Title: A NEW DISTRIBUTED MEASUREMENT INDEX FOR THE IDENTIFICATION OF HARMONIC DISTORTION AND/OR UNBALANCE SOURCES BASED ON THE IEEE STD. 1459 FRAMEWORK.

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Abstract

The number and power of time-varying nonlinear loads connected to the electricity network has increased progressively in recent years, resulting in voltage and current disturbances. In the current, deregulated electricity market, with the proliferating presence of Distributed Generation (DG), it is becoming increasingly important to identify the source of such power quality disturbances. This paper presents a new index based on distributed measurements that allows us to identify the location of sources of harmonic distortion and/or unbalance in distribution networks. The novelty of the proposal lies in the use of terms taken from a different decomposition of apparent power for harmonic distortion and unbalance in power systems under IEEE Std. 1459. From these new terms, a series of indicators have been defined that facilitate the evaluation of the harmonic distortion and voltage unbalance of each user with respect to the electric power supply. The proposed index is validated by means of an experimental platform in which different working conditions have been developed, including load with capacitor banks for power factor compensation.

Keywords: Power Quality, Harmonics, Unbalance, Distributed Measurements.

1. Introduction

At present, electric power distribution is characterised by a wide variety of loads at its points of production, with, in most cases, electronic power converters comprising single-phase or three-phase loads. As power networks develop towards decentralised generation systems, more units, largely from renewable sources, are being directly connected to the distribution network through electronic converters. Irregular patterns of consumption alongside this distributed generation (DG), contribute to an increase in harmonic distortion and current unbalance that together lead to an increase in network failure and equipment malfunction [1-3]. At the same time, the very elements that have allowed the development and modernization of electric power distribution networks are those that display greater sensitivity to the disturbances (that they cause] in the network, endangering the system. Consequently, identification of harmonic distortion and/or unbalanced sources in the system is essential, both to demand responsibility from the originator/s (the electrical supply system and/or customer installation), and to take the necessary measures to solve the problem.

The different approaches to tackling this problem can be classified into two groups. The first approach concerns measurements taken from a localised section [4-13], while the second concerns distributed measurement methods (that is, measurements taken simultaneously at different sections on the distribution network) [14-19]. Localised measurements offer the advantages of low cost and ease of implementation, but in some conditions the information recorded with regard to the state of network disturbances can be inaccurate. Different procedures within this group of approaches have been proposed, the most notable being: 1) the harmonic power flow direction method, [4]; 2) the method of projection and superposition, SPM, [8]; 3) Load connection/disconnection methods, [12]; 4) the critical impedance method, (CIM), [9]; and 5) hybrid methods that perform an estimation of the parameters of an equivalent linear load through individual measurements at the point of common coupling (PCC), [10]. Method 1) is the most commonly used; the side (network or consumer) that generates harmonic power is considered to contain the dominant harmonic source and so contribute to a greater harmonic distortion at the point of measurement. Despite being widely used, in some practical situations this method has been shown [4] to yield inaccurate information on the identification of the dominant harmonic source, either upstream or downstream of the measurement section. In addition, [8] clearly establishes that the method is unsuitable for assessing distortion emissions, and the authors go on to propose methods 2), SPM, and 4), CIM. In all these methods, the harmonic equivalent circuit is based on the Norton model and analysis is performed using the value of the Norton harmonic current sources. The Norton/Thevenin equivalent circuits are used systematically to represent the equivalent systems for each harmonic, and in this way the relationship between the harmonic impedance and the harmonic voltage source can be found from the measurements made at the PCC. Certainly, this type of method can detect the side contributing the highest level of distortion to the PCC. However, these procedures require knowledge of harmonic network/consumer impedances, and these will not always be possible to measure. Method 3) determines the harmonic or unbalance emission levels by connecting/disconnecting the consumer or by connecting/disconnecting an auxiliary element in parallel. The methods all have their advantages and shortcomings. In general, they require precise knowledge of the Norton network models and the consumer for each harmonic of interest, and their results only remain valid for the duration of the test. Method 5), here denominated 'hybrid', is based on the results of measurements taken only at the PCC, in order to find the part that does not distort a given consumption, thus providing a simple solution to locating the sources of distortion with the exclusive use of commercial measuring equipment. Within this philosophy, different solutions have been proposed, one of which, [10], enjoyed a certain prestige, but has since been proven inadequate in that it fails to solve the problem in its entirety [20, 21]. Furthermore, these solutions do not deal with the presence of unbalance as the dominant network disturbance.

Returning to the two broad approaches to the problem, the second group – methods of simultaneous, distributed measurements – enables the recording of accurate information regarding the state of distortion and unbalance of the complete power system, and is consequently considered capable of definitively resolving the issue. In practice, however, approaches of this nature have to date proved difficult to perform and require the use of expensive and more complex instrumentation from both a hardware and software perspective. What is required is the definition of new indices and corresponding methods for evaluating of the levels of periodic disturbances in the measurement section, [14-19]. Currently, advances in digital signal processing techniques and the interconnection of equipment allowing real-time communication over communication networks make it feasible to address the practical development of a distributed measurement system aimed at EPQ in electrical networks. However, it is necessary to define a distributed index that computes the information received from the different locations. Specifically in [15], an index was introduced to assess the levels of periodic disturbances that in practice represented the only distributed index managed in the scientific community. Other distributed indices have been proposed although with less diffusion [19]. These proposals are formed from the combination of three indices that have been extensively used to assess distortion and unbalance by localized measurement methods. The combination of these presupposes greater success in the identification of periodic disturbances. Tests in different conditions have demostrated that they cannot always clearly identify the source of disturbance, for which reason new proposals would be welcome.

This study proposes a new distributed measurement index for the identification of the sources of harmonic distortion and/or unbalance based in power terms on the IEEE Std. 1459 framework. The Std. 1459 presents a model of apparent power decomposition terms in conditions of distortion and asymmetry [22]. However, this model lacks a practical assessment of the unbalance caused by the load. The new index algorithm is defined using a new method of apparent power decomposition which separates it into four components. The new index introduces three significant developments. First, it is defined as a function of power terms in the Std 1459 framework, although it retains a fourth perturbation term. Second, the power terms used represent an evolution of the Std terms that most clearly separate distortion and unbalance. Third, the use of power terms avoids the need to resort to weighting factors for each addition, since each term is normalized by the power of the global system. The index is applied and validated by means of an experimental platform connected to a real, low-voltage network. Various cases are developed under the most unfavorable working conditions possible, including capacitive load banks for power factor compensation and sources of distortion and unbalance, and the proposed index is evaluated accordingly.

This paper is organized as follow: Section 2 describes the most significant distributed measurement indices. In section 3, a new distributed measurement index is defined, based on the IEEE Std. 1459 framework. Section 4 is divided into four parts: the first part describes the experimental platform used to perform the different tests; the second provides a detailed description of the measurement system; the third gives a comprehensive analysis of the three global indices, based on the results of different experimental tests; and the fourth, a discussion of the results obtained in the different tests is presented. Finally, Section 5 presents the conclusions.

2. Distributed measurements to identify sources of perturbation

The methods currently used to identify sources of distortion and/or unbalance in electrical networks, based on a single metering section, have limitations, particularly in the presence of capacitor banks [20, 21]. This paper proposes an alternative solution utilising methods based on distributed measurements: the simultaneous measurement of EPQ parameters in all consumers connected to the same network.

2.1. Global PQ Index

Among the indices based on distributed measurements, [15] proposes a global EPQ index (1),

$$\vartheta_{1k} = \frac{1}{3}\left(\frac{\xi_{slq_k}^{-1}}{\xi_{slq_s}^{-1}} + \frac{HGI_k}{HGI_s} + \frac{\eta_k^+}{\eta_s^+} \right) \tag{1}$$

The global EPQ index is defined as the combination of three indices based on measurements made in each line *"k"* (Load) connected to the PCC, where the subscript *"s"* refers to the electric power supply line in the PCC. This index is composed of the following three terms:

- The Supply and Loading Quality Index is defined [4] as:

$$\xi_{slq} = \frac{P_\Sigma}{P_{\Sigma+1}} \tag{2}$$

Where P_Σ is the total three-phase active power and $P_{\Sigma+1}$ is the total active power associated with the fundamental frequency, positive-sequence components of voltages and currents. It can be proven that $\xi_{slq} > 1$ when the predominant disturbance source is the supply, while $\xi_{slq} < 1$ when it is the load.

- The Harmonic Global Index is defined [23] as:

$$HGI = \frac{\left\| \bar{I}_{\Sigma L} \right\|^2}{\left\| \bar{I}_{\Sigma S} \right\|^2} \tag{3}$$

Where $I_{\Sigma L}$ is the vector of the three-phase collective root-mean-square (RMS) values of the current components associated with the harmonic active powers flowing back from the load to the supply, and $I_{\Sigma S}$ is the vector of the harmonic powers flowing from the supply towards the load. For a linear, balanced load, index (3) is zero.

- The ratio between the total harmonic distortion factors defined by the collective RMS values of the fundamental frequency, positive-sequence components of voltages and currents. While this ratio cannot be used to locate the source of disturbance, it perfectly quantifies its level:

$$\eta^{+} = \frac{ITHD_{+}}{VTHD_{+}} \tag{4}$$

It can be proven [15] that $\vartheta_{1k} = 1$ when the network is working under sinusoidal balanced conditions, $\vartheta_{1k} > 1$ when the load *"k"* causes network disturbances, and $\vartheta_{1k} < 1$ when the load *"k"* is linear and balanced.

2.2. Modified Global PQ Index

Included among the newly proposed distributed indices based on comparison with an ideal linear load [10], is the Modified Global PQ Index [19], defined as:

$$\vartheta_{2k} = \frac{1}{3}\left(\frac{UNL_k}{UNL_s} + \frac{HGI_k}{HGI_s} + \frac{\eta_k^{+}}{\eta_s^{+}} \right) \tag{5}$$

Where the ratio of ξ_{slq} indices has been replaced by the ratio of unbalanced nonlinear indices, UNL. The UNL index is defined as the ratio between the collective RMS values of the unbalanced nonlinear current and the collective RMS values of the measurement current. The value analysis of ϑ_2 follows the same dynamics as ϑ_1 but more firmly identifies the load responsible for the disturbance.

3. A proposal for a new distributed measurements index

3.1. Voltage and current components in unbalanced and non-sinusoidal conditions

In balanced non-sinusoidal three-phase systems, the harmonics of the voltage waveforms and phase currents can be divided into three groups with different phase sequences: The harmonics of order 3h +1 (for h = 0, 1, 2, ...), which have a direct phase sequence (positive sequence); the harmonics of order 3h+2, with a reverse phase sequence (negative sequence); and the order of 3h+3, with a phase homopolar sequence (zero sequence). However, in an unbalanced non-sinusoidal system, each one of the harmonic voltages and current spectrums will have a positive sequence component, a negative sequence component and a zero sequence component [24-28].

At any point in the power system, the voltage and current can be defined by the balanced and unbalanced components. The balanced components, V_b and I_b, are composed of the phasors of order 3h+1 positive sequence harmonics, order 3h+2 negative sequence harmonics and order 3h+3 zero sequence harmonics. Thus, the RMS value of this balanced voltage and current is:

$$V_b^2 = \sum_{\forall h}\left[\left(V_P^{3h+1}\right)^2 + \left(V_N^{3h+2}\right)^2 + \frac{1}{1+\xi}\left(V_Z^{3h+3}\right)^2\right] \tag{6}$$

$$I_b^2 = \sum_{\forall h}\left[\left(I_P^{3h+1}\right)^2 + \left(I_N^{3h+2}\right)^2 + \left(1+3\rho\right)\left(I_Z^{3h+3}\right)^2\right] \tag{7}$$

Where ξ is the ratio between the Y and Δ equivalent active load powers, and should generally be taken as 1; and ρ is the neutral wire resistance to the line resistance ratio, according to the Std. 1459, ρ = 1 [22]. The terms V_P, V_N, and V_Z, refer to the positive, negative and zero sequence components of the corresponding voltage harmonics, respectively. The remaining phasors of the symmetrical components of the harmonics are associated with the component of the unbalanced voltage and current, V_u and I_u, with RMS values:

$$V_u^2 = \sum_{\forall h}\left[\left(V_N^{3h+1}\right)^2 + \frac{1}{1+\xi}\left(V_Z^{3h+1}\right)^2 + \left(V_P^{3h+2}\right)^2 + \frac{1}{1+\xi}\left(V_Z^{3h+2}\right)^2 + \left(V_P^{3h+3}\right)^2 + \left(V_N^{3h+3}\right)^2\right] \quad (8)$$

$$I_u^2 = \sum_{\forall h}\left[\left(I_N^{3h+1}\right)^2 + \left(1+3\rho\right)\left(I_Z^{3h+1}\right)^2 + \left(I_P^{3h+2}\right)^2 + \left(1+3\rho\right)\left(I_Z^{3h+2}\right)^2 + \left(I_P^{3h+3}\right)^2 + \left(I_N^{3h+3}\right)^2\right] \quad (9)$$

In both RMS values, the value of the fundamental harmonic can be extracted. Thus, it is the fundamental balanced component of the voltage and current, V_{b1} and I_{b1},

$$V_{b1} \equiv V_P^1 \quad (10)$$

$$I_{b1} \equiv I_P^1 \quad (11)$$

And the fundamental unbalanced component, V_{u1} and I_{u1},

$$V_{u1} \equiv \sqrt{(V_N^1)^2 + \frac{1}{1+\xi}(V_Z^1)^2} \quad (12)$$

$$I_{u1} \equiv \sqrt{(I_N^1)^2 + \left(1+3\rho\right)(I_Z^1)^2} \quad (13)$$

The RMS value of the equivalent voltage and equivalent current is obtained from the decomposition of the voltage and current into four components:

$$V_e^2 = V_{b1}^2 + V_{u1}^2 + V_{bH}^2 + V_{uH}^2 \quad (14)$$

$$I_e^2 = I_{b1}^2 + I_{u1}^2 + I_{bH}^2 + I_{uH}^2 \quad (15)$$

where V_{bH} and I_{bH} are the balanced harmonic components of voltage and current, and V_{uH} and I_{uH} are the unbalanced harmonic components of voltage and current respectively.

$$V_{bH}^2 = V_b^2 - V_{b1}^2 \ ; \ V_{uH}^2 = V_u^2 - V_{u1}^2 \quad (14)$$

$$I_{bH}^2 = I_b^2 - I_{b1}^2 \ ; \ I_{uH}^2 = I_u^2 - I_{u1}^2 \quad (15)$$

3.2. Apparent Power Decomposition

The decomposition established in (14) and (15) of the respective voltage and current RMS values allows for the proposal of a partition of apparent power that satisfies the relation (16),

$$S_e^2 = \left(3V_e I_e\right)^2 = S_{b1}^2 + S_{u1}^2 + S_{bH}^2 + S_{uH}^2 \tag{16}$$

Which identifies the four terms of power,

$$S_{b1}^2 = 9V_{b1}^2 I_{b1}^2 \tag{17}$$

$$S_{u1}^2 = 9\left(V_{b1}^2 I_{u1}^2 + V_{u1}^2 I_{b1}^2 + V_{u1}^2 I_{u1}^2\right) \tag{18}$$

$$S_{bH}^2 = 9\left(V_{b1}^2 I_{bH}^2 + V_{bH}^2 I_{b1}^2 + V_{bH}^2 I_{bH}^2\right) \tag{19}$$

$$S_{uH}^2 = S_e^2 - S_{b1}^2 - S_{u1}^2 - S_{bH}^2 \tag{20}$$

Where S_{b1} is the balanced fundamental apparent power component, S_{u1} is the unbalanced fundamental apparent power component, S_{bH} is the balanced harmonic apparent power, and S_{uH} is the unbalanced harmonic apparent power.

3.3. A new proposed index

The new distributed measurement index proposed in this paper combines the terms of power discussed in the previous section with a modification of the Harmonic Global Index (HGI), defined as:

$$\vartheta_{3k} = \frac{1}{4}\left(\frac{S_{u1k}}{S_{u1s}} + \frac{S_{bH\,k}}{S_{bH\,s}} + \frac{S_{uH\,k}}{S_{uH\,s}} + \frac{HGIm_k}{HGIm_s}\right) \tag{21}$$

Where the HGI introduced here differs slightly from that presented in [23]:

$$HGIm = \frac{\left\|\bar{I}_{\Sigma L}\right\|}{\left\|\bar{I}_{\Sigma S}\right\|} \tag{22}$$

The novelty of this proposal is that it takes into account the fundamental unbalance, the balance harmonic and the unbalance harmonic apparent power components of all the consumers with respect to these same components of the network, in such a way that a precise information register is obtained about the state of distortion and unbalance of the entire energy system. Thus, it becomes unnecessary to introduce weighting factors for each of the ϑ_3 terms. This is certainly a significant advantage over other indices since an inadequate choice of these factors can lead to inaccurate results. However, like the other two distributed measurement indices, in order to avoid possible problems arising from a division by zero, it is assumed that whenever the denominator of a term is less than 10^{-3}, the result of the division is 1. Hence, it can be verified that when the supplied voltages are sinusoidal and balanced and the load connected to a generic branch, *"k"* is linear and balanced, the value of the index ϑ_3 is one. Each of the terms of the index ϑ_{3k} is the ratio of one index measured in one of the lines that feed each load with respect to the same index measured in the supply line to the PCC. The index ϑ_{3k} increases if the disturbance is caused by the load *"k"*, while it decreases if the disturbance is produced by the supply. Thus, $\vartheta_3 = 1$ represents the threshold between the disturbance causing load $\vartheta_3 > 1$, and the disturbed load, $\vartheta_3 < 1$.

4. Experimental results

4.1. Experimental platform

In order to validate and verify the stability of the new index proposed in this paper, we built a three-phase, four-wire experimental platform (400/230 V, 50 Hz). As shown in Figure 1, the system consisted of four different loads connected to the electricity supply network through line impedance (Z_L). The topology of the system could be modified in order to see the behavior of the different indices in different configurations, through a series of switches. The system could be supplied with a distorted source "A" (S_A ON and

S_B OFF), or with a distorted and unbalanced source "B" (S_A OFF and S_B ON), through operation of the S_A and S_B switches, while the loads could be connected or disconnected from the network through the switches S_1, S_2, S_3 and S_4. The line impedance Z_L had the common value of low-voltage distribution networks R_L= 0.15 Ω, L_L = 0.21 mH and the loads were configured as follows:

Load 1.- Linear and balanced, composed of three resistors connected in Star. This is an ideal load, since it does not inject harmonics or unbalance into the network.

Load 2.- Unbalanced and nonlinear, comprised of a single-phase rectifier with an R into dc side in parallel with a resistance in one phase and two resistors of different values in the remaining phases. This is the typical representative load of an office building.

Load 3.- Linear, inductive and balanced, in parallel with a capacitor bank to compensate the power factor of the load.

Load 4.- Distorted and balanced, comprised of a three-phase rectifier with an R into dc side. This is the typical load representative of industry.

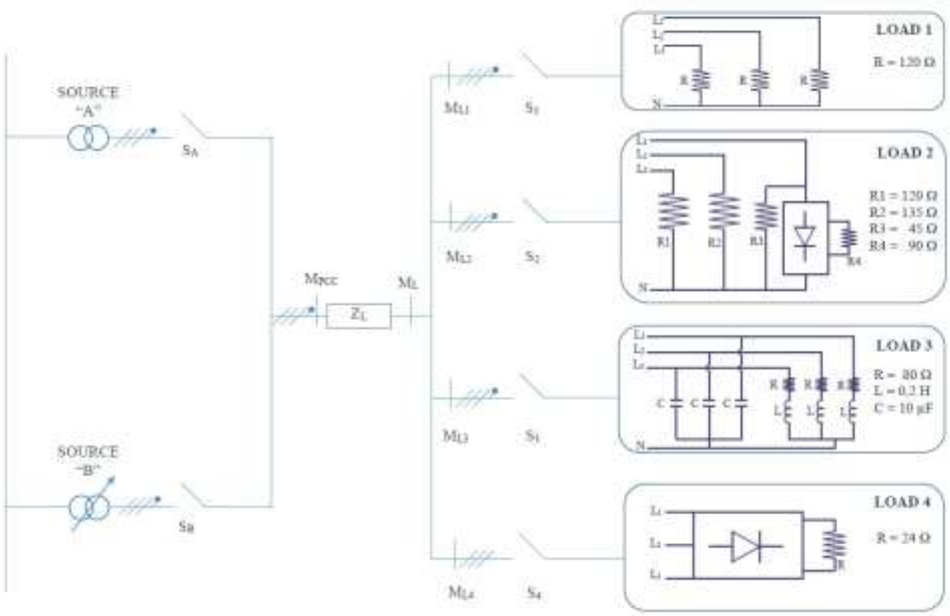
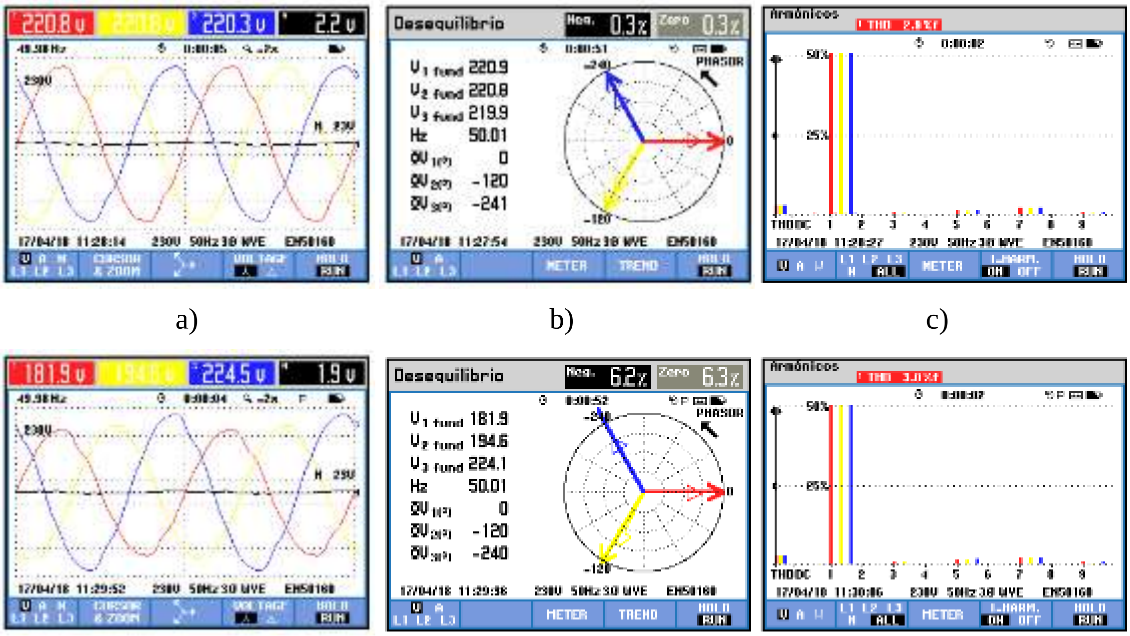


Figure 1. Power network employed for the experimental tests.

Finally, Figure 2 illustrates the voltage waveforms of the laboratory network used in the two test formats. Source A resulted in a small voltage distortion of 2.9% and a virtually non-existent unbalance. By contrast, source B, using a variable three-phase autotransformer, which modified the voltage of each phase of the power supply network (181.9, 196.4 and 224.5 V) resulted in a voltage unbalance in of 6.2%. These measurements have been made with Fluke 430 Series II Three-Phase Power Quality and Energy Analyzer, which complies with the stringent international IEC 61000-4-30 Class-A standard.



a) b) c)

d) e) f)

Figure 2. Voltage measurements of the power supply source to open circuit (S_A and S_B OFF): Test A source: Waveforms (a), phasors (b) and frequency spectrum (c); Test B source: Waveforms (d), phasors (e) and frequency spectrum (f).

4.2. The measurement system

The measurement system consisted of a data acquisition card (dSPACE-DS1005) with a DS2005 board, a signal conditioning system formed by three voltage sensors (LEM LV25-P), and three current sensors (LEM LA35-NP). The voltage transducers and the current transducers show a relative standard uncertainty on the gain of 0.04% and 0.05% respectively up to 5 kHz. Thus the voltage and current signals were taken simultaneously, avoiding the introduction of any phase change that could affect the accuracy of the measurements. Matlab and ControlDesk were used to develop a virtual instrument to store the instantaneous values of each phase voltage and line current, for data acquisition and processing. This virtual instrument was configured according to the IEC Std 61 000-4-7 and IEC Std 61 000-4-30 specifications, which recommended a window equal to ten cycles of the fundamental frequency and a sampling frequency of 6400 Hz, thus avoiding aliasing problems and leakage errors.

4.3. Cases and Results

To validate the proposed index, a series of cases have been developed that attempt to reproduce the typical working conditions of low voltage distribution networks.

Case 1: Linear balanced load and nonlinear unbalanced load.

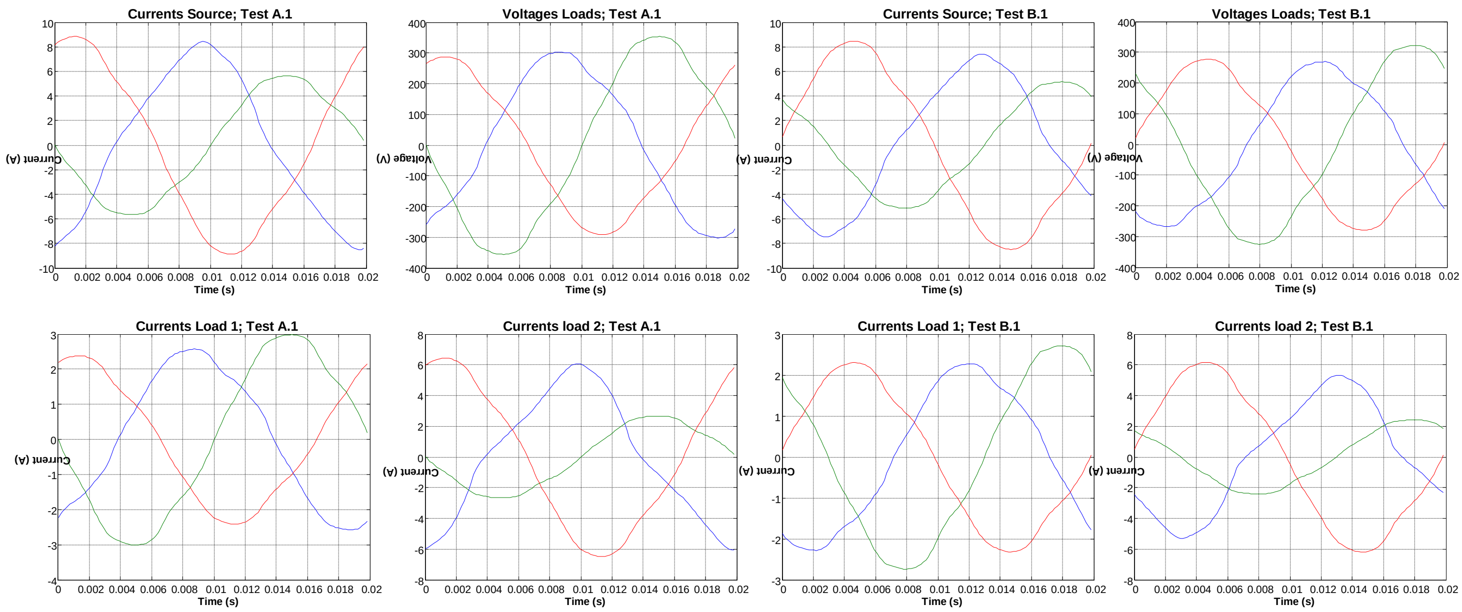
The Case 1 experimental platform is configured as follows:

Test A1: Distorted and balanced voltage supply (S_A ON), linear balanced load (S_1 ON) and nonlinear unbalanced load (S_2 ON). (S_B, S_3 and S_4 OFF).

Test B1: Distorted and unbalanced voltage supply (S_B ON), linear balanced load (S_1 *ON)* and nonlinear unbalanced load (S_2 ON). (S_A, S_3 and S_4 OFF).

Figure 3 shows the voltage and current waveforms obtained during tests A.1 and B.1. In the former, the power supply displays a THDV of 2.9 %, while load 2 introduces distortion and unbalance into the system. The resulting effect can be observed in the subsequent voltage that feeds the loads (see Voltage Loads; Test A.1, Figure 3.a.) and the direct consequences it has on load 1. In the latter, distortion and unbalance are introduced by the power supply and load 2, while load 1 is linear and balanced. Figure 3 b), shows the consequences with respect to the feeder voltage and its effect on linear balanced load 1 (Current Load 1; Test B.1, Figure 3.b).

In this case, both the power source and load 2 are sources of system disturbance and in both cases the three indices clearly identify load 1 as a non-disturbing load (values less than 1) and load 2 as a source of disturbance (values greater than 1). Comparing the results of the indices in the two tests, it can be observed that although the values of index ϑ_2 characterize the nonlinear unbalanced load in a more pronounced way, the values of proposed index ϑ_3 are more stable against variations in the disturbances of the power source.



a) b)

Figure 3. Voltage and current waveforms of the loads and source of case 1:

a) Test A.1 and b) Test B.1.

TABLE I. Case 1 Indices Values

Test A.1				Test B.1			
	ϑ_1	ϑ_2	ϑ_3		ϑ_1	ϑ_2	ϑ_3
Load 1	0.45	0.12	0.94	**Load 1**	0.57	0.25	0.77
Load 2	1.35	1.16	1.50	**Load 2**	2.57	1.53	1.61

Case 2: Linear balanced load and nonlinear balanced load.

The Case 2 experimental platform is configured as follows:

Test A2: Distorted and balanced voltage supply (S_A ON), linear balanced load (S_1 ON) and nonlinear balanced load (S_4 ON). (S_B, S_2 and S_3 OFF).

Test B2: Distorted and unbalanced voltage supply (S_B ON), linear balanced load (S_1 ON) and nonlinear balanced load (S_4 ON). (S_A, S_2 and S_3 OFF).

While in Test A, the source does not cause unbalance, in Test B the power source is the only source of unbalance. However, in both tests the power source and load 2 cause harmonics. Figure 4 shows voltage and current waveforms at every point in the installation.

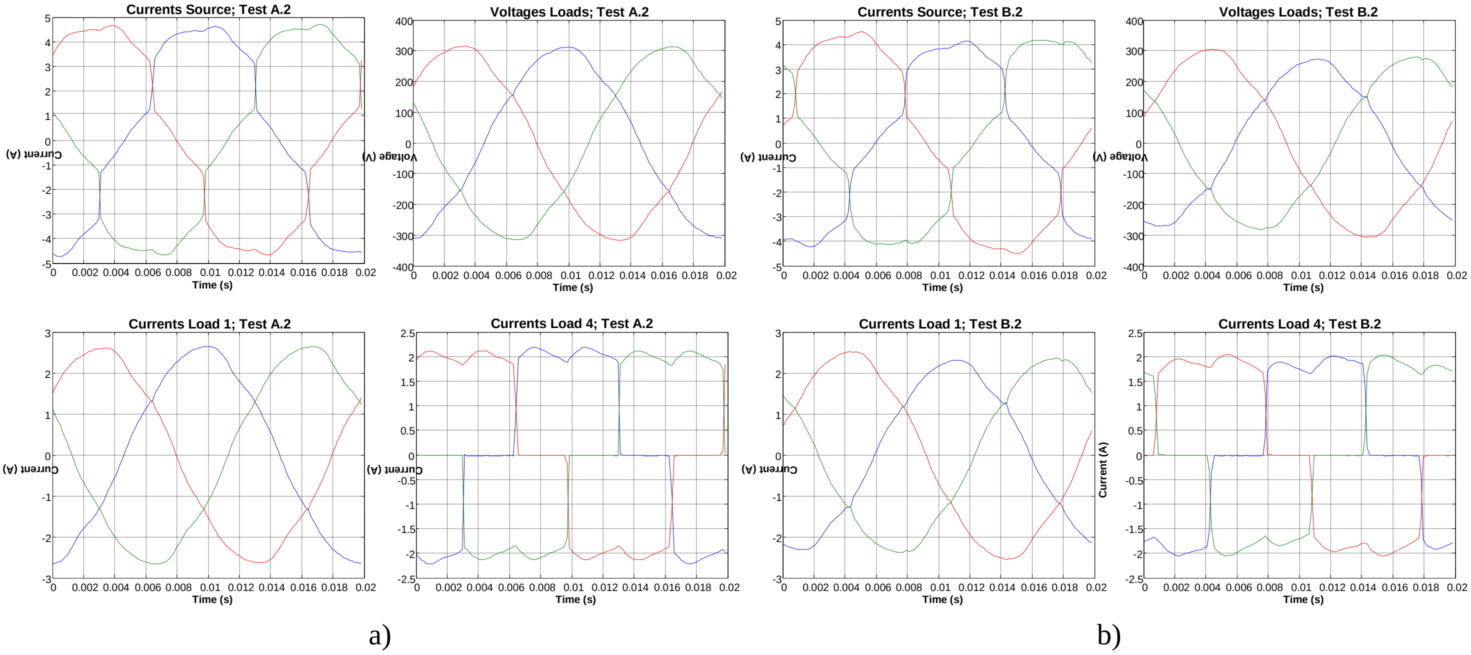


Figure 4. Voltage and current waveforms of the loads and source of case 2: a) Test A.2 and b) Test B.2.

Table II shows the Case 2 results. As in Case 1, the three indices clearly identify the linear balanced load (Load 1) versus the system disturbance sources (Source and load 4). In this case, it can be seen that index 3 best characterizes the linear balanced load and is more stable against the unbalance present in the network.

TABLE II. Case 2 Indices Values

	Test A.2				Test B.2		
	ϑ_1	ϑ_2	ϑ_3		ϑ_1	ϑ_2	ϑ_3
Load 1	0.40	0.84	0.30	**Load 1**	0.51	0.24	0.19
Load 4	2.85	3.48	1.86	**Load 4**	3.49	1.87	1.69

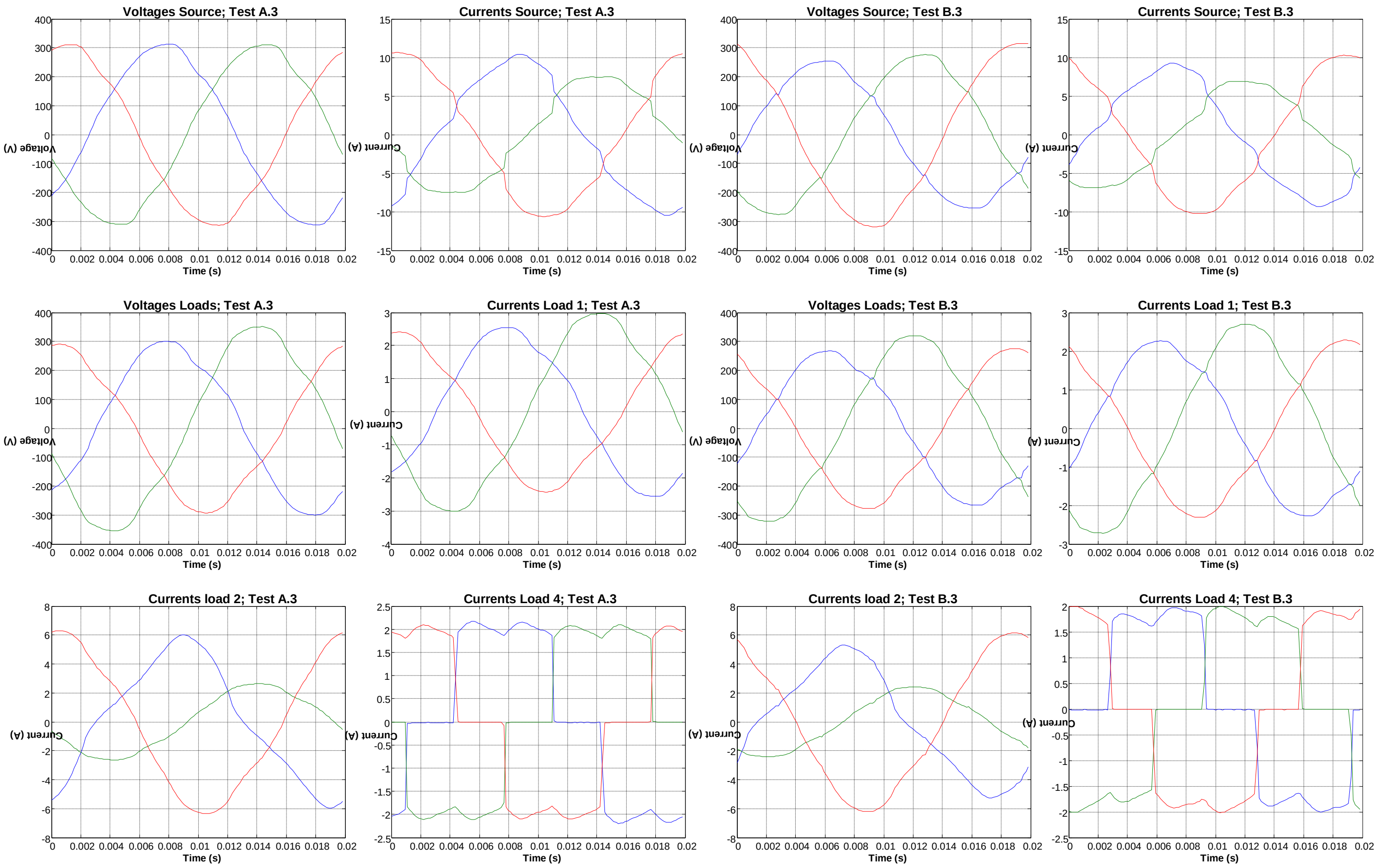
Case 3: Linear balanced load, nonlinear unbalanced load and nonlinear balanced load

The Case 3 experimental platform is configured as follows:

Test A3: Distorted and balanced voltage supply (S_A ON), linear balanced load (S_1 ON), nonlinear unbalanced load (S_2 ON) and nonlinear balanced load (S_4 ON). (S_B and S_3 OFF).

Test B3: Distorted and unbalanced voltage supply (S_B ON), linear balanced load (S_1 ON) nonlinear unbalanced load (S_2 ON) and nonlinear balanced load (S_4 ON). (S_A and S_3 OFF).

In order to Test the proposed method in the presence of several disturbances, the ideal load is connected to the distorted load (Load 4) and the distorted and unbalanced load (Load 3) in both tests. Figure 5 shows voltage and current waveforms at every point in the installation.



a) b)

Figure 5. Voltage and current waveforms of the case 3 loads and source: a) Test A.3 and b) Test B.3.

The results of Case 3 are presented in table III. In this case, indexes ϑ_1 and ϑ_3 identify the sources of distortion (Load 2 and Load 4) and the ideal Load (Load 1) in the two tests. However, in Test A, index ϑ_2 erroneously identifies load 4 as a linear load.

TABLE III. Case 3 Indices Values

	Test A.3				Test B.3		
	ϑ_1	ϑ_2	ϑ_3		ϑ_1	ϑ_2	ϑ_3
Load 1	0.48	0.16	0.30	**Load 1**	0.63	0.31	0.34
Load 2	1.94	1.51	1.14	**Load 2**	2.01	1.54	1.04
Load 4	1.19	**0.90**	1.99	**Load 4**	9.52	2.21	3.37

Case 4: Linear balanced load, Linear balanced load with capacitor bank and nonlinear unbalanced load.

The Case 4 experimental platform is configured as follows:

Test A4: Distorted and balanced voltage supply (S_A ON), linear balanced load (S_1 ON), nonlinear unbalanced load (S_2 ON) and linear balanced load with capacitor bank (S_3 ON). (S_B and S_4 OFF).

Test B4: Distorted and unbalanced voltage supply (S_B ON), linear balanced load (S_1 ON) nonlinear unbalanced load (S_2 ON) and linear balanced with capacitor bank (S_3 ON). (S_A and S_4 OFF).

It is of paramount importance that the behavior of the indices be considered when there are loads with capacitor banks for power factor compensation. Therefore, load 3 is connected to the system together with the Case 1 configuration. Figure 6 shows how the low distortion of the power supply and load 2 do not cause a considerable amplification of the distortion in the current source (see Currents Source, Test A.4; Figure 6a) and consequently in the power supply load voltage (see Voltage Loads, Test A.4, Figure 6a). In Test A, the system unbalance is generated by load 2 (see Currents load 2, Test A.4, Figure 6a) while in Test B, it is generated by both load 2 and the power source, source B (see Figure 6 b).

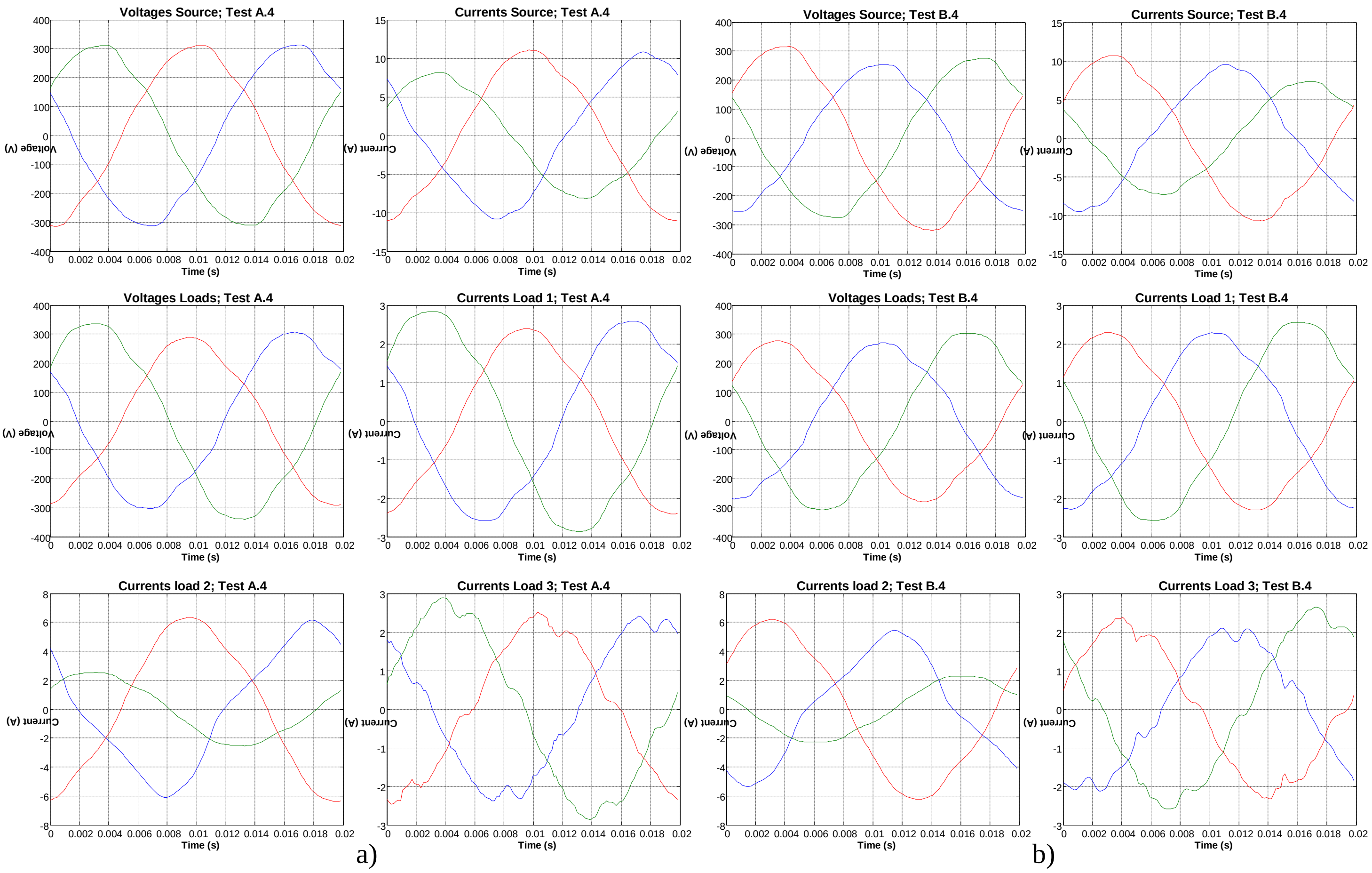


Figure 6. Voltage and current waveforms of the case 4 loads and source:

a) Test A.4 and b) Test B.4.

Table IV presents the Case 4 results. In Test A, the three indices perfectly identify the load responsible for the network disturbance (load 2), even identifying the capacitive load (Load 3) as non-disturbing. However, in Test B, index ϑ_1 erroneously determines the behavior of the capacitive load (Load 3).

TABLE IV. Case 4 Indices Values

	Test A.4				**Test B.4**		
	ϑ_1	ϑ_2	ϑ_3		ϑ_1	ϑ_2	ϑ_3
Load 1	0.48	0.16	0.66	**Load 1**	0.63	0.31	0.55
Load 2	2.18	1.61	1.54	**Load 2**	6.26	2.36	1.89
Load 3	0.50	0.29	0.65	**Load 3**	**1.17**	0.80	0.92

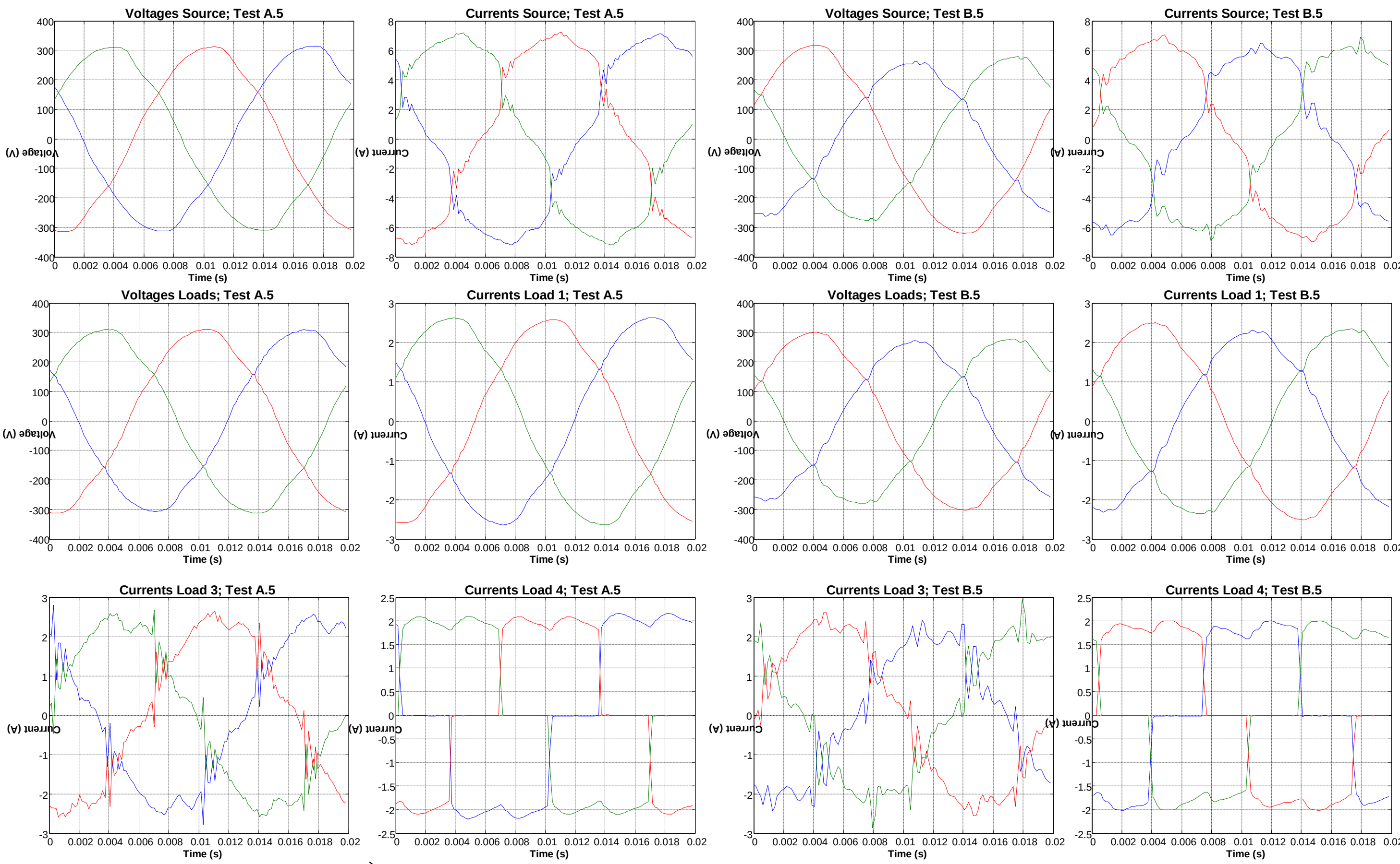
Case 5: Linear balanced load, Linear balanced load with capacitor bank and nonlinear balanced load

The Case 5 experimental platform is configured as follows:

Test A5: Distorted and balanced voltage supply (S_A ON), linear balanced load (S_1 ON), linear balanced load with capacitor bank (S_3 ON) and nonlinear balanced load (S_4 ON). (S_B and S_2 OFF).

Test B5: Distorted and balanced voltage supply (S_B ON), linear balanced load (S_1 ON), linear balanced load with capacitor bank (S_3 ON) and nonlinear balanced load (S_4 ON). (S_A and S_2 OFF).

In this case, load 2 has been replaced by load 4, with a higher distortion. As shown in Figure 7, this increased distortion causes amplification by the capacitor bank. The distorted amplified currents cause voltage drops in the inductive impedance of the network, causing the appearance of peaks in the voltage waveform feeding the loads.



a) b)

Figure 7. Voltage and current waveforms of the Case 5 loads and source:

a) Test A.5 and b) Test B.5.

The results of both experimental tests are given in table V. In each case the proposed index clearly identifies loads 1 and 3 as linear and balanced, while indices ϑ_1 and ϑ_2 erroneously mark the capacitive load as a source of disturbance.

TABLE V. Case 5 Indices Values

	Test A.5				**Test B.5**		
	ϑ_1	ϑ_2	ϑ_3		ϑ_1	ϑ_2	ϑ_3
Load 1	0.43	0.87	0.26	**Load 1**	0.54	0.27	0.16
Load 3	**1.32**	**1.37**	0.92	**Load 3**	**1.36**	0.99	0.75
Load 4	3.91	3.63	1.92	**Load 4**	3.61	1.92	1.57

Finally, Table VI shows both the average ($\bar{x}$) and the standard deviation (σ) resulting from the indices calculated in the different cases. From the average values, indices ϑ_2 and ϑ_3 perfectly identify the four charges while index ϑ_1 fails to identify the load containing the capacitor bank. With respect to the values of the standard deviation given by the indices, it is evident that, in the majority of cases, the proposed index shows a lower deviation, illustrating that it is reliable against changes in the working conditions of the system

TABLE VI. Statistical analysis of the results

	Load 1			**Load 2**			**Load 3**			**Load 4**		
	ϑ_1	ϑ_2	ϑ_3	ϑ_1	ϑ_2	ϑ_3	ϑ_1	ϑ_2	ϑ_3	ϑ_1	ϑ_2	ϑ_3
Average ($\bar{x}$)	0,51	0,35	0,44	2,71	1,61	1,45	**1,08**	0,86	0,81	4,10	2,33	2,06
Deviation (σ)	0,08	0,27	0,26	1,77	0,39	0,31	0,40	0,45	0,13	2,85	1,04	0,65

4.4. Discussion

According to the results of the ten tests carried out, the following can be established:

- In all the tests, the new index, ϑ_3, is able to identify the non-linear and/or unbalanced loads under different conditions of the supply voltage, both when they are individually connected and combined. By contrast, the ϑ_1 and ϑ_2 indexes are not always able to identify the linear and/or unbalanced character of these types of loads.

- It is noteworthy that in the tests where the capacitive load has been connected (A5, B5), the new index, ϑ_3, has identified it as a linear load, while the ϑ_1 and ϑ_2 indexes do not identify it as such. At this point it is necessary to indicate that in all the tests performed, the ϑ_1 index has only failed in those tests where the load with capacitors was connected. It is known that the presence of capacitors in environments with distortion produces an amplification thereof that is transferred to the voltage of PCC, [20, 21]. From this, it could be argued that as a distorting load, it would have to be classified as a source of distortion and be identified as such. This argument is not acceptable, since capacitor banks are still a very widespread element for the compensation of the power factor, and as such encouraged by the current tariffs.
- The statistical parameters calculated for the tests show that the highest dispersion value of the new index, ϑ_3, is 0.65. This accounts for its stability against the unbalances and distortion presented by the voltages at the terminals of the loads, which are always values lower than those determined by the ϑ_1 and ϑ_2 indexes. In the tests, ϑ_1 resulted in dispersion values of up to 2.85, while ϑ_2 resulted in values of up to 1,04. Although two situations of unbalance and distortion have been considered for the background voltage, the effect on the voltage of the different combinations of the connected loads implies a greater variety of situations for the supply voltage of the same.

5. Conclusions

Due to the limitations of the methods of locating sources of distortion and/or unbalance in electrical networks based on individual measurements from a specific section of the system, the use of methods based on distributed measurements is proposed as an alternative. A complete analysis of three distributed measurement indices is presented. Firstly, the Global PQ (ϑ_1), composed of three basic PQ indices: ξ_{slq}, HGI and the ratio

η^+. Secondly, index (ϑ_2), a modification of the Global PQ, where the ratio of ξ_{slq} index is replaced by the ratio of an unbalanced nonlinear index, UNL. And finally, the new distributed measurement index proposed in this paper (ϑ_3), based on the IEEE Std. 1459 framework and a ratio of the global harmonic index.

This new index has been tested in an experimental platform connected to a real low-voltage electrical network. In order to gain a more complete validation of the proposed index, several cases have been considered that reproduced the typical configurations present in low-voltage distribution networks. The results confirm that the ϑ_3 index presents better behaviour in comparison with the ϑ_1 and ϑ_2 indexes, with respect to the identification of non-linear and unbalanced loads and with respect to stability against variations in supply voltage. However, despite these different test results and the conclusions drawn from them, the study shows that the disturbance caused by the user strongly depends on the working conditions of the other users and the characteristics of the network. As a result, the topic remains open and there is a need for further research.

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