Unbalance and Harmonic Distortion Assessment in an Experimental Distribution Network

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***Abstract*— The identification of voltage and current harmonic distortion and voltage unbalance sources is one of the main problems in electric distribution systems. In order to overcome it, in this paper the use of two novel indices is proposed. On the one hand, the Load Characterization Index (LCI) is suggested to calculate the harmonic distortion introduced by the load. This index identifies linear and non-linear loads in the power systems. On the other hand, the Unbalance Current Ratio (UCR) is suggested to assign the responsibility for system unbalance to load and source sides. Both indices can be calculated only from the measurement of the current at the input of the load and the voltage at the Point of Common Connection (PCC). The main objective of this paper is to test the performance of these two indices on an experimental three-phase electrical network. In order to do that, several experimental tests have been considered.**

***Keywords* — Harmonic distortion source, distribution networks, nonlinear loads, unbalance**

I. INTRODUCTION

NOWADAYS, the assessment of electric power quality is becoming increasingly important due to the widespread use of nonlinear and time-varying loads. Otherwise, the uneven distribution of single-phase loads in the low voltage distribution system, among other causes, makes the voltage unbalance a problem in the power system. In this way, the IEEE Standard establishes the procedure to assess the voltage and current distortion and unbalance in the electric network PCC, [1-2]. Power monitoring equipment is frequently used to do that, [3-7]. However, the Standard does not regulate the procedure to assign the responsibility for the network harmonic distortion and/or unbalance to the different agents in the electric power system. This is a requirement to decrease these non-conformities, i.e., knowing the cause of the distortion and/or unbalance, the best location of the compensation systems is guaranteed and the most suitable procedure to mitigate them is established [8].

There are many proposals in technical papers to establish the responsibility of each agent for the harmonic distortion in power distribution networks [9-19]. One of the most significant methods is the based on the sign of the harmonic active power. It can be used with measurements in a single-point, [10-11], or with distributed measurements systems, [12–15]. This method is based on the fact that the harmonic active power flows from source to load if the load is linear whereas it flows in the opposite direction when it is a distorting load. One of the indices based on this concept is the Harmonic Global Index, HGI, which will be considered in the experimental results assessment.

Other methods are those based on the representation of load and source sides by means of their corresponding Norton circuits, [16]. There is a further technique called the critical impedance method, [17]. The drawback of these methods is the necessity of knowing the network and consumer harmonic impedances. Numeric techniques have also been used to establish each agent responsibility for the harmonic distortion in the electric network, for example, neural networks, [18].

Finally, there is another set of methods in the literature based on the current decomposition, [9, 20-21, 28]; among them, the Non-Colinear Index (NCI), [21], and the Non-Linear Index (NLI), [20], these will be used in the experimental results assessment in this paper. Another of those methods is the Load Characterization Index (LCI), [9], proposed by Herrera and Salmerón, which is based on the decomposition of current at the input of the load into two components: a current component which introduces harmonic distortion into the system and a second current component which does not introduce harmonic distortion, and whose harmonic distortion is the same as that of the voltage.

On the other side, there are several publications which deal with unbalance problems, [22-23]. Some authors consider the harmonic distortion problem together with the unbalance one, [24-27], in order to characterize the unbalance without assigning responsibility to the load and source. One of the indices to identify the unbalance is the Unbalance Current Ratio (UCR), [25], proposed by Herrera and Vázquez [25], which is based on the decomposition of the current at the input of the load into three components: the non-linear, the unbalanced, and the linear balanced currents.

The main objective of this paper is to validate the LCI and UCR performance in an experimental power system. To do this, several experimental tests have been carried out in the Distribution Network and Protection Laboratory, D-NAP, at the University of Strathclyde. This laboratory is a three phase 400 V electrical network that can be split into a number of sub-networks or microgrids with controllable loads and generators.

The main advantage of the LCI is that it is able to identify the true sources of distortion even when there are capacitors in the system, [6], from only voltage and current measurements at the load input. For calculating the unbalance, the UCR is used. UCR and LCI are complementary, using the same procedures to be calculated, and the results presented by both are concordant with other indices published and improved in the case of the capacitors presence. Thus, the experimental values of the used indices will be compared with the HGI, [10], the SRI, [21], and the DAQ, [20], to verify their performance and to prove the better results in the presence of capacitors.

This paper is organized as follows. Section 2 presents the Load Characterization Index. In Section 3, the Unbalance Current Ratio is defined to assign each agent's responsibility for system unbalance. Section 4 describes the experimental platform used to test them. In Section 5, the results of different practical cases are shown and finally, in Section 6, the conclusions are presented.

II. THE LOAD CHARACTERIZATION INDEX

The Load Characterization Index (LCI), [9], is the chosen index to quantify the load responsibility for the system harmonic distortion in the microgrid. It is based on the decomposition of current at the input of the load into two components: a first current component which introduces harmonic distortion into the system, I_{nl} in Fig. 1, and a second current component which does not introduce harmonic distortion, and whose harmonic distortion is the same as that of the voltage, I_l in Fig. 1. This current component does not have to be sinusoidal (even without introducing harmonic distortion into the system) because it may be influenced by the system distortion.

The equivalent single-phase circuit that models the load according to the procedure to calculate the LCI is shown in Fig. 2, [9]. The first one, Fig. 2(a), consists of a linear load in parallel to a harmonic current source. The second one, Fig. 2(b), consists of the same linear load as Fig. 2(a) in series to a harmonic voltage source, [9]. The linear load is formed from three parallel branches: an inductive impedance (a resistor R_{L1} in series with an inductor L_1), a resistor R_1 and a capacitor C_1. There are two circuits because the non-linear loads can be of two different kinds: current distortion sources or voltage distortion sources.

To decompose the current at the input of the studied load, it must be assumed that the fundamental component of the current flows through the linear circuit of the model, Fig. 1 and Fig. 2(a). Although there are infinite possibilities of sharing fundamental current among the three parallel branches in the linear part, a set of the different values for each element must be tested and the index is calculated for a specific number of circuits. Then an array of index values is obtained, this is an index value for each set of values considered for the elements. Thus, the objective of the method is to find out the circuit that best represents the actual load, taking into account that the linear current component should flow through the linear part of the equivalent circuit. Furthermore, the best index value is the lowest one and the circuit that provides the smallest value for the index will be considered the equivalent to the analyzed load. The current flowing through the linear circuit is not linear, but presents the same distortion as the voltage. The difference between the total current and that flowing through the linear circuit is the non-linear current supplied by the distortion source, [9].

When studying a linear capacitive load the circuit presented in Fig. 2(a) is not useful. Thus, the circuit in Fig. 2(b) must be considered. The source voltage is divided into the drop in the linear load and the voltage at the source terminals. The fundamental component of voltage at point of common coupling must drop into the linear circuit. In the same way as the explained with the circuit in Fig. 2(a), an array of index values is obtained, considering the lowest index value and the circuit achieving the smallest index value, [9].

If one of the indices, that corresponds to the circuit in Fig. 2(a) or that in Fig. 2(b), has a null value, the studied load is linear and the LCI value is null. Otherwise, the LCI value is the corresponding to the circuit in Fig. 2(a). In this way, the current is decomposed and not the voltage. The index value is calculated as the percentage of the non-linear current on the total, i. e. the ratio of the norm of the non-linear current and the total, [9]. Norm is the square root of the sum of the square of each component and each phase of the electrical magnitude (non-linear current, total current, etc.). The row corresponding to the index value obtained allows the values of elements presented in circuits of figure 2 to be established and the current required by them to be calculated. This current will be used later to calculate the UCR, Fig. 3.

Finally, the capacitor behavior and its effect in the network must be discussed. There are several ways of considering this element. Some consider that a component which amplifies the harmonics present in the network behaves as a non-linear load and so, the capacitor must be considered in this way. However, the technical standards promote the use of capacitance to compensate the power factor and so the users who must connect capacitors to improve their power factor should not be penalized by those same standards for the effect of that element in the network. It must be noted that the capacitor, which is a linear component, may be erroneously interpreted as a non-linear load in a network where the voltage is non-sinusoidal because it amplifies the present harmonics in the system.

III. THE UNBALANCE CURRENT RATIO

The UCR, [25], is used in this paper to assign responsibility to load and source for system unbalance in the experimental tests carried out in the network. The UCR and the LCI are complementary, as well as the procedures to calculate them. The linear current calculated in the LCI assessment (which flows through the linear circuit presented in Fig. 2(a), is now decomposed into two components: the unbalance current and the balanced linear one. To do that, a balance linear waveform is considered to establish the values of the parameters of the balance linear load circuit presented in Fig. 1. The difference between the linear current calculated in the LCI assessment and the required by this new circuit is assigned as the unbalanced linear current, I_{un}, [25].

Overall, the current at the input of the studied load is decomposed into three components: the non-linear, the unbalanced, and the linear balanced current as shown in Fig. 1. The balanced linear current is not balanced, but presents the same unbalance as the voltage. It does not introduce unbalance into the system. The unbalanced current is calculated as the difference between the linear current and the balanced linear one.

The balanced linear current must be obtained from the linear current. Firstly, the reference phase is established and then the equivalent impedance is calculated for the reference phase and for each harmonic order considered. A balanced circuit which consists of three sets of equivalent impedances such as those calculated, connected between each phase and the neutral wire is defined. This circuit does not introduce unbalance or harmonic distortion to the system either. The circuit is called balanced linear load as in Fig. 1.

Then, the unbalanced current is the difference between the linear current, I_l, and the balanced linear current, I_{bl}, and it is the only component that introduces unbalance into the system, Fig. 3.

The non-linear current consists of only the small imbalance in the harmonics characteristic of non-linear loads because the fundamental component of the current is completely contained in the linear current and the other harmonics are calculated regarding that fundamental component.

The UCR is then expressed as a percentage of the total current and can be defined as the ratio of the norm of the unbalanced current and the total current, being the norm the square root of the sum of the square of each component and each phase of the unbalance current and the total current. If the studied load is balanced, then the UCR is approximately zero and it does not introduce unbalance into the system. Otherwise, the load is partly responsible for the system unbalance.

IV. DISTRIBUTION NETWORK AND PROTECTION LABORATORY, D-NAP

The D-NAP facility is part of the Institute for Energy and Environment (InstEE) within the University of Strathclyde, in Glasgow. This laboratory can operate grid connected or variously islanded. It offers a flexible environment to test new components or algorithms on a LV network with frequency and voltage variable supply. This is capable of supporting the testing and evaluation of power connected equipment, demonstration of communication system integration, along with evaluating protection systems.

The D-NAP facility contains a range of configurable generators, motors, inverters, power supplies and a capacitor bank. A simplified scheme is shown in Fig. 4. These loads are connected together by a three phase 400 V network arranged across three bus bars. The network short circuit power is 500 kVA. Other devices can be attached to the network at different points, such as a rectifier, a regulator and single-phase electric heaters (P_1 and P_2 in the Fig. 4).

In this work, rectifiers and regulators were used as loads (in P_2) in order to introduce harmonic distortion, as described in the next section. For another set of experiments, balanced and unbalanced loads were required. Thus, a number of single phase electric heaters were purchased to enable a different electrical load to be placed on each phase (in P_1). The voltage and current measurements were taken by a power quality meter.

The dynamic loads are back to back electric drives capable of running either as generators (G_1 and G_2, Fig. 4) or motors (M_1 and M_2, Fig. 4). They have nominal real power levels of 2.2 kW (G_2), 5.5 kW (G_1), and two of 7.5 kW (M_1 and M_2), Fig. 4, these are controlled by a Siemens Simatic electric drive system. The 10 kW inverter (DC/AC converter in Fig. 4) is a custom designed, user programmable inverter with a number of generating modes, the power source is a controllable 20 kW DC source; for this work the inverter and power supply were driven in a constant output power mode. The power quality meter's voltage probes were connected to the bus bar of interest (where P_1, P_2, G_1 or G_2 are connected) and the current clamps were connected to the cable of interest (P_1, P_2, G_1 or G_2) and moved to measure the current waveform of each connected device and the common point of connection.

V. EXPERIMENTAL RESULTS

The purpose of this work is to test the validity of the LCI and UCR indices in distributed power systems as well as to compare these indices with other published indices, such as the HGI, the SRI and the DAQ to verify their performance. Another aim is to prove that the LCI and UCR work better than those other indices in the presence of capacitors.

HGI is an index based on the harmonic active power evaluation. If it fluxes from source to load, the load is considered linear; otherwise, the load is non-linear. SRI compares the current required by a load to the required by a resistive load. If those currents are the same, the load is considered linear. Otherwise, the load is non-linear. The procedure followed to calculate the DAQ is very similar to that followed to calculate the SRI, but in the case of the DAQ the load considered is an inductive impedance.

Thus, several experimental cases were carried out in the D-NAP facility. The different loads were connected and disconnected and voltage in the point of common connection and the current at the input of each load were measured. Five practical cases are analyzed in this section.

Balanced and non-linear loads:

- Case 1: Balanced regulator and balanced heaters (P_2 and P_1 respectively in Fig. 4).
- Case 2: A rectifier (P_2), balanced heaters (P_1), capacitors (P_1) and a generator (G_2), Fig. 4.

Unbalanced and non-linear loads:

- Case 3: unbalanced regulator and balanced heaters (P_2 and P_1 respectively in Fig. 4).
- Case 4: balanced regulator and unbalanced heaters (P_2 and P_1 respectively in Fig. 4).
- Case 5: unbalanced regulator (P_2), balanced heaters (P_1), capacitors (P_1) and a generator (G_1), Fig. 4.

Fig. 5 shows the voltage and current waveforms of isolated loads connected to the distribution network. In this case, the voltages are sinusoidal and balanced. The shown regulator and rectifier currents are balanced whereas the heater currents are unbalanced. The measurements are obtained from the Fluke 430 power quality meter.

These experimental cases (two balanced and three unbalanced) are representative enough of all those carried out. The results are shown in Tables I to V (each table corresponds to one experiment). The first column presents the analysed device (whose current is measured). The second one presents the UCR value. In the case of a perfectly balanced load, UCR must present a null value. Otherwise, the UCR's value will be greater than zero indicating an unbalanced load. The values of the LCI, HGI, SRI and DAQ are also shown in each table of results. In the case of a linear load, the last four columns should present a zero value. Otherwise, its value will be greater than zero indicating that it is a non-linear load.

Table I presents the results corresponding to Case 1. It can be seen that all the indices present similar values. The UCR identifies the loads as balanced and the other four identifies the second load as non-linear with values very similar among them and the first load as linear with values almost null. Table II presents the results corresponding to the case of a rectifier, balanced heaters, capacitor and a generator. In this case, it can be seen that the UCR identifies all the analysed loads (capacitor, heaters and rectifier) as balanced. With respect to the other four indices, their behaviour is different.

All of them identify the rectifier as non-linear and the heaters as linear. However, the only one who identifies the capacitor as linear is the LCI. The other three present a value not null for this device. Fig. 6(a) presents the spectrum of voltage at PCC and Fig. 6(b) the spectrum of current at capacitors input, both corresponding to phase 1. Effectively, it can be seen as capacitors amplify voltage harmonics.

Tables III and IV present the results corresponding to the cases of a regulator and heaters. In Case 3 whose results are presented in Table III the regulator is unbalanced and the heaters balanced and vice versa in that whose result are presented in Table IV. In both cases UCR identifies the balanced and unbalanced loads. In Table III the values of the UCR index for the loads are 88.59 for the regulator and 1.13 for the heaters. In Table IV those values are 4.59 and 41.46. In both experiments the results show that all the distortion indices (LCI, HGI, SRI and DAQ) identify the regulator as non-linear and the heaters as linear. Finally, Table V presents the results corresponding to Case 5 with an unbalanced regulator, balanced heaters, capacitor and a generator. The values given by the UCR show that this index identifies all the loads as balanced except the regulator. In addition, all the distortion indices identify the heaters as linear load and the regulator as non-linear. However, the results presented by these indices about the capacitor are different. In fact, only the LCI presents a null value for this device. Fig. 7 presents the spectrum of voltage at the PCC and Fig. 8 the spectrum of current at regulator input. It can be seen a high unbalance in current non-existing in voltage.

Therefore, the experimental results show on the one hand that the UCR underlines the balanced or unbalanced character of the loads without being affected by their linearity. On the other hand, the results show that the LCI identifies the linear and non-linear loads even in the presence of capacitors and it is not affected by the unbalanced environment.

VI. CONCLUSION

In this paper, indices to assess the harmonic distortion and the unbalance introduced by the different loads connected to the same point of common coupling have been applied to an experimental distribution network in the D-NAP facility. The indices are: the Unbalanced Current Ratio to analyze the unbalance and the Load Characterization Index to analyze the harmonic distortion. In addition, to compare the obtained LCI results with common indices, the Harmonic Global Index, the Non-Colineal Index and the Non-Linear Current are also presented. The experimental results presented in this paper show that the UCR identifies the loads which introduce unbalance into the system even with unbalanced and distorted voltages. In the same way, the LCI identifies the loads which introduce harmonic distortion to the system even with unbalance and distorted voltages. Moreover, the LCI identifies the capacitors as linear loads according to the Standard proposition of using this element to correct the power factor in the industrial installations.

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REFERENCES

[1] IEEE Standard Definitions for the Measurement of Electric Power Quantities under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions. IEEE Standard 1459, 2010.

[2] Sobhan Mohamadian and Abbas Shoulaie. (2011, July). Comprehensive Definitions for Evaluating Harmonic Distortion and Unbalanced Conditions in Three-and Four-Wire Three-Phase Systems Based on IEEE Standard 1459. *IEEE Trans. Power Del. 26(3),* pp.1774–1782.

[3] G. T. Heydt and W. T. Jewel. (1998, Apr.). Pitfall of electric power quality indices. *IEEE Trans. Power Del. 13(2)*, pp. 750-578.

[4] T. Lin and A. Domijan. (2005, Oct.). On power quality indices and real time measurement. *IEEE Trans. Power Del., 20(4)*, pp. 2552–2562.

[5] Y.-J. Shin, E.J. Powers, M. Grady, and A. Arapostathis. (2006, Jan.). Power Quality Indices for Transient Disturbances. *IEEE Trans. Power Del.,21(1)*, pp. 253-261.

[6] N. Locci, C. Muscas, and S. Sulis. (2007, Oct.). On the measurement of power-quality indexes for harmonic distortion in the presence of capacitors. *IEEE Trans. Instrum. Meas.56(5),* pp. 1871–1876.

[7] F.J. Alcántara, P. Salmerón. (2005). A new technique for unbalance current and voltage estimation with neural networks. *IEEE Trans. Power Systems, 20 (2)*, pp. 852–858.

[8] M. S. Kandil, S. A. Farghal, and A. Elmitwally. (2001, Nov.). Refined power quality indices. *IEE Proc. Gener. Transm. 148(6)*, pp. 590-596.

[9] Herrera RS., Salmerón P. (2012). Harmonic disturbance identification in electrical systems with capacitor banks. *Electric Power System Research 82(1),* pp. 18–26.

[10] C. Muscas. (1998, Jul./Aug.). Assessment of electrical power quality: indices for identifying disturbing loads. *ETEP 8, 8(4),* pp. 287–292.

[11] A.P.J. Rens, P.H. Swart. (2001, Sep/Oct.). On techniques for the localisation of multiple distortion sources in three-phase networks: time domain verification, *ETEP, 11*.

[12] C. Muscas, L. Peretto, S. Sulis, R. Tinarelli. (2006, Oct. 5). Investigation on multipoint measurement techniques for PQ monitoring. *IEEE Trans. Instrumentation and Measurement, 55*, pp. 1684-1690.

[13] D. Castaldo, A. Ferrero, S. Salicone, A. Testa. (2003, June 23-26). A Power-Quality Index Based on Multi-Point Measurements. Presented at IEEE Bologna Power Tech Conference.

[14] L. Critaldi, A. Ferrero, S. Salicone. (2002, Aug. 4). A distributed system for electric power quality measurement. *IEEE Trans. Instrumentation and Measurement, 51*.

[15] D. Castaldo, A. Ferrero, S. Salicone, A. Testa. (2003, Oct.). An index for assessing the responsibility for injecting periodic disturbances. Presented at 6th International. Workshop on Power Definitions and Measurement under Non-Sinusoidal Conditions.

[16] E. Thunberg, L. Söder. (1999, Jan. 1). A Norton approach to distribution network modeling for harmonic studies. *IEEE Trans. Power Del.14*, pp. 272-277.

[17] Ch. Chen, X. Liu, D. Koval, W. Xu, T. Tayjasanant. (2004, Jan. 1). Critical impedance method - a new detecting harmonic sources method in distribution systems. *IEEE Trans. on Power Del.19*, pp. 671-678.

[18] J. Mazumdar, R. G. Harley, F. C. Lambert and G. K. Venayagamoorthy. (2007, May). Neural Network Based Method for Predicting Nonlinear Load Harmonics. *IEEE Trans. Power Electronics, 22(3)*, pp. 1036-1045.

[19] W. Lu, X. Liu, and Y. Liu. (2003, Jan.). An Investigation on the Validity of Power-Direction Method for Harmonic Source Determination. *IEEE Trans. Power Del. 18(1)*, pp. 214-219.

[20] A. Dell'Aquila, M. Marinelli, V.G. Monopoli, P. Zanchetta. (2004, Jul. 3). New power-quality assessment criteria for supply under unbalanced and nonsinusoidal conditions. *IEEE Trans. Power Del.19*, pp. 1284-1290.

[21] K. Srnivasan and R. Jutras. (1998, Jan.). Conforming and non-conforming current for attributing steady state power quality problems. *IEEE Trans. Power Del. 13(1)*, pp. 212–217.

[22] J. G. Mayordomo, L. F. Beites, J. L. Gutiérrez. (1996). Assessment of unbalance emission level produced by loads using the apparent power components. *ETEP 1996, 6(6)*, pp. 381–386.

[23] Orts-Grau S, Alfonso-Gil JC, Gimeno-Sales FJ, Segui-Chilet S. (2010). New resolutions of the unbalance power according to Std. 1459. *IEEE Trans. Power Del. 25(1)*, pp. 341–350.

[24] Salmerón P., Herrera RS., Pérez Vallés A., Prieto J. (2009, Apr.). New Distortion and Unbalance Indices Based on Power Quality Analyzer Measurements, *IEEE Trans. Power Del. 24(2)*, pp. 501-507.

[25] Herrera RS., Vázquez J. R. Identification of unbalanced loads in electric power systems, *International Trans. Electrical Energy Systems*, DOI: 10.1002/etep.1772.

[26] Chicco G, Postolache P, Toader C. (2007). Analysis of three-phase systems with neutral under distorted and unbalanced conditions in the symmetrical component-based framework. *IEEE Trans. Power Del. 22(1)*, pp. 674-683.

[27] Zheng T, Makram EB, Girgis AA. (2003). Evaluating power system unbalance in the presence of harmonic distortion. *IEEE Trans. Power Del. 18(2)*, pp. 393–397.

[28] Srinivasan, K. (1996, Apr.). On Separating Customer and Supply Side Harmonic Contributions, *IEEE Trans. Power Del. 11(2)*.

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FIGURE CAPTIONS

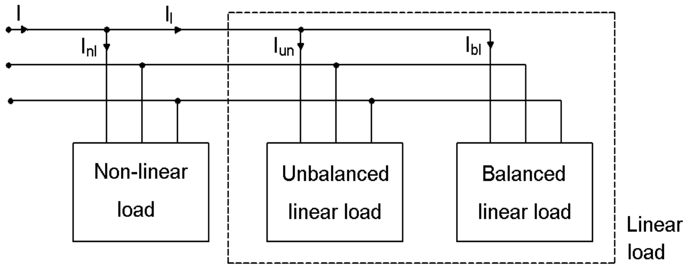
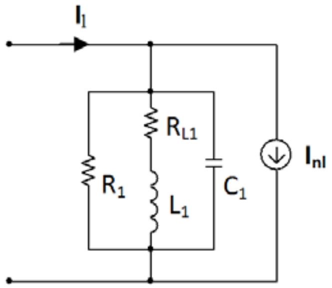
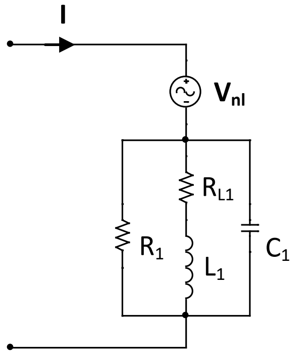


Fig. 1. Load current decomposition



a) Harmonic current source equivalent circuit



b) Harmonic voltage source equivalent circuit

Fig. 2. Load equivalent circuit per phase: (a) equivalent circuit including current source and (b) equivalent circuit including voltage source

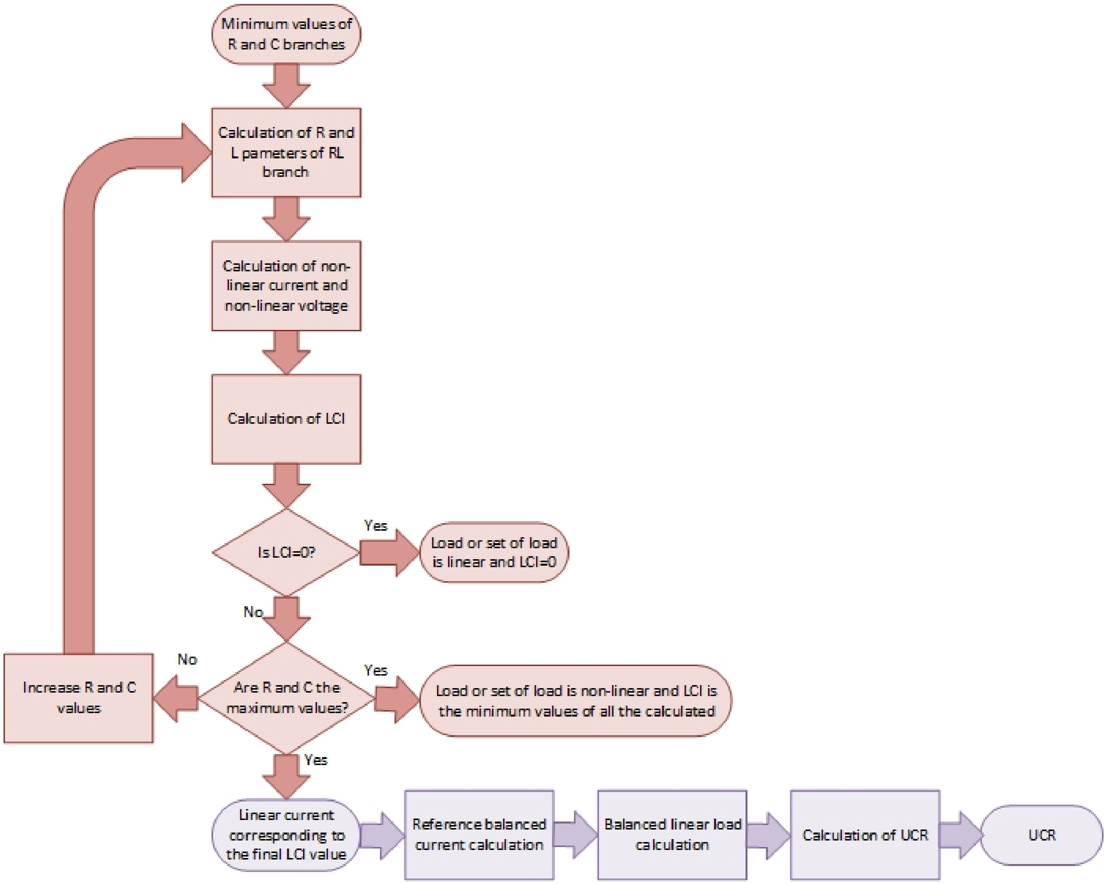


Fig. 3. LCI and UCR calculation flow chart

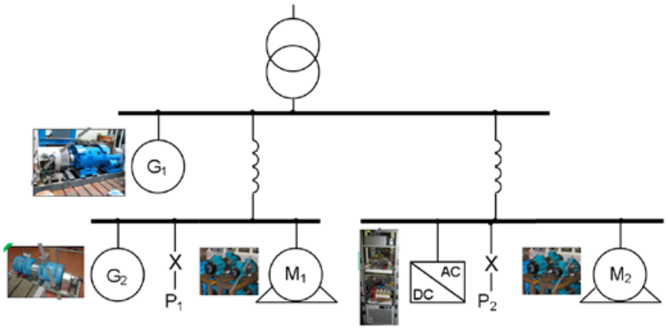
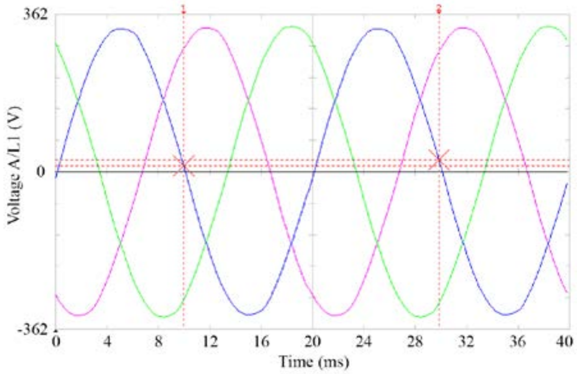
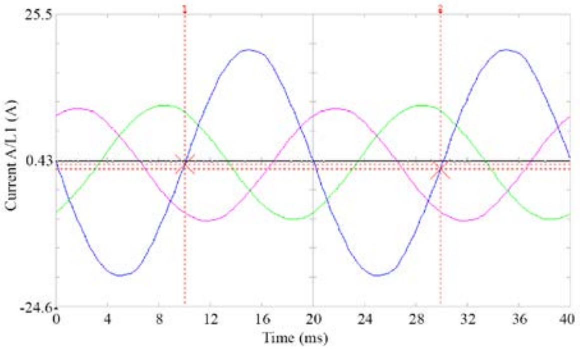


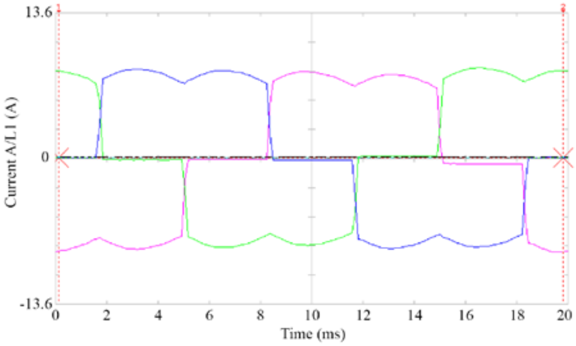
Fig. 4. Simplified network of D-NAP laboratory, where P1 is unbalance source (single-phase linear load) and P2 is harmonic current source



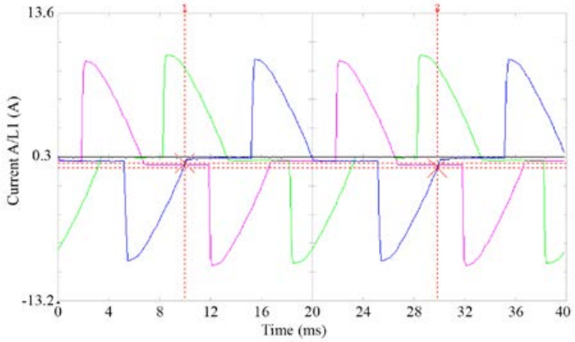
a) Voltage at the PCC



b) Unbalanced heaters current

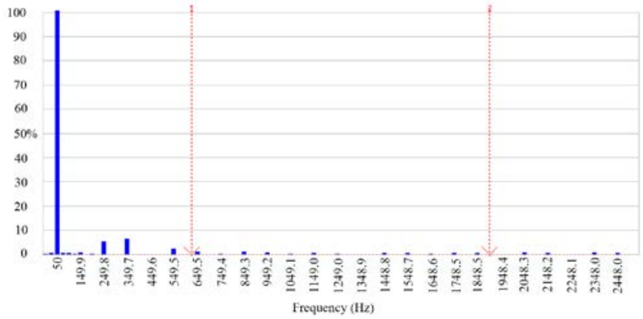


c) Balanced Rectifier current

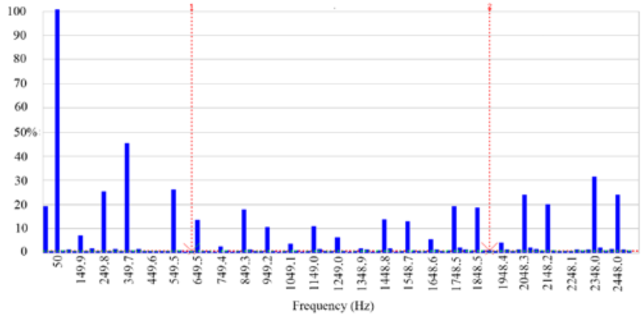


d) Balanced Regulator current

Fig. 5. Voltage and current waveforms of isolated loads connected to the distribution network

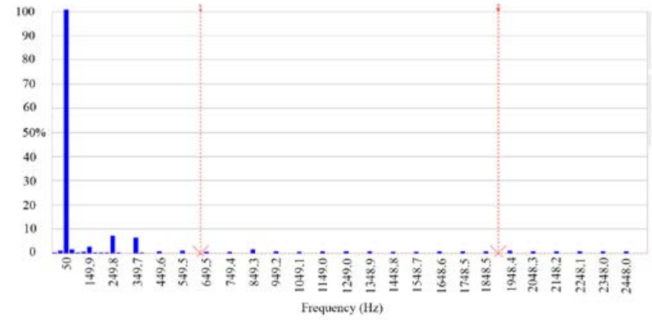


a) Voltage

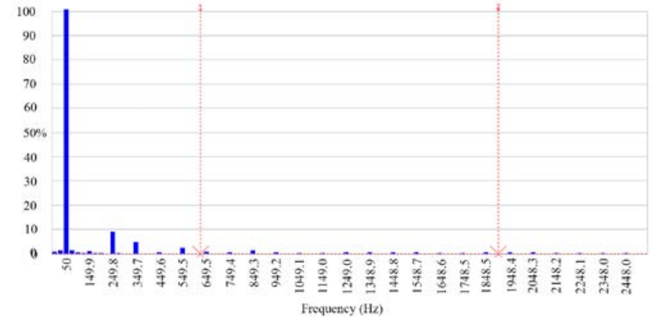


b) Current

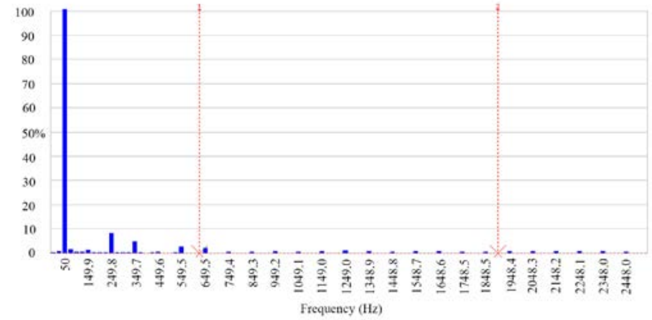
Fig. 6. Spectrum of voltage at PCC and current at the capacitors input in the case whose results are presented in table II



a) Phase a

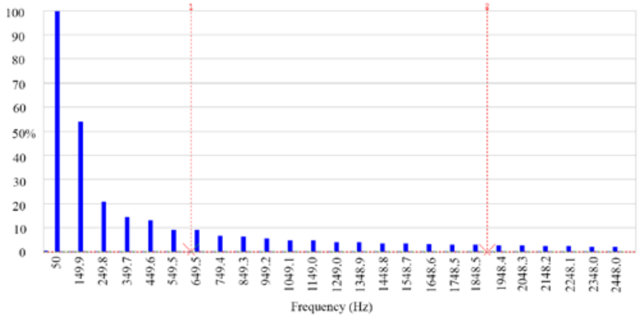


b) Phase b

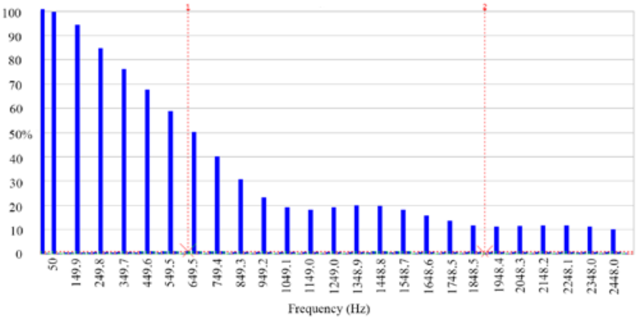


c) Phase c

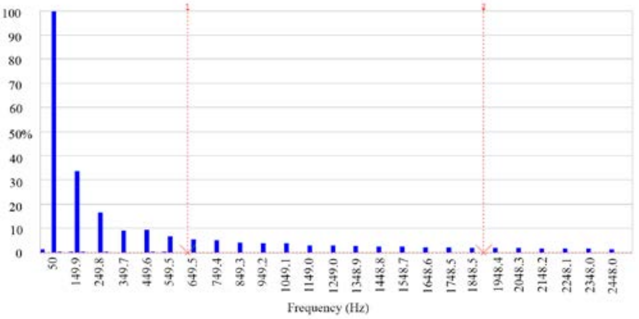
Fig. 7. Spectrum of voltage at PCC in the case whose results are presented in table V



a) Phase 1



b) Phase 2



c) Phase 3

Fig. 8. Spectrum of current at regulator input in the case whose results are presented in table V

TABLES

TABLE I
RESULTS OF CASE 1 WITH A BALANCED REGULATOR AND BALANCED HEATERS CONNECTED TO THE SYSTEM

Analyzed load	UCR	LCI	HGI	SRI	DAQ
Heaters	1,03	0,00	0,06	0,37	0,32
Regulator	4,79	53,35	56,84	55,30	55,26

TABLE II
RESULTS OF CASE 2 WITH A BALANCED RECTIFIER, BALANCED HEATERS, CAPACITOR AND A GENERATOR CONNECTED TO THE SYSTEM

Analyzed load	UCR	LCI	HGI	SRI	DAQ
Capacitors	1,97	0,00	8,80	9,10	8,87
Heaters	1,05	0,00	0,04	0,27	0,24
Rectifier	0,22	28,27	27,92	28,80	28,80

TABLE III.
RESULTS OF CASE 3 WITH AN UNBALANCED REGULATOR AND BALANCED HEATERS CONNECTED TO THE SYSTEM

Analyzed load	UCR	LCI	HGI	SRI	DAQ
Heaters	1,13	0,00	0,04	0,31	0,27
Regulator	88,59	40,44	41,86	42,40	42,32

TABLE IV
RESULTS OF CASE 4 WITH A BALANCED REGULATOR AND UNBALANCED HEATERS CONNECTED TO THE SYSTEM

Analyzed load	UCR	LCI	HGI	SRI	DAQ
Heaters	41,46	0,00	0,03	0,29	0,26
Regulator	4,59	53,12	56,41	55,14	55,11

TABLE V
RESULTS OF CASE 5 WITH AN UNBALANCED REGULATOR, BALANCED HEATERS, CAPACITORS AND A GENERATOR CONNECTED TO THE SYSTEM

Analyzed load	UCR	LCI	HGI	SRI	DAQ
Capacitors	2,84	0,00	10,25	10,49	10,43
Heaters	1,54	0,00	0,04	0,28	0,24
Regulator	88,66	40,65	28,60	42,12	42,12