Instantaneous approach to IEEE Std. 1459 power terms and quality indices

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Abstract

Based on an instantaneous analysis approach to the IEEE Std. 1459, the authors demonstrated in previous works that the effective apparent power should not be calculated including the rms neutral current and the rms line to line voltage terms. The use of these terms drives to expressions of power magnitudes that are overvaluated and disagree with well-accepted definitions. By using the instantaneous approach new power terms are proposed. Based on these terms, new power quality indices and new expressions of the unbalanced power terms are presented in this paper. An experimental case is used to compare the power magnitudes and power quality indices obtained with both approaches. Results demonstrate than the most significant power terms are over evaluated when IEEE Std. 1459 power definitions are used.

Keywords: IEEE Std. 1459, Power Quality Indices, Unbalanced Power, effective voltage, and effective current.

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1. INTRODUCTION

At present time, there is still not an universal consensus to quantify power in electrical systems. Power expressions are continuously improved obtaining more accurate expressions. The IEEE Std. 1459-2000 [1] presented a new power theory with an elegant decomposition of power terms. IEEE Std. 1459-2010 [2] was presented in 2010 as its most recently version. IEEE Std. 1459 includes definitions for the measurement of electric power quantities under sinusoidal, non-sinusoidal, balanced or unbalanced conditions, being explained its main ideas in [3–5]. In respect of previous standard, IEEE Std. 1459 separates fundamental and harmonic power terms and includes a power term that quantifies the effects of fundamental voltage asymmetries and fundamental current unbalances as part of the non-efficient powers.

Std. 1459 definitions are still under debate. A new resolution of the unbalance power (S_{U1}) has been presented in [6] and [7]. S_{U1} decomposition presented in [7] follows a similar decomposition to the one used in the IEEE Std. 1459 for the non-fundamental effective apparent power (S_{eN}). Works presenting redefinitions of the power magnitudes or novel power quality indices can be found in the literature [8–15]. In [16] the author disagrees with the definition of the non-fundamental power, stating that "the definition of non-fundamental power S is flawed". In [17], some contradictions in useless active and reactive power were found when definitions of V_e and I_e included in the IEEE Std. 1459 are used. In [18] (section 6.4), for the calculation of the effective current (I_e), the author suggests not to include the rms neutral current arguing that the rms currents (I_a, I_b, I_c, e I_n) cause the conductors' heating, nevertheless, in overhead lines the heat transfer conditions for each line conductor is not affected by the currents flowing in the

neutral conductor. In [19], effective power factors ($PF_e=P/S_e$) larger than 1 were found when zero-sequence voltage components exist. One of the most significant standards, the DIN 40110-2: 2002-11 [20], defines the collective voltage (V_Σ) (effective voltage for IEEE Std. 1459) as a function of rms line to neutral voltages without including the rms line to line voltages. Following an instantaneous approach based on well-established concepts used in IEEE Std. 1459, in [21] is proposed a new quantification of the unbalance power (S_{U1}), while in [22] is proposed a new quantification of the non-fundamental effective apparent power (S_{eN}). The instantaneous power approach establishes a relationship between the instantaneous power flows, due to the different power terms, with the different power magnitudes that quantify the corresponding power terms. As a result of the instantaneous approach, new definitions of effective voltage (V_e) and current (I_e) are used to obtain the correct decomposition of all the power magnitudes defined in IEEE Std. 1459.

The analysis of non-sinusoidal and unbalanced electrical systems is still under research, as is demonstrated by field works [23–27]. By using the new power terms obtained through the instantaneous approach, new power quality indices and a new definition of the unbalanced power terms are presented in this paper. Also, an experimental case is analyzed using IEEE Std. 1459 power definitions and by mean of the instantaneous analysis approach to compare the power magnitudes and power quality indices obtained with both approaches. The results presented in this paper, complete the approach proposed by the authors in their previous works ([6], [7], [21], [22]).

The organization of the paper is as follows. In section 2, the instantaneous approach for the calculation of IEEE Std. 1459 power magnitudes [2] and unbalance power magnitudes [7] is summarized, based on new V_e and I_e definitions. In section 3,

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according to voltage, current, and power definitions proposed in the paper, new power quality indices are presented to measure the electric power quality. In section 4 some experimental results are presented using the instantaneous approach, being compared with the values obtained using IEEE Std. 1459 definitions. In section 5, the paper concludes with a summary of the main benefits that the instantaneous approach provides.

2. IEEE STD. 1459 POWER MAGNITUDES BY MEANS OF AN INSTANTANEOUS POWER APPROACH

A proper power theory should be understood from a basic level, must directly relate the power magnitudes with phenomena in electrical systems providing physical interpretation, and must establish equations and models that provide an accurate quantification of electrical magnitudes.

IEEE Std 1459 uses the instantaneous power expression in [1], p. 3, 4. In sections 3.1.1.1-3.1.1.3 the instantaneous approach is used to determine active and reactive components in linear single-phase systems. In section 3.2.1.1 is used to establish that the sum of the three instantaneous powers is equal to the active power (P) when the three-phase system is sinusoidal (only contains fundamental components of the voltages and currents) and balanced. The instantaneous power approach in single-phase systems is necessarily used to define the power term that quantifies the reactive power. The instantaneous reactive power exists as a bidirectional power flow without an average value, being quantified by the peak value of the instantaneous reactive power. In three-phase systems, the sum of the three single-phase instantaneous reactive powers yields to a nil power flow at any instant, which makes impossible to quantify this power terms by means of its average, as is done for the active power.

The instantaneous power approach used in the IEEE Std. 1459 was extended in [21,22] for unbalanced and non-linear three-phase systems. Three-phase power flows are analyzed in [21,22] finding three different situations: a) power flows that have an average value that permits its quantification, as the active power; b) power flows with a nil average value but with a sinusoidal variation that permit their quantifications by means of the peak value of the oscillation, as occurs with some of the power flows quantified by means of the unbalance power; c) power flows with a nil average value and a nil instantaneous value, that are quantified by means of the sum of amplitudes of the single-phase oscillations, as occurs with the reactive power.

IEEE Std. 1459 resolution of S_e, V_e and I_e are presented in [1] section 3.2.4.3 as follows:

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2 + I_n^2}{3}} \tag{1}$$

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

$$S_e = 3V_e I_e \tag{3}$$

IEEE Std. 1459 power quantities are obtained by the resolution of S_e, V_e, and I_e into different terms. Well-accepted power magnitudes are defined using the corresponding rms voltage and current terms: fundamental apparent, active, and reactive positive-sequence powers (S_1^+, P_1^+, and Q_1^+ respectively); harmonic active and reactive powers (P_H and Q_H); and current distortion power, voltage distortion power, and harmonic apparent power (D_{eI}, D_{eV}, and S_{eH} respectively). After the establishment of the effective power, new power magnitudes are defined by means of the subtraction of the previously defined power magnitudes. As an example, the unbalance power (S_{U1}) and the non-fundamental effective apparent power (S_{eN}) are defined as follows:

$$S_{U1}^2 = \left(S_{e1}\right)^2 - \left(S_1^+\right)^2 \tag{4}$$

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$$S_{eN}^2 = S_e^2 - S_{e1}^2 \qquad (5)$$

The IEEE Std 1459 approach has no complete physical meaning, and some power terms are in disagreement when are operated following the instantaneous approach presented in [21,22]. As demonstrated in [17], if IEEE Std. 1459 fundamental voltage and current definitions (V_{e1} and I_{e1}) are used, power magnitudes that include fundamental zero-sequence components yield to expressions of active and reactive powers that disagree with IEEE Std. 1459 definitions. In [22], following a similar procedure, if IEEE Std. 1459 non-fundamental voltage and current definitions (V_{eH} and I_{eH}) are used, power magnitudes that include same-order, non-fundamental, and zero-sequence components yield to expressions of harmonic active and reactive powers that are in disagreement with IEEE Std. 1459 definitions. The problems arise as a $\sqrt{2}$ factor that multiplies the harmonic active and reactive power definitions. According to [17,21,22] the instantaneous power approach provides full physical meaning and directly relates the power magnitudes with phenomena in electrical systems. The instantaneous power approach allows the correct quantification of the three-phase power flows, providing a power theory that can be simultaneously used for the development of improved measurement systems, engineering economic decisions, implementation of efficient active power compensators, and even detecting inefficient sources.

Based on the instantaneous power approach developed for fundamental unbalance [21], and for non-fundamental [22] three-phase systems, this section presents a summary of the revised IEEE Std. 1459 electric power quantities under sinusoidal, non-sinusoidal, balanced or unbalanced conditions. As a novelty, IEEE Std. 1459 power magnitudes included in [2] and the unbalance power magnitudes defined in [7] are redefined here taking into account the instantaneous power approach. A three-phase four-wire

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electrical system with a non-sinusoidal asymmetric supply and an unbalanced non-linear load is used in the paper to compare the power terms obtained by means of IEEE Std. 1459 and the instantaneous approach.

The instantaneous power approach starts from the definitions of the effective current ($I_{e\#}$) and the effective voltage ($V_{e\#}$) proposed by [22]. Following the same nomenclature used in [22], subscript "#" denotes the magnitudes proposed by means of the instantaneous power approach. For a full physical meaning and following [20], $I_{e\#}$ is calculated without including the rms neutral current and $V_{e\#}$ is calculated without including the rms line to line voltages as follows:

$$I_{e\#} = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}} \tag{6}$$

$$V_{e\#} = \sqrt{\frac{V_a^2 + V_b^2 + V_c^2}{3}} \tag{7}$$

With (6) and (7) a new expression of the effective apparent power ($S_{e\#}$) is obtained:

$$S_{e\#} = 3V_{e\#}I_{e\#} = \sqrt{V_a^2 + V_b^2 + V_c^2}\sqrt{I_a^2 + I_b^2 + I_c^2} \tag{8}$$

Power magnitudes are detailed separately in the next subsections for unbalanced linear loads (Subsection 2.1) and for non-linear loads (Subsection 2.2).

2.1 Fundamental power magnitudes in three-phase unbalanced systems

In this case the three-phase fundamental supply line to neutral voltages are not equal ($V_{a1} \neq V_{b1} \neq V_{c1}$). $V_{e\#}$ coincides with the fundamental effective voltage ($V_{e1\#}$) because the supply voltage only contains fundamental components. $V_{e1\#}$ is calculated in terms of V_{a1}, V_{b1}, and V_{c1} as appears in (9). By means of the use of the symmetrical components, $V_{e1\#}$ is also calculated in (9) using the fundamental positive-, negative-, and zero-sequence voltage components (V_1^+, V_1^-, and V_1^0 respectively):

$$V_{e\#} = V_{e1\#} = \sqrt{\frac{V_{a1}^2 + V_{b1}^2 + V_{c1}^2}{3}} = \sqrt{\left(V_1^+\right)^2 + \left(V_1^-\right)^2 + \left(V_1^0\right)^2} \qquad (9)$$

The fundamental currents through the unbalanced linear load are not equal ($I_{a1} \neq I_{b1} \neq I_{c1}$ and $I_{n1} \neq 0$). In this case, $I_{e\#}$ coincides with the fundamental effective current ($I_{e1\#}$). $I_{e1\#}$ is resolved in terms of I_{a1}, I_{b1}, and I_{c1} as appears in (10). By means of the use of the symmetrical components, $I_{e1\#}$ is also calculated in (10) using the fundamental positive-, negative-, and zero-sequence current components (I_1^+, I_1^-, and I_1^0 respectively):

$$I_{e\#} = I_{e1\#} = \sqrt{\frac{I_{a1}^2 + I_{b1}^2 + I_{c1}^2}{3}} = \sqrt{\left(I_1^+\right)^2 + \left(I_1^-\right)^2 + \left(I_1^0\right)^2} \qquad (10)$$

In this case, $S_{e\#}$ corresponds to the fundamental effective apparent power ($S_{e1\#}$), calculated as follows:

$$S_{e\#} = S_{e1\#} = 3V_{e1\#}I_{e1\#} \qquad (11)$$

The fundamental positive-sequence apparent power (S_1^+), active power (P_1^+), and reactive power (Q_1^+) coincide with the expressions defined in the IEEE Std. 1459:

$$\left(S_1^+\right)^2 = \left(3V_1^+ I_1^+ \cos\theta_1^+\right)^2 + \left(3V_1^+ I_1^+ \sin\theta_1^+\right)^2 = \left(P_1^+\right)^2 + \left(Q_1^+\right)^2 \qquad (12)$$

According to [1], P_1^+ is the unique power term related to the energy delivery from the generator to the load. Due to that, V_1^+ and the fundamental positive-sequence active current ($I_1^{+-a} = I_1^+ \cos\theta_1^+$) are considered efficient and related to the useful transfer of energy.

The unbalance current ($I_{U1\#}$) is calculated in (13) by means of $I_{e1\#}$ and I_1^+. $I_{U1\#}$ can be expressed in terms of the symmetrical components as follows:

$$I_{U1\#}^2 = I_{e1\#}^2 - \left(I_1^+\right)^2 = \left(I_1^-\right)^2 + \left(I_1^0\right)^2 \qquad (13)$$

The unbalance voltage ($V_{U1\#}$) is calculated in (14) by means of $V_{e1\#}$ and V_1^+. $V_{U1\#}$ can be expressed in terms of the symmetrical components as follows:

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$$V_{U1\#}^2 = V_{e1\#}^2 - \left(V_1^+\right)^2 = \left(V_1^-\right)^2 + \left(V_1^0\right)^2 \qquad (14)$$

The unbalance power ($S_{U1\#}$) is calculated in (15) by means of $S_{e1\#}$ and S_1^+. Following

[7], $S_{U1\#}$ can be resolved into the voltage unbalance power (S_{U1V}), the current unbalance

power (S_{U1I}), and the unbalance apparent power (S_{U1U}) as follows:

$$S_{U1\#}^2 = \left(S_{e1\#}\right)^2 - \left(S_1^+\right)^2 = S_{U1V\#}^2 + S_{U1I\#}^2 + S_{U1U\#}^2 \qquad (15)$$

$S_{U1V\#}$ quantifies the power caused by voltage asymmetries, $S_{U1I\#}$ quantifies the power

caused by current unbalances, and $S_{U1U\#}$ quantifies the power caused for both

asymmetric voltages and unbalanced currents. Using the proposed expressions for $V_{U1\#}$

and $I_{U1\#}$, the power terms $S_{U1V\#}$, $S_{U1I\#}$, and $S_{U1U\#}$ are calculated by means of the

instantaneous approach as follows:

$$S_{U1V\#}^2 = 9 \cdot \left(V_{U1\#}\right)^2 \cdot \left(I_1^+\right)^2 = 9 \cdot \left(\left(V_1^-\right)^2 + \left(V_1^0\right)^2\right) \cdot \left(I_1^+\right)^2 \qquad (16)$$

$$S_{U1I\#}^2 = 9 \cdot \left(V_1^+\right)^2 \cdot \left(I_{U1\#}\right)^2 = 9 \cdot \left(V_1^+\right)^2 \cdot \left(\left(I_1^-\right)^2 + \left(I_1^0\right)^2\right) \qquad (17)$$

$$S_{U1U\#}^2 = 9 \cdot \left(V_{U1\#}\right)^2 \cdot \left(I_{U1\#}\right)^2 = 9 \cdot \left(\left(V_1^-\right)^2 + \left(V_1^0\right)^2\right) \cdot \left(\left(I_1^-\right)^2 + \left(I_1^0\right)^2\right) \qquad (18)$$

When compared with the magnitudes defined in [7], this new resolution of $S_{U1\#}$ leads to

lower values for the terms $S_{U1I\#}$ and $S_{U1U\#}$, resulting in an overall reduction of $S_{U1\#}$. With

the use of the proposed $I_{e1\#}$ and $V_{e1\#}$, the fundamental power magnitudes are properly

quantified. Also an extended resolution of the unbalance power is proposed,

distinguishing between terms produced by voltage asymmetries or current unbalances.

In [21] can be found the instantaneous analysis of the power flows and is demonstrated

that using IEEE Std. 1459 some well-known power terms do not agree with their

definition.

2.2 Power magnitudes in a three-phase non-sinusoidal and unbalanced system

In this case the supply voltages, including fundamental and harmonic components, are

connected to an unbalanced non-linear load that demands fundamental and harmonic currents. $V_{e\#}$ is divided into $V_{e1\#}$ and the non-fundamental effective voltage ($V_{eH\#}$) as follows:

$$V_{e\#}^2 = V_{e1\#}^2 + V_{eH\#}^2 \qquad (19)$$

$V_{e1\#}$ is defined in (9). $V_{eH\#}$, by means of (7), is expressed as a function of the non-fundamental rms voltages from line to neutral as follows:

$$V_{eH\#} = \sqrt{\frac{V_{aH}^2 + V_{bH}^2 + V_{cH}^2}{3}} \qquad (20)$$

Following the same approach for the currents, $I_{e\#}$ is resolved into $I_{e1\#}$ and the non-fundamental effective current ($I_{eH\#}$) as follows:

$$I_{e\#}^2 = I_{e1\#}^2 + I_{eH\#}^2 \qquad (21)$$

$I_{e1\#}$ is defined in (10). $I_{eH\#}$, by means of (6), is expressed as a function of the non-fundamental rms phase currents as follows:

$$I_{eH\#} = \sqrt{\frac{I_{aH}^2 + I_{bH}^2 + I_{cH}^2}{3}} \qquad (22)$$

Using the new expressions for effective voltages and currents (9), (10), (19), (21), the non-fundamental effective apparent power ($S_{eN\#}$) is resolved in three terms as follows:

$$S_{eN\#}^2 = D_{eI\#}^2 + D_{eV\#}^2 + S_{eH\#}^2 \qquad (23)$$

where $D_{eI\#}$ is the current distortion power (24), $D_{eV\#}$ is the voltage distortion power (25), and $S_{eH\#}$ (26) is the harmonic apparent power. $S_{eH\#}$ is resolved into P_H and the harmonic distortion power ($D_{eH\#}$).

$$D_{eI\#}^2 = 9 \cdot \left(V_{e1\#}\right)^2 \cdot \left(I_{eH\#}\right)^2 \qquad (24)$$

$$D_{eV\#}^2 = 9 \cdot \left(V_{eH\#}\right)^2 \cdot \left(I_{e1\#}\right)^2 \qquad (25)$$

$$S_{eH\#}^2 = 9 \cdot \left(V_{eH\#}\right)^2 \cdot \left(I_{eH\#}\right)^2 = P_H^2 + D_{eH\#}^2 \qquad (26)$$

P_H and the harmonic reactive power (Q_H), included into $D_{eH\#}$, are defined as in the IEEE

Std. 1459:

$$P_H = 3 \sum_{h=2,3,\ldots\infty} V_h \cdot I_h \cdot \cos(\theta_h) \qquad (27)$$

$$Q_H = 3 \sum_{h=2,3,\ldots\infty} V_h \cdot I_h \cdot \sin(\theta_h) \qquad (28)$$

With the use of the proposed $V_{eH\#}$ and $I_{eH\#}$, the power magnitudes are not undervalued or overvalued. Also P_H and Q_H, are in agreement with the expressions defined in the IEEE Std. 1459. In [22] can be found the instantaneous analysis of the power flows and is demonstrated that using IEEE Std. 1459 some well-known power terms do not agree with their correct definition.

3. NEW POWER QUALITY INDICES UNDER THE INSTANTANEOUS APPROACH

In order to improve the measurement of the electric power quality in electric installations, some IEEE Std. 1459 power quality indices are modified using the definitions proposed in the paper. A merit factor should compare inefficient magnitudes (magnitudes related to current and voltage phase shift, unbalance, and distortion) with useful magnitudes.

The proposed equivalent total harmonic distortion for voltage ($THD_{eV\#}$) and current ($THD_{eI\#}$) must be defined in respect of the voltage and current terms that appear in the single one useful active power: P_1^+ [2]. Both terms are defined as follows:

$$THD_{eV\#} = \frac{V_{eH\#}}{V_1^+} \qquad (29)$$

$$THD_{eI\#} = \frac{I_{eH\#}}{I_1^{+-a}} \qquad (30)$$

Factors $THD_{eV\#}$ and $THD_{eI\#}$ quantify the harmonic distortion of voltage and current waves respectively. $THD_{eV\#}$ is defined as the ratio between $V_{eH\#}$ (voltage term related to

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distorted voltage waves) and V_1^+ (useful voltage). $THD_{eI\#}$ is defined as the ratio between $I_{eH\#}$ (current term related to distorted current waves) and $I_1^{+\_a}$ (the useful current component related to P_1^+).

The total voltage unbalance factor (TU_V) quantifies the voltage asymmetries. The total current unbalance factor (TU_I) quantifies the current unbalances. TU_V and TU_I were defined in [6] and now are redefined as follows:

$$TU_{V\#} = \frac{V_{U1\#}}{V_1^+} \tag{31}$$

$$TU_{I\#} = \frac{I_{U1\#}}{I_1^{+\_a}} \tag{32}$$

The effective power factor ($P_{Fe\#}$) is redefined in (33). $P_{Fe\#}$ quantify the power quality in electrical systems, comparing the unique power that represent the useful transfer of power (P_1^+) [2] with the global power demanded by loads ($S_{e\#}$).:

$$P_{Fe\#} = \frac{P_1^+}{S_{e\#}} \tag{33}$$

The proposed power magnitudes and power quality indices are useful for revenue purposes, engineering economic decisions, determination of the pollution source, and active compensators sizing.

4. EXPERIMENTAL RESULTS

The proposed resolution is applied to an experimental case where a symmetric and fundamental power supply is applied to an unbalanced and nonlinear load. Fig. 1 (left) shows the phase to neutral supply voltage waveforms (v_{a_s}, v_{b_s}, v_{c_s}) applied into load terminals. A comparison is performed between the different electrical magnitudes and power quality indices following the IEEE Std. 1459 and the instantaneous power approach. During the tests, the load rms fundamental line to neutral voltages (V_{a1}, V_{b1},

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and V_{c1}) are balanced and approximately equal to 125 V. Some voltage distortion is measured in the experimental tests due to power network normal conditions (THD_{eV}=1.97%).

The load used in the test is implemented using an unbalanced linear load in parallel with a balanced three-phase non-linear load. Fig. 1 (right) shows the load current waveforms (phases a-b-c and neutral from top to bottom). The waveforms are captured with a Lecroy Wavejet 324 oscilloscope. The balanced per-phase non-linear load is built using a single-phase uncontrolled rectifier with an LC filter and a resistive load (L=5.0 mH, C=2.2 mF, R=100 Ω). The unbalanced linear load is connected from phase terminals (a-b-c) to neutral wire (n) and has the following values:

- $Z_{a\ load} = (R_{a\ load} = 65.9\ \Omega\ //\ L_{a\ load} = 67.2\ mH)$.

- $Z_{b\ load} = L_{c\ load} = 67.2\ mH$.

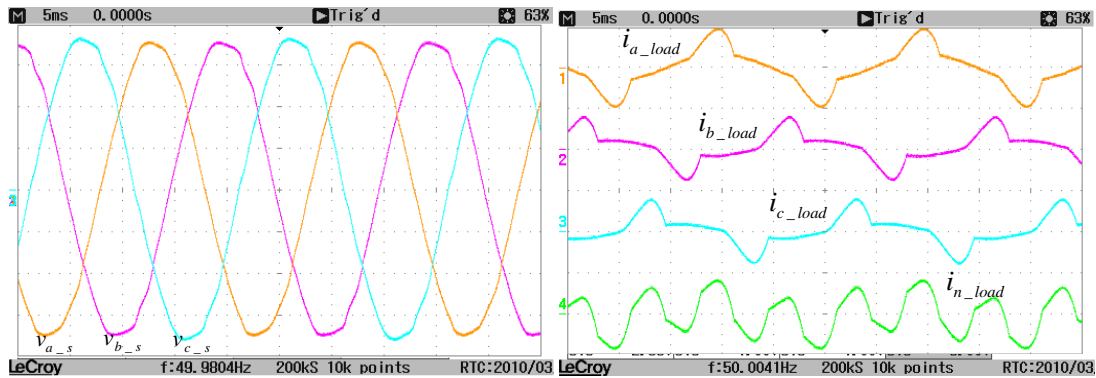- $Z_{c\ load} = L_{c\ load} = 69.7\ mH$.

Fig. 1 Experimental supply voltages (left) and currents (right).

Table 1 shows a comparison between the voltages, currents, power magnitudes, and power quality indices in the load under IEEE Std. 1459 approach and under the instantaneous approach proposed in the paper. Some magnitudes give the same value under both approaches and magnitudes not defined in IEEE Std. 1459 include the label n.d. in the corresponding cell.

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Table 1: Experimental voltages, currents, power magnitudes, and power quality indices in the load.

V_e=127.19 V	V_{e1}=127.15 V	V_{eH}=2.50 V	V_{U1}= n.d.	
$V_{e\#}$=127.20 V	$V_{e1\#}$=127.16 V	$V_{eH\#}$=2.92 V	$V_{U1\#}$= 1.66 V	
I_e= 4.87 A	I_{e1}=3.76 A	I_{eH}=3.10 A	I_{U1}=n.d.	
$I_{e\#}$= 4.01 A	$I_{e1\#}$=3.64 A	$I_{Eh\#}$=1.68 A	$I_{U1\#}$=0.83.	
$S_1^+ = 1350.33$ VA		$P_1^+ = 1063.50$W		$Q_1^+ = 1350.33$ var
S_e=1859.54 VA	S_{e1} =1434.37 VA	S_{eN} =1183.40 VA	S_{eH} =23.29 VA	D_{eI} =1182.84 VA
$S_{e\#}$ = 1529.46 VA	$S_{e1\#}$ =1387.62 VA	$S_{eN\#}$ =643.23 VA	$S_{eH\#}$ =14.73 VA	$D_{eI\#}$ =642.27 VA
D_{eV} =28.24 VA	S_{U1} =483.76 VA	THD_{eI} = 82.46%	THD_{eV} =1.97%	
$D_{eV\#}$ =31.81 VA	$S_{U1\#}$ =319.52 VA	$THD_{eI\#}$ = 46.29%	$THD_{eV\#}$ =2.29%	

The effective voltages (V_e, V_{e1}, V_{eH}) are defined in the IEEE Std. 1459 as a function of the rms line to neutral voltages and the rms line to line voltages. Due to rms line to line voltages do not include the zero-sequence voltage components, IEEE Std. 1459 terms (V_e, V_{e1}, V_{eH}) are undervalued respect to the proposed effective voltages ($V_{e\#}$, $V_{e1\#}$, $V_{eH\#}$). The small differences in the case under analysis are explained because the measurements are done in the real power network available in our laboratories. It includes with very low voltage harmonic components (quantified by V_{eH}) and asymmetries (quantified by $V_{U1\#}$).

The values of the proposed effective currents ($I_{e\#}$, $I_{e1\#}$, $I_{eH\#}$) are lower than the IEEE Std. 1459 effective currents (I_e, I_{e1}, I_{eH}). I_e, I_{e1}, I_{eH} are defined as a function of the phase and neutral rms currents and the inclusion of the rms neutral current causes an overvaluation of 21.6% for I_e, a 3.4% for I_{e1}, and an 84.2% for I_{eH}, in relation to $I_{e\#}$, $I_{e1\#}$, $I_{eH\#}$ respectively.

Undervalued voltages and overvalued currents cause, in the case under analysis, the overvaluation of S_e (21.6%), S_{e1} (3.4%), S_{eN} (84.0%), S_{eH} (58.1%), D_{eI} (84.2%), S_{U1}

(51.4%), and THD_{eI} (78.1%). The power D_{eV} (−11.2%) and the distortion THD_{eV} (−14%) are undervalued due to their dependence on V_{eH}. The undervaluation is represented with the minus sign.

Table 2 shows a comparison between the voltages, currents, power magnitudes, and power quality indices in the system under the approach proposed in [21] (following IEEE Std. 1459 decomposition of power terms) and under the instantaneous approach, first proposed in [22].

Table 2: Unbalance voltages, currents, power magnitudes, and power quality indices in the load.

$V_{U1} = 1.31$ V	$I_{U1} = 1.26$ A	$S_{U1} = 483.76$ VA
$V_{U1\#} = 1.67$ V	$I_{U1\#} = 0.84$ A	$S_{U1} = 319.52$ VA
$S_{U1U} = 4.99$ VA	$S_{U1I} = 483.54$ VA	$S_{U1V} = 13.94$ VA
$S_{U1U\#} = 4.18$ VA	$S_{U1I\#} = 319.01$ VA	$S_{U1V\#} = 17.69$ VA
$TU_I = 45.49$ %	$TU_V = 1.03$ %	$P_{Fe} = $ n.d.
$TU_{I\#} = 30.01$ %	$TU_{V\#} = 1.31$ %	$P_{Fe\#} = 0.69$

The unbalance approach proposed by [21] yields to expressions of V_{U1} undervalued (−21.5%) and I_{U1} overvalued (50%). In this case, S_{U1} (51.4%), S_{U1U} (19.4%), and S_{U1I} (51.6%) are overvalued while S_{U1V} (−21.2%) is undervalued, always when are compared with their corresponding values under the instantaneous approach.

It seems that values of TU_I and TU_V do not follow the criterion that IEEE Std. 1459 terms related to voltages are undervalued while terms related to currents are overvalued. It is due to TU_I and TU_V are defined in the instantaneous approach using different current and voltage terms. TU_I proposed in [7] compares I_{U1} with I_{e1}, while $TU_{I\#}$ compares $I_{U1\#}$ with $I_1^{+\_a}$. With the proposed definition $TU_{I\#}$ results lower than TU_I in this case. I_{e1}, must not be used in the calculation of TU_I due to I_{e1} is including I_1^- and I_1^0, terms that are related to the current unbalance. A similar consideration can be done for

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TU_V. TU_V proposed in [7] compares V_{U1} with V_{e1}, while $TU_{V\#}$ compares $V_{U1\#}$ with V_1^+, resulting in values of TU_V smaller than the obtained for $TU_{V\#}$. V_{e1}, must not be used in the calculation of TU_V due to V_{e1} is including V_1^- and V_1^0, terms that are related to the voltage asymmetries.

The value of TU_I is higher than the value of TU_V, both defined in [21]. The value of $TU_{I\#}$ is also higher than the value of $TU_{V\#}$. Both approaches indicate that the fundamental current unbalance is larger than the fundamental voltage asymmetry. The factor $P_{Fe\#}$ is less than 1, indicating the presence of useless powers in the electrical system.

5. CONCLUSIONS

This paper proposes new expressions of effective voltage ($V_{e\#}$) and effective current ($I_{e\#}$) that are determined by means of the analysis of instantaneous power flows in electrical systems. In comparison with IEEE Std. 1459, $V_{e\#}$ is defined without including rms line to line voltages and $I_{e\#}$ is defined without including the neutral current. By means of the new expressions of $V_{e\#}$ and $I_{e\#}$, several power magnitudes included in the IEEE Std. 1459 have been redefined. Also power terms included in the latest decomposition of the unbalance power are redefined following the instantaneous approach.

The correct quantification of power magnitudes is mandatory for revenue purposes, where the final users have to pay overcharges for the non-efficient power terms that are present in their installations. Also the correct quantification of power magnitudes has effect in the sizing of the active power compensator that can reduce or eliminate the non-efficient power terms demanded in an installation.

An experimental case is analyzed using IEEE Std. 1459 power definitions and by mean

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of the instantaneous analysis approach summarized in this paper. Results demonstrate than the most significant power terms are overvaluated when IEEE Std. 1459 power definitions are used. Also new unbalance power definitions (S_{U1V}, S_{U1I}, S_{U1U}) are included in the study.

The IEEE Std. 1459 effective voltages (V_e, V_{e1}, V_{eH}) are undervalued due to include in their expressions line to line voltages, while the IEEE Std. 1459 effective currents (I_e, I_{e1}, I_{eH}) are overvalued due to include in their expressions the neutral current. The power magnitudes that depend on effective currents are overvalued and the power magnitudes that depend on effective voltage are undervalued.

The use of the proposed $V_{e\#}$ and $I_{e\#}$ provides the right quantification of all the power magnitudes that exist in electric power systems under sinusoidal, non-sinusoidal, balanced or unbalanced conditions. The proposed power quality indices compare inefficient magnitudes with useful magnitudes permitting the proper power quality evaluation in power networks.

The definitions of IEEE Std. 1459 following the proposed instantaneous approach can provide a simultaneous common base for revenue purposes, evaluation of electric energy quality, engineering economic decisions, determination of major harmonic polluters, and design of mitigation equipment such as active compensators.

6. ACKNOWLEDGMENTS

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7. ANNEX

The load voltages and currents components are included in the following tables. These values have been used for the calculation of the voltage, current, and power terms included in tables 1 and 2. The calculations have done using the method described in [28]. The origin of angles is V_1^+ in phase a.

Table 3: Voltages (V), currents (A), and THDs (%) obtained in the load terminals.

$V_a = 125.46$	$V_{a1} = 125.44$	$V_{aH} = 2.49$	$THC_{Va} = 1.95$
$V_b = 126.82$	$V_{b1} = 126.78$	$V_{bH} = 3.24$	$THC_{Vb} = 2.56$
$V_c = 129.26$	$V_{c1} = 129.23$	$V_{cH} = 3.00$	$THC_{Vc} = 2.32$
$V_{ab} = 218.82$	$V_{ab1} = 218.79$	$V_{abH} = 3.60$	$THC_{Vab} = 1.65$
$V_{bc} = 220.95$	$V_{bc1} = 220.92$	$V_{bcH} = 3.24$	$THC_{Vbc} = 1.47$
$V_{ca} = 220.85$	$V_{ca1} = 220.82$	$V_{caH} = 3.59$	$THC_{Vca} = 1.63$
$I_a = 4.83$	$I_{a1} = 4.52$	$I_{aH} = 1.70$	$THC_{Ia} = 37.61$
$I_b = 3.54$	$I_{b1} = 3.14$	$I_{bH} = 1.64$	$THC_{Ib} = 52.23$
$I_c = 3.52$	$I_{c1} = 3.08$	$I_{cH} = 1.71$	$THC_{Ic} = 55.52$
$I_n = 4.80$	$I_{n1} = 1.65$	$I_{nH} = 4.51$	$THC_{In} = 273.33$

Table 4: Fundamental and first harmonic components of the load voltages (V) and currents (A) (magnitude and phase-shift)

h	Phase A	Phase B	Phase C	Neutral
1	$V_{a1} = 125.44V\angle0°$ $I_{a1} = 4.52\,A\angle-28.62°$	$V_{b1} = 126.78V\angle-120.35°$ $I_{b1} = 3.14\,A\angle-166.18°$	$V_{c1} = 129.23V\angle-239.74°$ $I_{c1} = 3.08A\angle-283.65°$	$I_{n1} = 1.65A\angle2.59°$
3	$V_{a3} = 1.63V\angle26.93°$ $I_{a3} = 1.53\,A\angle100.58°$	$V_{b3} = 2.51V\angle36.47°$ $I_{b3} = 1.45\,A\angle92.69°$	$V_{c3} = 2.29V\angle54.04°$ $I_{c3} = 1.53\,A\angle97.56°$	$I_{n3} = 4.5A\angle5.15°$
5	$V_{a5} = 1.66V\angle109.05°$ $I_{a5} = 0.68\,A\angle211.90°$	$V_{b5} = 1.83V\angle238.15°$ $I_{b5} = 0.69\,A\angle41.24°$	$V_{c5} = 1.82V\angle15.77°$ $I_{c5} = 0.73\,A\angle88.21°$	$I_{n5} = 0.09A\angle155.54°$
7	$V_{a7} = 0.45V\angle258.83°$ $I_{a7} = 0.24A\angle82.28°$	$V_{b7} = 0.59V\angle197.05°$ $I_{b7} = 0.29A\angle143.16°$	$V_{c7} = 0.23V\angle88.58°$ $I_{c7} = 0.26A\angle39.00°$	$I_{n7} = 0.09A\angle-3.72°$
9	$V_{a9} = 0.60V\angle194.14°$ $I_{a9} = 0.19\,A\angle10.54°$	$V_{b9} = 0.76V\angle183.51°$ $I_{b9} = 0.21\,A\angle27.56°$	$V_{c9} = 0.76V\angle184.62°$ $I_{c9} = 0.20\,A\angle15.98°$	$I_{c1} = 0.59A\angle-109.43°$

The symmetrical components for the case under analysis are the following:

$$I_1^+ = 3.54 \text{ A} \qquad I_1^- = 0.63 \text{ A} \quad I_1^0 = 0.55 \text{ A}$$
$$V_1^+ = 127.15 \text{ V} \quad V_1^- = 0.82 \text{ V} \quad V_1^0 = 1.45 \text{ V}$$

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