + \left(V_h^0 I_1^{+a}\right)^2 + \left(V_h^0 I_h^0\right)^2\right]. \tag{50}$$

The expressions of S_{e_c2} and S_{eN_c2} contain the same terms as that of (39) and (40), but all of the factors that multiply the terms between brackets are equal to one. The last term in (50) includes P_H and Q_H as defined in (26) and (28), respectively, avoiding the erroneous factors found in (45) and (46).

The analysis of these new expressions yields new definitions of the effective voltage and current valid for all kinds of situations in the electrical system.

IV. Effective Quantities in Unbalanced and Nonlinear Systems

The IEEE Standard 1459 states in its introduction that "This trial-use standard is meant to provide definitions extended from the well-established concepts." Two different approaches are used in the IEEE Standard 1459 to obtain new definitions. The first approach uses some voltage and current components to define power magnitudes. For example, the fundamental positive-sequence voltage and current are used to define P_1^+ and Q_1^+, as seen in (12) and (16). The second approach uses the subtraction of some fundamental power magnitudes to some effective power to obtain a new power magnitude. Examples of this second approach are the definitions of S_{U1}, as in (9), and S_{eN}, as in (22).

The approach used in this paper to calculate S_{U1} and S_{eN} in the studied cases is based on the use of the voltage and current components in the expressions of S_e. The number of voltage and current components in the analysis of S_{U1} is limited to six, corresponding to the fundamental positive-, negative-, and zero-sequence voltage and current components. The case of a balanced nonlinear load that demands harmonic zero-sequence current is selected to limit the number of voltage and current components when S_{eN} is analyzed. The flow of current through the neutral wire is the common feature between the two studied cases.

After resolving S_e by means of the voltage and current components, problems arise with some commonly accepted power magnitudes such as the harmonic active power and the fundamental zero-sequence active power. The problems come up when zero-sequence components of voltage and current exist in the power system. In all of these cases, the expressions of the power magnitudes include a factor that yields to expressions of the power magnitudes that do not coincide with the commonly accepted power magnitudes.

After the results presented in cases 1 and 2 for two different three-phase four-wire electrical systems, it is necessary to modify the definitions of V_e and I_e included in IEEE Standard 1459. To remove the erroneous factors, the proposed definitions of the effective voltage $V_{e\#}$ and the effective current $I_{e\#}$ are as follows:

$$V_{e\#} = \sqrt{\frac{V_a^2 + V_b^2 + V_c^2}{3}} \tag{51}$$

$$I_{e\#} = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}}. \tag{52}$$

With (51) and (52), a new expression of the effective apparent power $(S_{e\#})$ is obtained

$$S_{e\#}^2 = 9V_{e\#}^2 I_{e\#}^2 = \left(V_a^2 + V_b^2 + V_c^2\right)\left(I_a^2 + I_b^2 + I_c^2\right) \tag{53}$$

which yields to a new expression of the fundamental effective apparent power $(S_{e1\#})$

$$S_{e1\#}^2 = 9V_{e1\#}^2 I_{e1\#}^2 = \left(V_{a1}^2 + V_{b1}^2 + V_{c1}^2\right)\left(I_{a1}^2 + I_{b1}^2 + I_{c1}^2\right). \tag{54}$$

$S_{e1\#}$ can be expressed by means of the fundamental symmetrical components [28] as follows:

$$S_{e1\#}^2 = \left(\left(V_1^+\right)^2 + \left(V_1^-\right)^2 + \left(V_1^0\right)^2\right) \cdot \left(\left(I_1^+\right)^2 + \left(I_1^-\right)^2 + \left(I_1^0\right)^2\right). \tag{55}$$

With the proposed expressions of $V_{e\#}$, $I_{e\#}$, and $S_{e\#}$, the definitions of the new unbalance power $(S_{U1\#})$ and the new nonfundamental effective apparent power $(S_{eN\#})$ are as follows:

$$S_{U1\#}^2 = S_{e1\#}^2 - \left(S_1^+\right)^2 \quad (56)$$

$$\begin{aligned} S_{eN\#}^2 &= S_{e\#}^2 - S_{e1\#}^2 \\ &= 9\left[(V_{e1\#}I_{eH\#})^2 + (V_{eH\#}I_{e1\#})^2 \right. \\ &\qquad \left. +(V_{eH\#}I_{eH\#})^2\right]. \end{aligned} \quad (57)$$

All of these power quantities obtained from (51) and (52) provide a numerical result that is smaller than that obtained using the definitions included in IEEE Standard 1459. The different active and reactive power terms calculated by means $V_{e\#}$ and $I_{e\#}$ agree, for any case, with the well-known definitions included in IEEE Standard 1459.

V. Result and Discussion

A three-phase unbalanced nonsinusoidal system is analyzed in IEEE Standard 1459 [1, p. 33, Annex A.3]. The Appendix includes a summary of the voltages and currents in the electrical system under analysis. The values represent a distribution system that includes all types of useless powers as, in fact, occurs in real electrical systems.

Using the equations defined in IEEE Standard 1459 and the Stokvis–Fortescue transformation, some calculation errors found in Annex A.3 in IEEE Standard 1459 are reported in the Appendix and in Table I. The two main errors V_1^+ and V_1^0 are highlighted.

Table I shows a comparison between the main electrical magnitudes in the system under the IEEE Standard 1459 approach and the approach proposed in this paper. Magnitudes that give the same value under both approaches are in the middle of the two columns. The current and power magnitudes calculated by the IEEE Standard 1459 definitions present, in the example, an overvaluation that varies between 13% for S_{eH} to 83% for S_{U1}, with a 47% increase for S_e with respect to $S_{e\#}$. Table II presents the variation of the different magnitudes according to the approach used in their calculation. Effective voltages with the new approach are slightly higher than those calculated by means of IEEE Standard 1459. The factors 1/2 in (4) and $1/\sqrt{2}$ in (42) are responsible for an undervaluation of the zero-sequence fundamental and harmonic voltages in the IEEE Standard 1459 definitions. It results in a $D_{eV\#}$ that is greater by the proposed approach in this paper than by the means of IEEE Standard 1459.

The power factor and total harmonic distortion are merit factors of the electrical system. IEEE Standard 1459 defines the effective power factor (P_{Fe}), the fundamental positive-sequence power factor (P_{F1}^+), and the equivalent total harmonic distortion $(\mathrm{THD}_{eV}$ and $\mathrm{THD}_{eI})$ as follows:

$$P_{Fe} = \frac{P}{S_e} \quad (58)$$

$$P_{F1}^+ = \frac{P_1^+}{S_1^+} \quad (59)$$

$$\mathrm{THD}_{eV} = \frac{V_{eH}}{V_{e1}} \quad (60)$$

$$\mathrm{THD}_{eI} = \frac{I_{eH}}{I_{e1}}. \quad (61)$$

TABLE I
Magnitudes of the Three-Phase Unbalanced Nonsinusoidal System Under Analysis

	IEEE 1459	*New Approach (#)*
V_e (V)	280.25	282.02
V_{e1} (V)	278.46	278.50
V_{eH} (V)	31.72	44.39
I_e (A)	165.13	111.64
I_{e1} (A)	107.40	79.02
I_{eH} (A)	125.43	78.86
I_1^+ (A)	63.38	
I_1^- (A)	21.52	
I_1^0 (A)	42.00	
V_1^+ (V)	**278.41**	
V_1^- (V)	0.66	
V_1^0 (V)	**7.48**	
S_e (va)	138839.10	94456.83
S_{e1} (va)	89721.70	66023.58
S_1^+ (va)	52939.75	
P_1^+ (W)	51867.53	
Q_1^+ (va)	10600.75	
S_{U1} (va)	72438.70	39452.45
S_{eN} (va)	105954.30	67549.83
S_{eH} (va)	11934.99	10503.33
D_{eI} (va)	104782.78	65893.12
D_{eV} (va)	10219.50	10524.13
P (W)	51329.87	
P_{A1} (W)	25253.44	
P_{B1} (W)	26470.36	
P_{C1} (W)	−0.13	
P_1^- (W)	−35.24	
P_1^0 (W)	−108.63	
P_H (W)	−393.80	
THD_{eI} (%)	116.79	99.80
THD_{eV} (%)	11.39	15.94
P_F	0.370	0.543
P_{F1}^+	0.980	
P_{FT}	0.374	0.549

TABLE II
Factors of Variation Between Magnitudes for the Three-Phase Unbalanced Nonsinusoidal System

$V_e = 0.99\ V_{e\#}$	$V_{e1} = 0.99\ V_{e1\#}$	$V_{eH} = 0.71\ V_{eH\#}$
$I_e = 1.48\ I_{e\#}$	$I_{e1} = 1.36\ I_{e1\#}$	$I_{eH} = 1.59\ I_{eH\#}$
$S_e = 1.47\ S_{e\#}$	$S_{e1} = 1.36\ S_{e1\#}$	$S_{U1} = 1.83\ S_{U1\#}$
	$S_{eN} = 1.56\ S_{eN\#}$	
$D_{eI} = 1.59\ D_{eI\#}$	$D_{eV} = 0.97\ D_{eV\#}$	$S_{eH} = 1.13\ S_{eH\#}$

A new merit factor introduced in [6] and [20] is denoted here as the total power factor (P_{FT}). P_{FT} measures the relationship between the active power under ideal operating conditions (P_1^+) and S_e

$$P_{FT} = \frac{P_1^+}{S_e}. \quad (62)$$

The merit factors also present some variations between both approaches. By means of the IEEE Standard 1459 definitions, the THD_{eI} is 1.17 times higher than $\mathrm{THD}_{eI\#}$. The THD_{eV} is 0.71 times smaller than $\mathrm{THD}_{eV\#}$, the power factors P_F and P_{FT} are the worst per the IEEE Standard 1459 approach, and only P_{F1}^+ is equal in both approaches.

TABLE III
VOLTAGES AND CURRENTS FOR THE THREE-PHASE UNBALANCED NONSINUSOIDAL SYSTEM UNDER ANALYSIS

h	Voltage phasors (V_{rms})	Current phasors (A_{rms})
1	$\overrightarrow{V_{a1}} = 271.03\angle -0.74°$	$\overrightarrow{I_{a1}} = 99.98\angle -22.00°$
	$\overrightarrow{V_{b1}} = 283.19\angle -121.20°$	$\overrightarrow{I_{b1}} = 93.47\angle -120.80°$
	$\overrightarrow{V_{c1}} = 281.13\angle +121.30°$	$\overrightarrow{I_{c1}} = 0\angle 0°$
	$\left\|\overrightarrow{I_{n1}}\right\| = 178.08$	
3	$\overrightarrow{V_{a3}} = 27.86\angle +6.76°$	$\overrightarrow{I_{a3}} = 68.82\angle +100.00°$
	$\overrightarrow{V_{b3}} = 28.53\angle +6.28°$	$\overrightarrow{I_{b3}} = 79.75\angle +99.49°$
	$\overrightarrow{V_{c3}} = 23.55\angle +9.70°$	$\overrightarrow{I_{c3}} = 0\angle 0°$
	$\left\|\overrightarrow{I_{n3}}\right\| = 21.00$	
5	$\overrightarrow{V_{a5}} = 13.33\angle +142.30°$	$\overrightarrow{I_{a5}} = 34.89\angle -175.00°$
	$\overrightarrow{V_{b5}} = 15.69\angle +167.40°$	$\overrightarrow{I_{b5}} = 42.29\angle +65.09°$
	$\overrightarrow{V_{c5}} = 11.65\angle +157.70°$	$\overrightarrow{I_{c5}} = 0\angle 0°$
	$\left\|\overrightarrow{I_{n5}}\right\| = 63.26$	
7	$\overrightarrow{V_{a7}} = 20.16\angle +146.70°$	$\overrightarrow{I_{a7}} = 27.88\angle -65.00°$
	$\overrightarrow{V_{b7}} = 23.25\angle +125.20°$	$\overrightarrow{I_{b7}} = 45.80\angle -167.90°$
	$\overrightarrow{V_{c7}} = 17.83\angle +136.50°$	$\overrightarrow{I_{c7}} = 0\angle 0°$
	$\left\|\overrightarrow{I_{n7}}\right\| = 67.73$	
9	$\overrightarrow{V_{a9}} = 23.41\angle -47.40°$	$\overrightarrow{I_{a9}} = 5.92\angle +48.00°$
	$\overrightarrow{V_{b9}} = 29.94\angle -49.19°$	$\overrightarrow{I_{b9}} = 40.58\angle +41.89°$
	$\overrightarrow{V_{c9}} = 22.27\angle -47.35°$	$\overrightarrow{I_{c9}} = 0\angle 0°$
	$\left\|\overrightarrow{I_{n9}}\right\| = 65.73$	

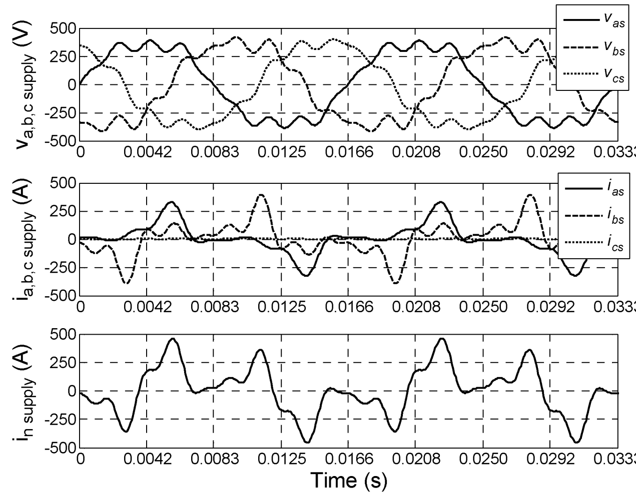

Fig. 4. Phase-to-neutral voltages (top), line currents (middle), and neutral current (bottom) waveforms in the electrical system under analysis.

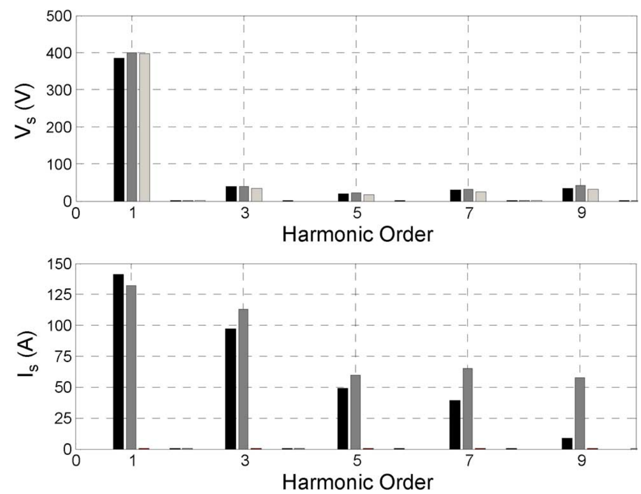

Fig. 5. Harmonic spectrum of voltages (top) and currents (bottom) in the system under analysis.

VI. CONCLUSION

The resolution of S_e by means of the electrical system voltages and currents permits calculating some power quantities that are a function of other power quantities in IEEE Standard 1459. Power magnitudes that include fundamental and harmonic zero-sequence components yield expressions of active and reactive powers that are in disagreement with well-established definitions. The problems arise as factors that multiply the commonly accepted definitions.

If the expressions of the effective voltage and current are modified to eliminate these factors, new expressions of the effective voltage and current are defined. Some power magnitudes included in IEEE Standard 1459 are redefined in this paper while others are kept equal. The results obtained with the new definitions are compared with the existing ones by means of one of the examples included in IEEE Standard 1459. Current and power quantities following IEEE Standard 1459 definitions always produce higher results, with a 47% of increase for S_e and an 83% increase for S_{U1} with respect to the quantities obtained by means of the proposed definitions. Only PF_1^+ remains equal under both approaches while the remaining power factors result in the worst values when IEEE Standard 1459 definitions are used.

The analysis performed in this paper gives an explanation for the overvaluation of some of the IEEE Standard 1459 power quantities. The modifications performed in $S_{e\#}$ maintain the definition of the fundamental positive-sequence powers P_1^+ and Q_1^+ as they appear in IEEE Standard 1459. The resolution of $S_{e\#}$ for unbalanced and nonlinear loads also contains an unbalance power $(S_{U1\#})$ and a nonfundamental effective apparent power$(S_{eN\#})$. With the new definitions, the useless active powers (P_1^-, P_1^0, and P_{H}), obtained after resolving the power definitions, agree with the commonly accepted expression for these magnitudes.

APPENDIX

Table III shows the voltages and currents phasors in the system under analysis, both expressed in rms values. The values correspond to the three-phase unbalanced nonsinusoidal system analyzed in IEEE Standard 1459 [1, p. 35, Annex A.3]. The load in phase c is disconnected, thus increasing the load current unbalance. The voltages are measured between phase and neutral.

The phase-to-neutral voltages are represented in the top plot at Fig. 4. The order of the waveforms is $a-b-c$. The origin of angles is $\omega t=0$, with a fundamental frequency of 60 Hz. The load-current waveforms are represented in the midplot, and neutral current is represented in the bottom plot. Current through line c is equal to zero at any instant.

Harmonic content of the phase-to-neutral supply voltages (top plot) and the supply currents (bottom plot) are represented in Fig. 5. For each harmonic order, the bars represent phases $a-b-c$ (from the left). Since the current through line c is equal to zero, only two bars appear in the current spectrum.

Some of the values included in Table III are different from their corresponding values in [1, Table A.5] because some mistakes exist in the example presented in IEEE Standard 1459. The erroneous terms are the following: the phase angle for the fifth harmonic component (β_{b5}) is equal to -65.09° and I_{n1} (%) is equal to 126% (equivalent to 125.93 A). Also, some values included in Table I are modified with respect to the values included in Annex A.3 of IEEE Standard 1459 because there are some errors in the calculations. The corrected terms are as follows. V_1^+ is equal to 278.41 V instead of 288.49 V, and V_1^0 is equal to 7.48 V instead of 2.98 V. Small calculation errors also exist in V_1^-, S_e, and all of the active powers.

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