Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Experimental Investigation of existing Methodologies for the Responsibilities Assignment Problem

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***Abstract*—Currently several methodologies exist to assess the Responsibilities Assignment Problem in Power Quality. In this paper an experimental setup with two known disturbing electrically and mechanically coupled loads has been used to provide a reference disturbance setup for comparing these methodologies. The results and discussion extracted from this experiment is reported in this paper. The setup offered the possibility of adjusting the active power direction under several operative conditions and under two different feeding network configurations. Quantities defined in the standards IEEE 1459 and DIN 40110 are also employed to broaden the analysis and diagnostic possibilities.**

***Index Terms*—Disturbance origin, Harmonics, Power Quality, Responsibility assignment.**

I. Introduction

The identification of disturbance origin is a challenging task for professionals and researchers dedicated to Power Quality analysis. In [1] a conceptual definition related to this task was proposed, named Responsibilities Assignment Problem in Power Quality, $\mathcal{R}_{\mathcal{A}}\mathcal{P}$, This Problem can be explained by recourse to its general characteristics, summarized as follows:

- When problems associated with power quality are present, it is desirable to establish the origin and direction of the disturbances, in some cases this task is mandatory.
- Power quality conditions depend on all agents (Utilities and Customers) connected to the electric grid and their electrical equipment.
- When steady state disturbances are studied, they can be generated in several locations of a system. In this manner, an agent cannot be classified as *disturbing* or *responsible* without considering the possibility that another agent contributes significantly to the disturbances.
- Disturbances may alter their characteristics in time.
- The impact of power quality disturbances on equipment behavior, also including failure or damage, results from the interaction of disturbances provoked by all agents connected to the system.
- The grade of responsibility of each agent depends on the magnitude of his contribution.

In this manner, the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ in Power Quality can be defined as the qualitative and quantitative determination of the contributions of each agent belonging to an electric system with respect to a specific Power Quality condition. In this paper this problem is studied by means of an experimental setup comprising two different known disturbing loads, driven at several operation states and using two feeding configurations. The $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ is a general concept but this paper is concentrated on stady state disturbances, especially harmonics.

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II. Laboratory Setup

The experimental setup complies two non-linear electrically and mechanically coupled loads that can be driven on different operation conditions with the capability of interchanging up to 200kW. The loads have the following characteristics.

- **Load 1**: One Induction Machine fed by a 12-pulse power converter with capacitive smoothing.
- **Load 2**: Two Direct Current Machines operated in parallel and fed by a 6-pulse power converter with inductive smoothing.

The feeding has two configuration options:

- **Separated Trafos**: The bus bars of both loads are isolated, each is fed by its corrsponding Transformers 1 and 2, as shown in Fig. 1. (Switches S1 to S4 closed and S5 open, repectively).
- **Trafo 2**: Both loads are fed by Transformer 2. (Switch S2 open, switches S3 to S5 closed).

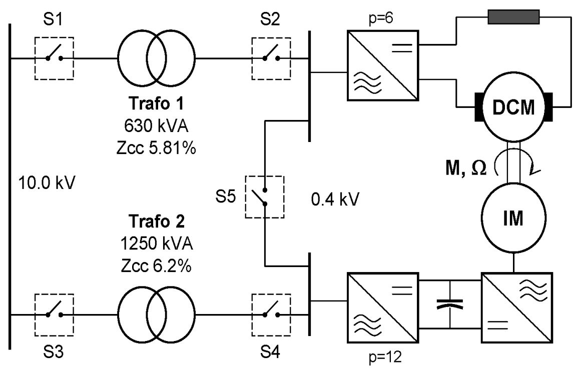

Fig. 1. Laboratory Setup

A schematic diagram of the load setup can be seen in Fig. 1, the two DC Machines are shown as one. The loads are mechanically coupled through the drive shaft, defining the power flow direction. The control schemes of the converters

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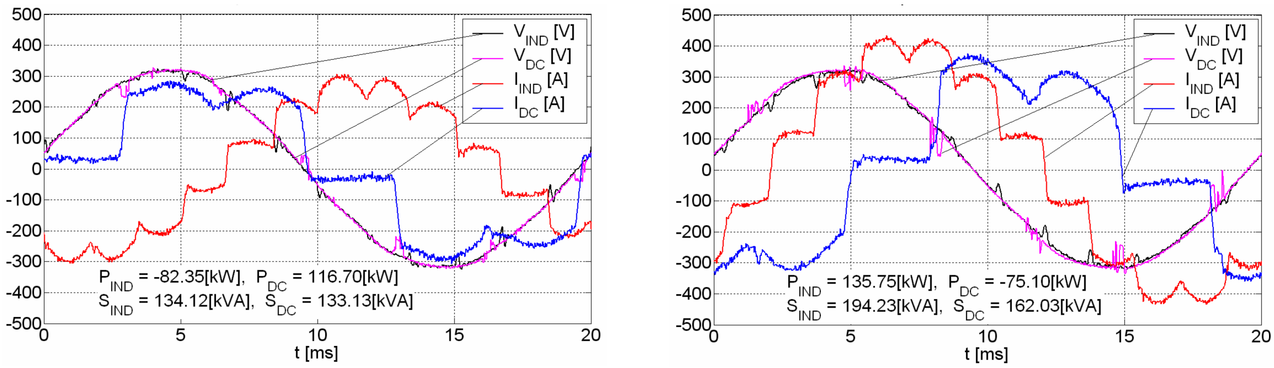
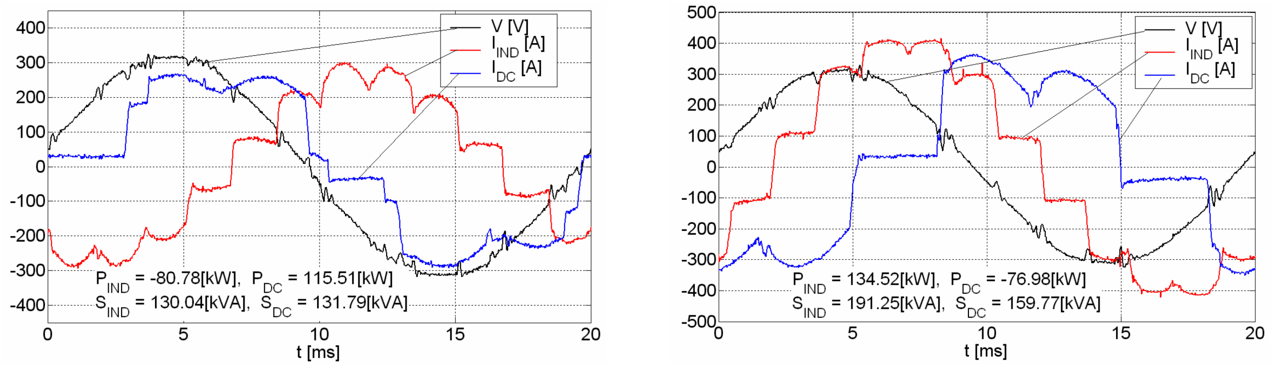


(a) -2000 rpm / T = 0.2 pu

(b) +1500 rpm / T = 0.3 pu

Fig. 2. Waveforms for Separated Trafos configuration



(a) -2000 rpm / T = 0.2 pu

(b) +1500 rpm / T = 0.3 pu

Fig. 3. Waveforms for Trafo 2 configuration

TABLE I
STATES FOR THE FEEDING CONFIGURATION SEPARATED TRAFOS

	Speed [rpm]				
Torque [pu]	0	500	1000	1500	2000
0.0	p	-	-	-	-
0.1	p	-	n/p	-	n/p
0.2	p	n/p	n/p	n/p	n/p
0.3	p	n/p	n/p	n/p	-

TABLE II
STATES FOR THE FEEDING CONFIGURATION TRAFO 2

	Speed [rpm]				
Torque [pu]	0	500	1000	1500	2000
0.0	p	-	-	-	-
0.1	p	n/p	n/p	n/p	n/p
0.2	p	n/p	n/p	n/p	n/p
0.3	p	n/p	n/p	n/p	-

allow for the DC Machines to adjust a determined rotation speed and direction, the Induction Machine control permits the adjustment of the torque. Currents and voltages have been measured at the 0.4 kV feeding bus bars of each load using a digital oscilloscope Lecroy, sampling the signals at 50kHz and recording 20 cycles per operation state.

Several operation states were chosen for each feeding configuration, Tables I and II show which. The torque is presented in pu with respect to the Induction Machine nominal torque, in the tables "p" and "n" mean positive and negative rotation directions. The operation of the laboratory setup at torque 0.3 pu and 2000 rpm could cause damages in the setup, that is why this operative states were not droven.

III. WAVEFORMS DESCRIPTION AND SPECIAL CHARACTERISTICS

Figs. 2 and 3 show waveforms of the measured signals. In order to make the presentation of these signals easier, only those of phase "b" are depicted for the operation states with the highest apparent and active power conditions achieved during the tests.

Voltages: For the configuration Separated Trafos both voltages are presented. As can be seen, both voltage signals are almost the same except for the notches caused by the commutation of the power converters. The influence of the commutation of one power converter on the voltage of the other one was studied, it was found that the 10kV side short circuit capacity is high enough to avoid the transmission of the notches from one side to the other. For the Trafo 2 configuration, the conmutation notches caused by both converters are present on the voltage signal.

Currents for Load 1: Load 1, Induction machine fed by a 12-pulse converter, has the similar waveform for different operation states. The higher the active power (absorbed or delivered) the higher the current peak value, for different operation states the fundamental frequency phase displacement is always close to zero. In comparison to Load 2, current rms values increase corresponding to the active power, as can be seen in Figs. 2 and Fig. 3 for both feeding configurations.

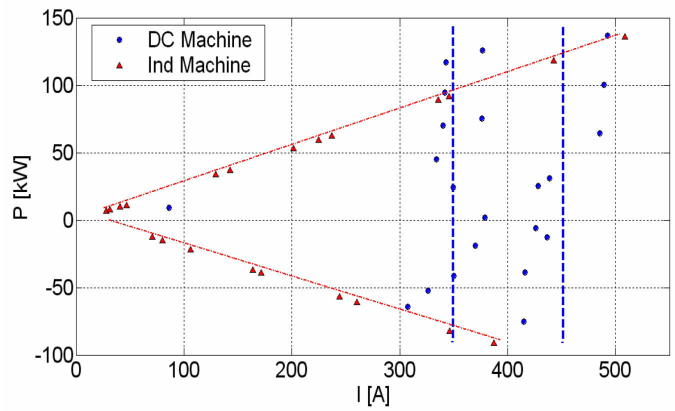


Fig. 4. Fed from Separated Trafos. Load 1 Induction Machine with △, Load 2 DC machine with ○

Currents for Load 2: Load 2, DC Machines fed by the six-pulse converter, has the same current waveform for the different operation states with its magnitude remaining almost unchanged. This current is displaced in time with respect to the voltage in order to adjust the active power injected to or delivered by the DC machines, which corresponds to the usual operation scheme of this kind of converter. For example, Figs. 2(a) and 2(b) show a displaced current that absorbes 116.7 kW from the system or injects 75.1 kW into it, respectively.

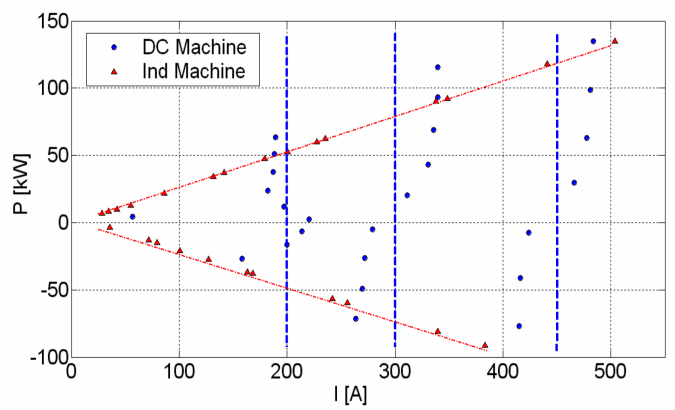


Fig. 5. Fed from Trafo 2. Load 1 Induction Machine with △, Load 2 DC machine with ○

When the active power absorbed or delivered by Load 2 increases, an elevation of the current rms value can be appreciated. For the configuration with Separated Trafos, the current has values around 350 A and 450 A, as it is shown in Fig. 2. and Fig. 3 illustrates this for the Trafo 2 configuration, in this case the current has values around 200 A, 300 A and 450 A.

As mentioned above, the setup permitted to control the active power flow by means of controlling the power coverters, which for the signals implicate different phase positions with respect to the voltage and changes in current rms values. For the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ this setup has clearly defined characterisitics and presents usual loads with noticeable harmonics, which makes it specially valuable to evaluate this problem.

Presence of two common non-linear loads: The power converters used in this setup are widely employed for different purposes in electric facilities worldwide. Additionally, the feeding configuration enables to study the interaction of these non-linear loads.

Intense non-linear disturbing currents: This laboratory setup is capable of interchanging up to 200 kW at the 400 V bus bar, involving highly distorted currents from 200 A to 500 A in both loads.

Waveform: One of the most important characteristics of this setup is the presence of non-linear current waveforms, which do not change their wave shape, they are only displaced in time or modified in amplitude. For the case of the 6-pulse converter, the wave shape remains almost unchanged for all possible operation states, which with respect to the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ means that, independent of the active power direction or the operation state of other loads, this load disturbs always in the same way and in the same amount.

IV. AVAILABLE METHODS FOR THE $\mathcal{R}_{\mathcal{A}}\mathcal{P}$

Many researchers have proposed methods to investigate the origin and dimension of power quality disturbances. Some of the most discussed are listed in the bibliography [2] [3] [4] [6] [7]. Among the different approaches employed to understand and find a solution for the Responsibilities Assignment Problem, most of them resort to power quantities to determine the disturbance direction. In this paper three methods have been employed and compared using measurements extracted from the experimental setup, these methods are the *Critical Impedance Method - CIM* [2], the *Multi-Point Method - MPM* [3] [4] and the *Harmonic Pollution Method - HPM* [7]. Special attention has been paid to the MPM because the source location plays a definitive role and this index represents an interesting alternative, as it will be explained in the results.

A. Critical Impedance Method - CIM

This method was developed by Xu et al [2] to establish the major contributor to the harmonic distortion between a Customer and its Utility, both connected to a Point of Common Coupling. This procedure was not directly thought to determine the major contributor among several customers or utilities. This method supposes a knowledge of the Utility and the Customer equivalent impedances and a proper measurement at the Point of Common Coupling. The circuit in Fig. 6 shows the simplified model to deduce the CIM, as a reference condition the active power is defined as positive when it flows from the customer to the source. The method must be applied to each frequency component individually. In Fig. 6 the impedance X represents the aggregated impedance of the Customer and the Utility equivalent circuits, and E_C and E_U their equivalent voltage sources.

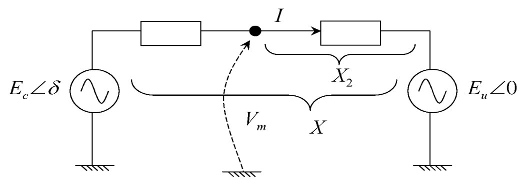


Fig. 6. Circuit model for Critical Impedance Method

The power absorbed by the Utility side can be calculated as:

$$\begin{aligned} P &= E_U I \cos(\theta) = E_U E_C \sin(\delta)/X \\ Q &= E_U I \sin(\theta) = E_U (E_C \cos(\delta) - E_U)/X \end{aligned} \tag{1}$$

According to (1), the real part of the power absorbed by the Utility, P, depends on the product of the RMS values of the equivalent voltage sources, E_C and E_U, and the sinus of the angle difference δ. Although this quantity has information about the magnitudes of the equivalent sources, it does not describe which is the higher one. On the other hand, the imaginary part of non-active power Q defined by (1), comprises the difference between the magnitudes, therefore it appears as a better indicator to determine which side contributes more. The CIM tries to evaluate the capability of one side to inject the imaginary part of the power Q into the other side.

B. Multi-Point Measurements based Index - MPM

This Method has been proposed by Ferrero et al [3] [4]. The basic principle of this method is the calculation of indexes extracted from measurements at the location of a specific customer, which will be compared with the same indexes calculated from the measurements at the main feeder of this customer. The method offers the possibility of assessing the responsibilities of several users connected to the same feeder. The assessment of each Customer is made by calculating three indexes and weighing them. These indexes are listed below.

1) Supply and Load Quality Index: This index, ξ_{slq}, was proposed by Ferrero et al in [5], und establishes a relationship between the total active power and the total active power associated to the fundamental positive sequence component.

2) Global Total Harmonic Distortion Factor Ratio: The following index η^+, explained in detail in [4], provides information about the distortion of a three-phase system by means of indexes extracted from the collective, fundamental collective and positive sequence collective RMS voltage and current values. The ratios between the global harmonic factors, as stated in [3], reflect the tendency of a load to amplify the voltage distortion into the current distortion due to the presence of nonlinearity or resonance in the load itself.

3) Harmonic Global Index: This index, ξ_{HGI}, was proposed by Muscas in [6], and relates a three-phase collective RMS current value of the components associated to the harmonic power flowing from the load backward to the source and that of the power flowing from the source toward the load.

4) MPM weighed Index: By calculating the indexes related to each line connected to the PCC, including the feeder line, these indexes can be improved. A new index, υ_k will be used to evaluate the contribution of Customer k:

$$\upsilon_k = \frac{1}{w_1 + w_2 + w_3}\left(w_1 \frac{\xi_{slq_k}^{-1}}{\xi_{slq_s}^{-1}} + w_2 \frac{\xi_{HGI_k}}{\xi_{HGI_s}} w_3 + \frac{\eta_k^+}{\eta_s^+} \right) \tag{2}$$

with:

$$\begin{aligned} w_1 &= 1 & w_2 &= w_2' w_3 \\ w_3 &= \frac{I_{\Sigma_k}}{I_{\Sigma_{n_k}}} \Big/ \frac{I_{\Sigma_s}}{I_{\Sigma_{n_s}}} & w_2' &= \frac{N}{\sum_{k=1}^{N} \frac{\xi_{HGI_k}}{\xi_{HGI_s}}} \end{aligned} \tag{3}$$

where s subscript means "supply" and k means "k-customer", N is the number of connected customers, I_{Σ_k} the current collective rms value of the customer k and $I_{\Sigma_{n_k}}$ its rated value. Under sinusoidal conditions, $\upsilon_k = 1$, becomes $\upsilon_k > 1$ when the disturbance is being originated by the customer connected to the line k, and becomes $\upsilon_k < 1$ when the distortion comes from the supply system.

C. Harmonic Pollution Method - HPM

The Harmonic Pollution Method, proposed by Emanuel et al [7], suggests an approach to quantify the contribution of the customers to a specific element of interest. This method does not evaluate the origin of the disturbances but calculates the amount of the harmonic distortion provided by a specific Customer to another Customer or element inside the system. The method evaluates a cost function depending on the contribution of each element connected to the system,

$$\xi = f\left[\sum_{h,h\neq 1} (w_h I_h)^2\right] \tag{4}$$

where w_h is a weighing factor, whose value depends on the harmonic order h and the behavior of the element itself. The method projects the current of each customer on the current at the point under evaluation. Those contributions tending to increase the magnitude of the current I_{Ch} are included in the set P, the reducing contributions in the set N.

$$\sum_{h,h\neq 1} w_h^2 I_{Ch}^2 = \sum_{h,h\neq 1} w_h^2 \left[A_h \sum_{k=1}^{P} \tilde{I}_{pkh}^2 + B_h \sum_{j=1}^{N} \tilde{I}_{njh}^2 \right] \tag{5}$$

In (5) $\tilde{I}_{pkh}$ represents the positive contribution of customer k belonging to the set P to the distortion at the point C, and $\tilde{I}_{njh}$ the negative contribution of the customer j belonging to the set N.

V. Consideration of German Standard DIN 40110

The Standard IEEE 1459 [11] represents a valuable compilation of power definitions, their interpretation and usage for electric power measurements under unbalanced and nonsinusoidal conditions. The German Standards [9] and [10] contain also power definitions widely used in Germany and also known in other countries, but their utilization is not common out of Germany. An interesting approach of the German standard is the definition of **zero-sum** quantities for voltages and currents, which are meant to describe voltages and currents in time or frequency domain following Kirchhoff's Laws. For a n conductors circuit, each one denoted μ, collective RMS values of currents and voltages are calculated as:

$$I_\Sigma = \sqrt{\sum_{\mu=1}^{n} I_\mu^2} \qquad U_\Sigma = \sqrt{\sum_{\mu=1}^{n} U_{\mu 0}^2} \tag{6}$$

Many quantities in [9] and [10] are defined slightly different in comparison to those of [11], except the Active Power, defined in the same manner for both standards as follows:

$$P_\Sigma = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T \mathbf{u}_{\mu 0}^T \mathbf{i}_\mu dt \tag{7}$$

where $\mathbf{u}_{\mu 0}$ and $\mathbf{i}_\mu$ are vectors containing the zero-sum voltages and currents. The Apparent Power can be calculated from (6) as:

$$S_\Sigma = U_\Sigma I_\Sigma \tag{8}$$

Apparent Power is defined in [11] through the product of the equivalent effective current and voltage. Depending on the presence of neutral conductor in the circuit the Equivalent voltage and current are derived differently in [11]. The Apparent Power matches in [11] and [10] when the Equivalent voltage V_e is derived as:

$$V_e^2 = \frac{1}{36}\left[3(V_a^2 + V_b^2 + V_c^2) + 3(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)\right] \tag{9}$$

in this case $\sqrt{3}V_e = U_\Sigma$, corresponding to $\xi = 3$ according to [8].

The scope of both standards is to present and define quantities for measuring electric power, the short comparison presented above is meant to put the German standard into context considering that the IEEE 1459 standard is more widely known than the German. The German standards contain a very valuable approach to decompose the signals under any condition of asymmetry or distortion, which can be employed in time and frequency domain as well. This decomposition is based on the Fryze's idea [12] of representing a single-phase load by a suitable **equivalent active conductance** G_a fed by the same voltage as the load.

$$G_a = P_\Sigma / U_\Sigma^2 \qquad i_{a\mu} = G_a u_{\mu 0} \tag{10}$$

$$i_{x\mu} = i_\mu - i_{a\mu} \tag{11}$$

where $i_{a\mu}$ is the **active current**, proportional to the voltage, and $i_{x\mu}$ is the **non-active current**. An additional quantity can be derived to represent the current part related to the Reactive power. In this paper the Reactive power is calculated from the fundamental frequency component of the voltage delayed in time a quarter of period [9], this is:

$$\begin{aligned} Q_\mu &= \langle u_{\mu 0}^1(t - T/4), i_{x\mu}\rangle \\ Q_\mu &= \frac{1}{T}\int_0^T u_{\mu 0}^1(t - T/4) i_{x\mu} dt \end{aligned} \tag{12}$$

from the reactive power, an equivalent susceptance can be calculated as:

$$B_\mu = Q_\mu / U_{\mu 0}^1 \tag{13}$$

leading to the definition of the reactive part of the non-active current, for the sake of simplicity is defined in this paper a **reactive current** as:

$$i_{x\mu Q} = B_\mu u_{\mu 0}^1(t - T/4) \tag{14}$$

The non-active current can split now into the reactive current and the non-active non-reactive current component, simply called in this paper **distorted current**.

$$i_{x\mu D} = i_{x\mu} - i_{x\mu Q} \tag{15}$$

The current decomposition presented above comprises a set of orthogonal components of the current, the active current is proportional to the voltage, the non-active current and its components, the reactive and distorted currents, are orthogonal to the voltage. Due to these characteristics, the apparent power can be split into components, based on the RMS values of the current components as follows:

$$\begin{aligned} S_\Sigma^2 &= P_\Sigma^2 + N_\Sigma^2 \\ S_\Sigma^2 &= P_\Sigma^2 + (U_\Sigma I_{x\Sigma})^2 \\ S_\Sigma^2 &= P_\Sigma^2 + (U_\Sigma I_{x\Sigma Q})^2 + (U_\Sigma I_{x\Sigma D})^2 \end{aligned} \tag{16}$$

The quantities presented above do not show explicitly the presence of unbalance in the signals. However, the asymmetry components can be split also, according to [10], calculating the equivalent active conductances for each conductor. The laboratoy assembly presented in this work has a set of symmmetrical signals, therefore the inclusion of asymmetry analysis possibilities would not lead to apreciable conclusions, that is why the asymmetry components are not going to be depicted in this paper.

VI. Results

The above mentioned methodologies were applied to all operation states. For the sake of simplicity and to avoid an unnecessary use of space, only some selected results are presented in this paper, which are noteworthy to clarify the analysis of the measurements.

In Section III some special characteristics of the laboratory setup were listed, among them the presence of a non-changing current wave shape is counted. For Load 1, which has the same current wave shape for all operation states but its magnitude increases as the active power gets higher, it is expected that any $\mathcal{R}_\mathcal{A}\mathcal{P}$ method judges this load as a disturbing one for high active power levels and not-disturbing for low active power levels. For Load 2, DC Machines fed by the 6-pulse power converter, considering that it presents always the same wave shape, it is expected that any $\mathcal{R}_\mathcal{A}\mathcal{P}$ method judges this load as a disturbing one. This active power levels can be expressed in terms of effective current values or rated apparent powers, which must be compared to the short circuit capacity in order to provide a concrete value range for high and low levels at the connection point of the load, in the same manner as [13] suggests. Considering that the loads in the experimental setup are strong enough to disturb the system, in this paper we will concentrate on the qualitative evaluation of the methods.

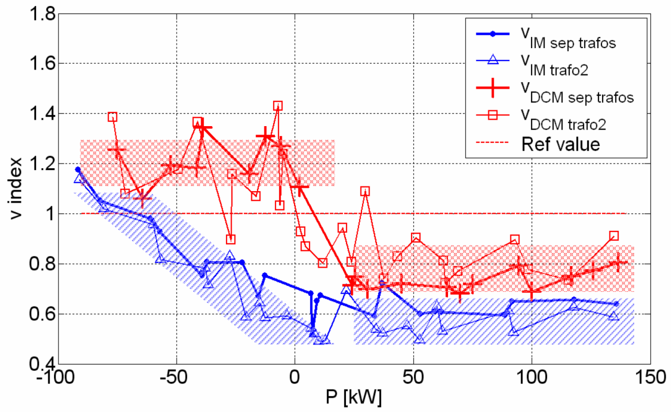


Fig. 7. υ Index according to MPM vs. active power for both feeding configurations

Fig. 7 shows the application of MPM on the measured signals, the υ index has been drawn vs. the active power of each state. The Load 1 seems to be non-disturbing for almost all cases, except for the highest negative active powers. For negative active power values, Load 2 appears to be a disturbing one but not for the positive values. Regarding the characteristics of the signals, both valorations seem to be wrong, Load 1 should be disturbing for high negative and positive active power levels, and Load 2 should be disturbing for any state.

The signals contain not only components related to the disturbance under evaluation, but also the useful and desired parts of the signals, or at least harmless, mainly the active and reactive power components. If the "harmless" parts of the signals are substracted, a new set of signals with only "non-desirable" content can be derived, concentrating the analysis on the non-usable disturbing content and providing an improvement for the method. Following this idea, a first modification of the MPM method was carried out extracting the active current components $i_{a\mu}$ (10) of the measured currents, by means of the decomposition suggested in Section V, this mean, the MPM was applied to the set of non-active currents $i_{x\mu}$ (11). The results are shown in Fig. 8.

For this first modification no significative improvement can be appreciated for the evaluation of Load 1. However, Load 2 seems to be judged as disturbing for high negative and positive active power levels, but not low active power levels. The

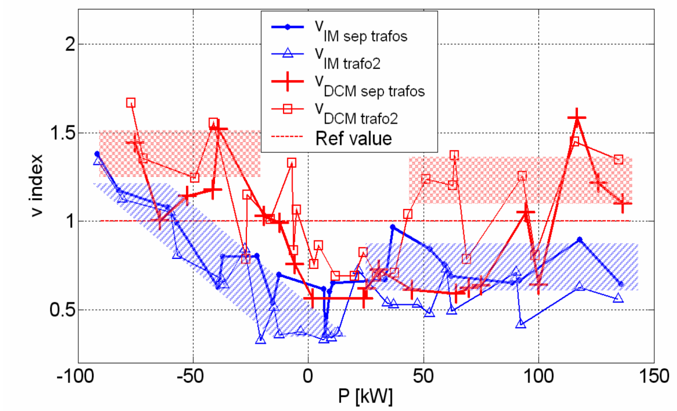


Fig. 8. First modification of MPM Index υ vs. active power - Active current substracted, Non-active current evaluated

first modification is not yet capable of improving completely the MPM according to the authors' criteria, therefore further modifications have been employed.

A second modification was carried out, this time the reactive current $i_{x\mu Q}$ (14) was removed from the measured currents, Fig. 9 shows the results. This modification does not seem to contribute to an improvement of the method, the 1 assessment has the same bahavior of the original method and for Load 2 the states with low active power levels are more disturbing than those of higher power levels, which does not agree with the expectations.

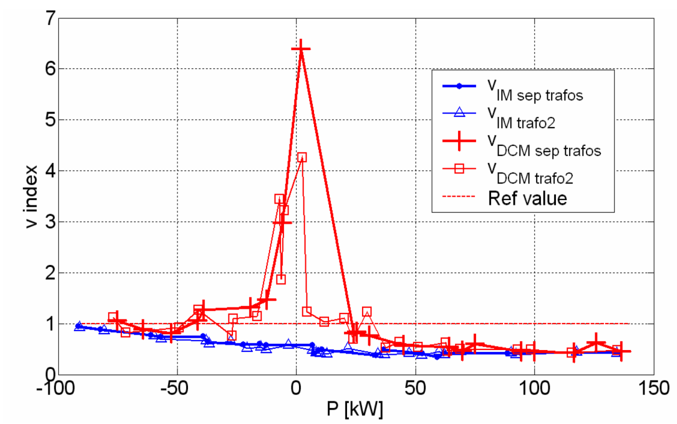


Fig. 9. Second modification of MPM Index υ_2 vs. active power - Reactive current substracted

A third modification was tried, this time active current (10) and reactive current (14) were removed, in this manner the MPM is applied to the distorted current $i_{x\mu D}$ (15). The results are presented in Fig. 10. This modification fulfills the expectation of the authors. The modified υ index for Load 1 increases as the power increases, for negative or positive values.

For Load 2 the υ index tends to behave uniformly, variations are present, but the index tends to be around a central value, resulting on the tendence the authors were searching for.

The authors did not modify the original MPM weighing factors (3) in order to keep the method as close as possible to that proposed in [3] and [4]. Although the behavior of the modified MPM is what the authors wanted to achieve, the index values are below the assessment reference of the MPM method, the reason for this could be that the composing indexes do not use the same signals any longer. In this manner either the assessment reference should be reevaluated for the modified MPM or the weighing factors could be reviewed.

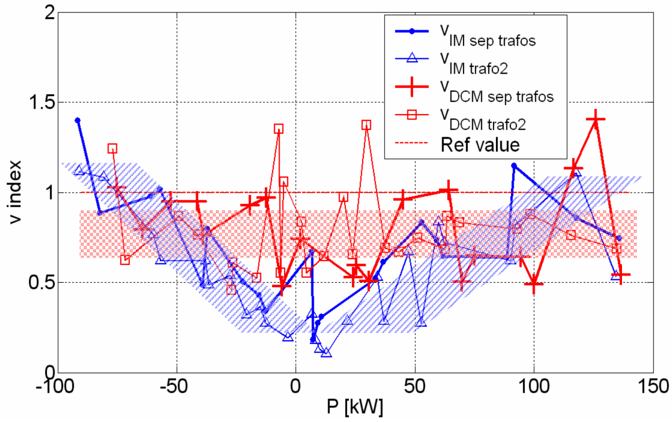


Fig. 10. Third modification of MPM Index υ_2 vs. active power - Active und Reactive currents substracted, Distorted Current remaining

VII. Discussion

A. Experimental Reference Case

The laboratory setup employed in this paper, constructed at the Institute for Electrical Power Engnineering and Power Electronics of the Ruhr University of Bochum - Germany, allows the adjustment of two widely used non-linear loads to several operative points, generating intense currents with powers flowing in different directions with the capability of interchanging up to 200 kW. The most crucial contribution of this experimental reference case is to dispose of a set of signals, whose distorting conditions are known in advance.

B. Critical Impedance Method - CIM

This method [2] represents a very interesting approach to analyze the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ in frequency domain und has contributed important considerations. One of them is an explanation of the reasons why the active harmonic power can lead to wrong conclusions about the location of a distorting source.

From the authors viewpoint, the CIM has a disadvantage. The method relies strongly on the modelling of the feeding system and the loads, which for many cases can be accurately solved and employed, especially for the feeding system, as can be seen in many technical papers and standards. Nevertheless, the modelling of non-linear loads can be carried out in diverse ways, taking into account any assumptions, which -for modelling and simulation purposes- can represent accurately the load behavior and its interaction with the system at certain determined operation states.

However, different modelling alternatives could lead to different results when responsibilities are being evaluated, even when the system and the load remain unchanged, because different load models can have different power and current flow representations, this means that one modelling technique has to be chosen to evaluate the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$, and it ought to be able to solve this task at any possible load and system operative condition. On the other hand, no method can be employed for every case when non-linear load are being modelled; many methods can be employed for specific conditions but no one can be used for any case. Therefore, considering that a $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ method must be as free of wrong evaluation sources as possible, the authors think that a method based on modelling techniques is not the most suitable option to assess responsibilities, for this reason the Critical Impedance Method was initially studied but no longer investigated in the end.

C. Multi Point Method - MPM

The MPM is possibly one of the most important approaches currently available to evaluate the source of disturbances, gathering technical contributions of several researchers, providing it with a good technical background.

The utilization of indexes extracted from measurements is a common practice in engineering, even when the indexes could not have a clear physical meaning. The index υ in the Multi Point Method results from the mixture of three different indexes, derived from quite different treatments of the measured signals, making the analysis of a determined value of the index a very difficult task. Although this index shows technical advantages, it would be desirable to have an index, whose internal analysis and interpretation was easier to explore and explain.

According to the authors, the method itself was not able to recognize the reference disturbing loads, that is why the authors thought about using modified versions of the method to find a better result. The modified versions consist in applying the MPM method to sets of signals without active, reactive or both current components. The modifications led to a better behavior of the method, further investigation is required to define new index reference levels or a different weighing scheme for the composing indexes.

D. Harmonic Pollution Method - HPM

This method presents a valuable alternative to ponder the contributions of several customers or utilities connected in a system to the disturbance condition on a specific one. It requires simultaneous measurements on the analyzed systems and the knowledge of the system impedances as the loads impedances as well. An advantage of the method is that it proposes a decomposition method based on currents measured in the system or their estimations, it does not demand the usage of power quantities, which could raise the uncertainty and accuracy of the method.

Another advantage is that the contributions of customers or utilities to a specific point are calculated from the current frequency components, in this manner the evaluation is made using quantities with a clear physical meaning, which makes its implementation and usage for analyzers easier, in standards or even for academical purposes.

Although the method does not consider a detailed knowledge of the loads impedances, which would demand the selection of a modelling technique, the equivalent customer current sources must be determined in some manner, that requires suppositions about the load behavior, implying some modelling assumption. As mentioned above, this assumptions could detriment the capabiltiy of the method to evaluate responsibilities. The target of the method is not the source determination but the amount of the contribution, therefore the authors consider that, although the Harmonic Pollution Method could require the realization of loads modelling tasks, this could not implicate an intolerable detriment of its efficacy.

E. Application of German Standard DIN 40110

The current decomposition proposed in this paper, based on [9] and [10] and the FBD Power theory recently presented in [12], provides a method to split the current into active, non-active, reactive and distorted components, according to the names used in this paper for these currents. This decomposition is defined in time domain and can be extended to frequency domain, if necessary. As mentioned above, a set of measured signals contain information about the delivered or generated active and reactive power and also about power quality disturbances, such as distortion, asymmetry, etc. The application of this decomposition technique allows the analyzer to concentrate on a specific component of the current, and that is possible under any load operative condition because the decomposition is universally applicable. The components proposed in Section V can lead themselves to a disturbance source determination method, further investigation is being currently explored by the authors.

VIII. CONCLUSIONS

This paper discusses the application of currently available methods to evaluate responsibilities related to power quality. A laboratory setup has been used to carry out a reference test to evaluate responsibilities, providing a set of reference cases to assess the mentioned $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ evaluation methods. Some desirable and undesirable characteristics of the methods have been highlighted and modifications to the methods by means of the concepts of the German standard DIN 40110 have been suggested. Some characteristics of the methods have been discussed from the application of the methods. The usage of power quantities defined in the DIN 40110 technical standards has been discussed and some recommendations for their application are listed too.

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BIOGRAPHIES

Andrés Pavas 1978, received the BSc.(2003) and MSc.(2005) degrees in Electrical Engineering from the National University of Colombia, at present is developing doctoral studies at the same institution. Eng. Pavas has been researcher in the Program of Acquisition and Analysis of Electromagnetic Signals of the National University of Colombia-PAAS-UN Group since 2001, where has proposed and executed research projects related to power quality and lightning protection. Eng. Pavas has been enrolled in teaching activities in the areas of electric machinery and power quality. Eng. Pavas has been awarded with the Scholarship for Outstanding Posgraduate Students of the National University of Colombia and a Sandwich Scholarship of the German Academic Exchange Service (DAAD) to develope his dissertation at Ruhr University of Bochum-Germany. His research interests are power quality, electromagnetic compatibility and probabilistic aspects of power quality.

Volker Staudt 1962, received his Diploma in 1987 and his doctorat in 1993 from the faculty of electrical engineering information technology of the Ruhr-University Bochum, Germany. He finished his habilitation successfully in 2000 at the same faculty in the field of Electrical power engineering and power electronics. Since 1988 he is working as a scientist at the Ruhr-University Bochum. Dr. Staudt is member of the German association of electrical engineers, VDE, and senior member of the IEEE. He is active in several German standardisation committees and associated editor to the IEEE transactions on power electronics. His main fields of research are power definitions, compensation strategies, signal analysis with special regard to power electronics and electrical drives as well as control of inverter fed induction machines.

Horacio Torres-Sánchez 1949, received the BSc. (1976) and MSc. (1982) degrees from National University of Colombia in Electrical Engineering and Power System respectively, Ph.D. studies (Wissentschaflicher Mitarbeiter) at the High Voltage Institute - Technical University of Darmstadt (Germany) (1978-1982), where he investigated Transients Analysis in GIS (SF6). He started his career with Siemens as Director of Transformer design (1975). He joined the National University of Colombia (1978) and is now Titular and Emeritus Professor and Director of the Research Program on Acquisition and Analysis of Signals - PAAS-UN. Professor Torres is a member and responsible of the Task Force C4.4.04 "Lightning in Tropical Regions" of the Study Committee C4 of CIGRE (International Council on Large Electric Systems) and Member of the IEEE. He has co-authored of more than 60 papers and 7 books in the area of Lightning and Power Quality related topics.