UNIVERSIDAD NACIONAL DE COLOMBIA

Study of Responsibilities Assignment Methods in Power Quality

by

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Universidad Nacional de Colombia
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Bogotá - Colombia, December the 29th of 2012

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Submitted for the degree of
Doctor of Philosophy in Engineering - Electrical Engineering
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Advised by
Prof. Horacio Torres-Sánchez
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To my friends.

To Francisco, Teresa and Luz María, I owe them what I am.

To the only woman, with whom I see the sunrise and the sunset, my beloved wife Angela.

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Abstract

The present document is a research report on the study of responsibilities assignment in power quality, theme proposed to be carried out as thesis for the degree of Doctor of Philosophy in Electrical Engineering at the National University of Colombia - Bogotá, the doctoral studies have been advised by the Professor Horacio Torres-Sánchez, who works at the National University of Colombia.

A doctoral research project was proposed to guide the development of the doctorate. Besides a justification and a theoretical background about the analysis of responsibilities in power quality, the following preliminary objectives were proposed:

- To develop a methodology aimed to establish the responsibilities of different agents involved in a distribution network regarding power quality disturbances.
- Reviewing and studying of analysis tools useful to determine responsibilities of agents connected to a distribution system. Frequency domain, time domain and non-sinusoidal conditions aimed power theories are some of the analytic tools to be considered.
- Study, review and application of deterministic and random modeling and simulation techniques, in order to represent electric systems and power quality disturbances. Deterministic tools have been widely studied and additional efforts will be required just for specific cases. Random tools require the study of random variables, stochastic processes and Monte Carlo simulation techniques.
- Application of the methodology to real cases.

This document reports the doctoral research, which was carried out in the National University of Colombia and the Ruhr University of Bochum - Germany. Along this document the main results achieved in the doctoral studies will be listed as well as the accomplishments of the preliminary proposed objectives.

In order to introduce the reader to the theme investigated along the doctoral studies, a presentation of the Analysis of responsibilities is made in Chapter 1. In this chapter the conceptual realization of the analysis of responsibilities is described, such realization has

been called the Responsibilities Assignment Problem $\mathcal{R_AP}$, once it is presented in terms of a problem to be solved, some details are necessary to orientate the finding of a suitable solution. The mentioned problem leads to new matters of discussion like:

- How should the responsibilities be assessed?
- How ought to be assigned the responsibilities?
- For the currently available methods to assess and assign responsibilities, in what manner must be carried out an evaluation to determine their usefulness and suitability?

The precedent issues require a direction to facilitate and orientate the evaluation of the reviewed methods and to develop new ones, experimental cases and reference conditions will be proposed as basement for this purpose.

Power Quality disturbances can be understood as any deviation from the conditions a customer or a utility needs to satisfy determined energy necessities, such disturbances have been listed and analyzed in technical standards. The analysis of deviations in the quality of the electric power demands the analysis of the electric power itself, an analysis leading to identify and quantify the disturbances in terms of power quantities and electric signals like voltages and currents. In the Chapter 2. A Review of power definitions will be done to provide a frame of reference to decompose power in parts related to the disturbances under consideration in the present thesis.

As it was mentioned, reference conditions and experimental setups must be established to allow a comparative and critical revision of any $\mathcal{R_AP}$ assessing method. Measurements and simulations have been carried out, a description of the setups, the measurements themselves and their usefulness is going to be presented. Simulations have been carried out as well, they shall be described in a similar way in Chapter 3.

Once the conceptual foundation has been set already and the technical aspects and experimental cases have been presented too, a review of currently available methods is possible. Several methods shall be investigated, the Critical Impedance Method, the Multi-Point Method and the Harmonic Pollution Method among others, a critical assessment from the technical and conceptual perspective will be carried out, the assessment will yield desirable and undesirable characteristics of each method, which may be used to improve the methods or to develop new ones. This review can be found in Chapter 4.

The doctoral research led to the development of a new method to assess responsibilities, the so called Method of Disturbances Interaction $\mathcal{M_DI}$, this method will be presented in Chapter 4 as well. Preliminary research results conducted to an improvement proposal for the Multi-Point Method, such improvement will be shown as well.

Power quality disturbances evolve and change in time, their behavior cannot always be forecasted easily, the statistical analysis of disturbances is needed. A Statistical analysis procedure of the indicators to assess responsibilities in power quality is presented. The proposed method and the statistical analysis offer the possibility of an integration of responsibilities assessment in the currently available standards, this part will be found in Chapter 5.

Finally, the conclusions extracted from the thesis are presented along with a summary of the reviewed bibliography.

Keywords: Power Quality, Responsibilities, stationary disturbances, electric signals processing, electric power theories.

Resumen

El presente documento es un reporte de investigacion sobre el estudio de responsabilidades en calidad de potencia eléctrica. Este tema se propuso para ser desarrollado como tesis para adquirir el titulo de Doctor en Filosofia en Ingeniería - Ingeniería Eléctrica en la Universidad Nacional de Colombia - Bogotá. Los estudios doctorales fueron asesorados por el Profesor Horacio Torres-Sánchez, quien trabaja como profesor en la Universidad Nacional de Colombia.

Se propuso un proyecto de investigacion doctoral para dirigir el desarrollo de los estudios doctorales. Además de la debida justificación y presentación de los antecedentes teóricos necesarios, los siguientes objetivos preliminares fueron propuestos:

- Desarrollar una metodología orientada a determinar responsabilidades de diferentes agentes presentes en una red de distribución e involucrados en una condición de perturbacion estacionaria de calidad de potencia.

- Revisar y estudiar las herramientas de análisis disponibles para determinar responsabilidades de agentes conectados a un sistema de distribución. Teorías de potencia electrica definidas en dominio del tiempo, la frecuencia y para condiciones no-sinusoidales son algunas de las herramientas analíticas a ser consideradas.

- Estudiar y revisar técnicas de simulación y modelado, tanto determinísticas como aleatorias, para representar sistemas eléctricos y perturbaciones de calidad de potencia. Los métodos determinísticos han sido ampliamente estudiados, de manera que se requirirán esfuerzos adicionales sólamente para casos particulares. Las herramientas de simulación estocástica requieren el estudio de variables aleatorias, procesos estocásticos y simulación de Monte Carlo.

- Aplicación de las metodologías a casos reales.

El presente documento presenta la investigación doctoral que fue desarrollada en la Universidad Nacional de Colombia y la Universidad del Ruhr de Bochum - Alemania. A lo largo del documento se enlistan los principales resultados logrados en el doctorado, así como tambien el cumplimiento de los objetivos propuestos.

Para introducir al lector en el tema de investigación, se hace una presentación del Análisis de Responsabilidades en el Capítulo 1. En este capítulo se describe la conceptualización del análisis de responsabilides, la cual ha sido llamada Problema de Asignación de Responsabilidades $\mathcal{R}_{\mathcal{A}}\mathcal{P}$, posteriormente se enlistan algunos requerimientos necesarios para encontrar una solución apropiada. El problema mencionado conduce a nuevos aspectos de discusión como:

- ¿Cómo se deberían evaluar las responsabilidades?
- ¿Cómo deben asignarse las responsabilidades?
- Para poder determinar la validez de los métodos existentes actualemente para evaluar responsabilidades, ¿de qué manera deben evaluarse?

Los aspectos anteriores requieren un direccionamiento para facilitar y orientar la evaluación de los métodos revisados y los propuestos, montajes experimentales y condiciones de referencia serán propuestos con este propósito.

Las perturbaciones de calidad de potencia pueden entenderse como cualquier desviación de las condiciones que un cliente requiere para satisfacer sus necesidades específicas. El análisis de las desviaciones en la calidad de la potencia eléctrica exige el análisis de la potencia en sí, que servirá para identificar y cuantificar las perturbaciones en términos de cantidades de potencia y señales eléectricas. En el Capítulo 2 se presenta una revisión de las definiciones de potencia, las cuales otorgan un marco de referencia para descomponer la potencia en porciones relacionadas con las perturbaciones estudiadas en esta tesis.

Como se mencionó anteriormente, deben establecerse condiciones de referencia y montajes experimentales para permitir una revisión comparativa y crítica de cualquier método disponible para resolver el $\mathcal{R}_{\mathcal{A}}\mathcal{P}$. En la investigación conducida se desarrollaron mediciones que se describirán en el Capítulo 3.

Una vez que los fundamentos conceptuales hayan sido establecidos, asi como los experimentos hayan sido presentados, los métodos de evaluación de responsabilidades pueden ser evaluados. Varios métodos serán investigados: el método de la Impedancia Crítica, el método de Mediciones Multi-Punto y el método de Polución Armónica. Una evaluación de carácter crítico, desde las perspectivas técnica y conceptual, será realizada para cada método. Dicha evaluación proveerá características deseables e indeseables de cada método, las cuales servirán para su mejormiento o para la elaboración de un método novedoso. La evaluación de los métodos se presentará en el Capítulo 4.

La investigación doctoral condujo al desarrollo de un nuevo método para evaluar responsabilidades, el cual fue denominado Método de Interacción de Perturbaciones $\mathcal{M}_{\mathcal{D}}\mathcal{I}$, en el Capítulo 4 será descrito. Algunos resultados preliminares relacionados con el mejoramiento del método Multi-Punto se presentarán tambien.

Las perturbaciones de calidad de potencia evolucionan y cambian con el tiempo, de tal manera que su comportamiento no puede ser predicho con facilidad. De acuerdo con lo anterior, es necesario el análisis estadístico de las responsabilidades. En el capítulo 5 se presenta el análisis estadístico de los indicadores propuestos para evaluar responsabilidades.

Finalmente se presentan las conclusiones principales de la investigación desarrollada y un resumen general de la bibliografía consultada.

Palabras clave: Calidad de Potencia, responsabilidades, perturbaciones estacionarias, procesamiento de señales eléctricas, teorías de potencia eléctrica.

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CHAPTER 1

Analysis of Responsibilities in Power Quality

> *Fights between individuals, as well as governments and nations, invariably result from misunderstandings in the broadest interpretation of this term. Misunderstandings are always caused by the inability of appreciating one another's point of view.*
>
> *Nicola Tesla - 1905*

Nowadays Power Quality represents one of the most important issues in Electrical Engineering. The determination of disturbances origin and the knowledge of how these disturbances flow across the electric systems is a very difficult task, for which many researchers have proposed alternatives to find an applicable, reliable and precise solution. There are many details concerning Responsibilities Assignment, either methodological as technical aspects, some of them are treated in this chapter with the aim of presenting a basic background leading to a technical discussion about this theme.

Power quality disturbances may be classified as proposed in [iee95], for the sake of simplicity a shorter classification can be performed splitting the disturbances into two groups according to its occurrence:

Sudden or transient disturbances

All disturbance whose beginning and ending cannot be determined in advance. Such disturbances usually superimpose on the stationary signals, they can last shorter and longer in comparison to the period of the power signal. Examples of sudden disturbances are surges caused by lightning or maneuver, service interruptions, dips and swells, events compromising the system's stability, etc.

Stationary disturbances

These are disturbances present almost all the time and are closely related to the operation of the system and its loads. Stationary disturbances change in time as the loads and the system vary their operative conditions. Some examples of stationary disturbances are voltage drops, phase displacement caused by reactive loads, unbalance, harmonic waveform distortion. Interharmonic and subharmonic disturbances can be considered as quasi-stationary conditions, but their treatment may differ from the techniques to study stationary conditions.

Stationary Power Quality disturbances are able to produce different kinds of effects on systems and equipment [Bol00][CCV09]. Some effects on lifetime reduction and the efficiency reduction can be listed. This thesis concentrates on **Stationary disturbances** specifically because the location of steady disturbances has not been solved yet. Sudden or stationary disturbances location has not been solved either, however its treatment will not be taken into account in this thesis.

The currently available methods for assessing responsibilities in power quality can be listed according to the principle they are based on. There are mainly three principles for determining the origin of disturbances, they are listed in the following paragraphs:

Impedance characteristics.

Load and system impedances determine how energy flows at any possible operative condition. Under desirable operation conditions, specific impedance values can be identified from system's characteristics. These impedance value has been called critical impedance. If any deviation from the critical impedance appears in the system, a judgment about the disturbance behavior and origin can be carried out. Contributions following this idea have been presented in [XL00][CLK$^+$04][LXT04].

Power flow.

Disturbances are related to the electric power consumption and flow, electric power can be decomposed into components, each one containing information about different phenomena. Power quantities have in many cases a magnitude and a direction, just like active and reactive power do. Thus, a power quantity may provide information on magnitude and direction of a disturbance, as long as the disturbance can be accurately describe by a power quantity. Examples of this approach may be found in[TA95][SvWC94][CF94][Mus98], other methods based on the previous ideas have been proposed in [DC03][CFST04].

Comparison to reference or ideal conditions.

Feeders and loads can behave in such a way, that a minimal or barely existing level of disturbance is present in the system. From these point of view, a reference level for power quality disturbance can be defined. Technical standards regarding power quality limits propose limits for disturbances, one of the most known examples is the IEEE Standard 519 [iee93]. Any deviation from these ideal or reference behavior would imply the increase of disturbances. The comparison of the electric signals (or indicators extracted from the signals) to the references provide information about the accomplishment of the limit conditions, the origin and propagation of disturbances as well. Typical power quality analysis comprises the analysis of standard limits accomplishment, additional analysis can be performed to carfully investigate the origin of disturbances. Some examples can be found in [SJ98][PST09]. In [PST10] a proposal for reference is presented, this proposal will be described in detail in a subsequent chapter.

An additional classification of the method for assessing responsibilities can be presented, regarding the number of performed measurements:

Single point or single section measurements.

Analysis of disturbances origin and propagation is carried out at a single point of common coupling in order to decide if the disturbances have been originated at the customer's installation or anywhere else in the utility. Examples of the application and evaluation of single point responsibilities assessments are listed in [DEP00a][XL00][CLK+04], the methods presented in [DC03] and [DEP00b] can be applied to a single point studies too.

Multiple points or sections measurements.

Disturbances are observed in systems composed by several loads, feeders and other elements. The origin and propagation of disturbances is assessed among all of them to determine one or several disturbing sources. Several alternatives have been published using these kind of analysis [Ema95][DEP00b][CFST04], recently a new proposal has been developed in [PST10] and will be presented in posterior chapters.

There is a global agreement regarding the evaluation of power quality based on measurements, i.e., power quality requires to measure and record electric signals in order to determine the accomplishment of standards or the verification of any particular condition. The analysis of responsibilities has the same characteristics, then measurements must be acquired to identify and to assign the origin of disturbances. Simulation and modeling can support the analysis of responsibilities, however responsibilities assignment may lead to legal implications, thus any judgment must be based on facts and actual observed conditions.

Given the dynamic conditions of the system and the presence of non-linear devices, it is always desirable to evaluate the origin and propagation of disturbances by means of multiple point measurements, which must be carried out in a suitable manner to capture voltages, currents, powers and any information aimed to recognize the disturbances. Several standards describe the methods for measuring, recording and processing electric signals for power quality purposes [iee95][iee93][IEC02][IEC08][CEN00].

This chapter introduces the conceptual definition of the responsibilities assignments in power quality, definitions and reference conditions to assess the origin of disturbances are presented too. The chapter is divided in three parts. The first one contains the presentation and description of the Responsibilities Assignment Problem, a conceptual realization proposed in this thesis.

It was found along the development of the thesis that customers and utilities need to be treated in a similar manner in order to set a method conducting to a fair treatment of every part. This treatment cannot neglect the particular characteristic of all involved parts, but a particular treatment helps to keep the analysis of responsibilities away of any prejudice. The definition of agent in the context of responsibilities analysis is presented in this chapter too.

The last section of the chapter is closely related to the first one, where the necessity of defining reference conditions to asses responsibilities will be mentioned. The third section of the current chapter presents the reference conditions, upon them a new method will be proposed in a subsequent chapter.

1.1 Responsibilities Assignment Problem

The Responsibilities Assignment Problem - $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ in Power Quality is a conceptual abstraction proposed in this thesis to define the set of tasks to be solved for determining the agents involved in the detriment of the power quality stationary conditions and how these agents contribute to such undesirable situation. The $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ can be explained by resorting to its general characteristics, summarized in the following subsections.

1.1.1 Location of Disturbances' Origin

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. Although this task may seem pretty clear and doubtless, the term ”origin” needs context with regard to the assessment of disturbances. Let us suppose that a simple electric system depicted on Figure 1.1 is operating.

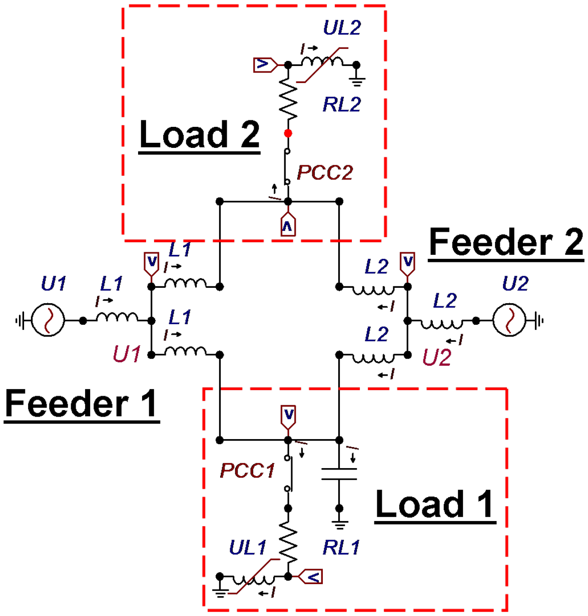
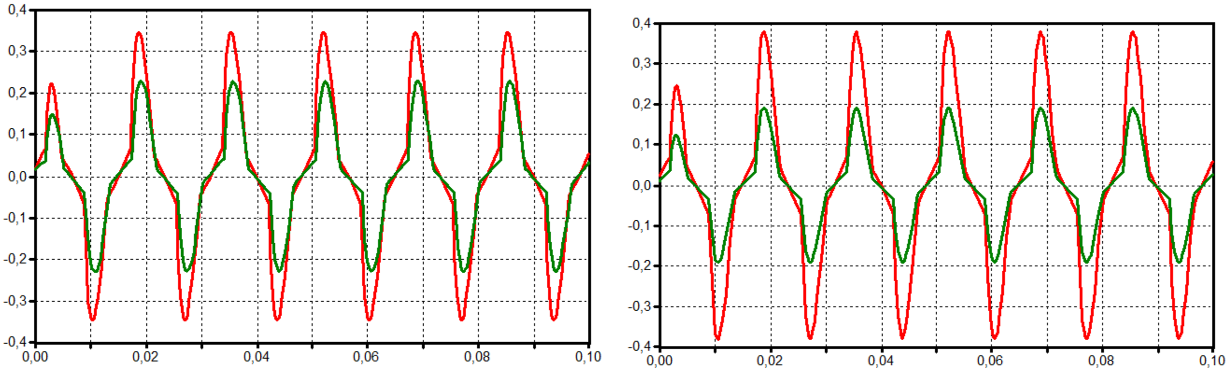


Figure 1.1: Responsibilities assessment example

Flux [Wb-turn]	0	0.1325	0.2650	0.5653
i_{L1} [mA]	0	13.0	26.0	546
i_{L2} [mA]	0	26.0	52.0	1092.0

Table 1.1: Current-flux characteristics for saturable coils 1 and 2

The system is composed by two feeders and two non-linear loads. The feeders' short circuit impedances are purely inductive, Feeder 1 short circuit impedance (10mH) is a half of that of Feeder 2 (20mH), their voltage sources are 120 V and 127 V at 60 Hz, respectively. Loads are mainly non-linear saturable coils, Load 1 and 2 have the same non-linear Flux-Exciting current characteristic but Load 2 currents are twice the currents of Load 1, values can be found in Table 1.1. Series resistances are 484Ω and 384Ω for Load 1 and Load 2, respectively. The customer belonging Load 1 decides to install a 3.2μF capacitor bank with the aim of improving the power factor and voltage drop, conditions affected by the presence of the non-linear coils. Current waveforms before the capacitor connection are shown on Figure 1.2, they are are distorted but accomplish limits for harmonic distortion.



(a) Loads currents

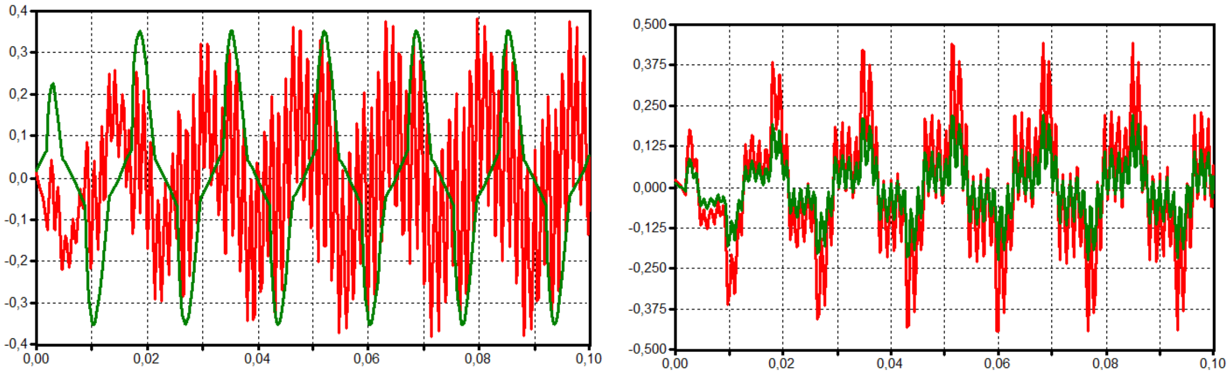
(b) Feeders currents

FIGURE 1.2: Current waveforms for normal condition. Left: Load currents (green small one Load 1, red big one Load 2). Right: Feeders currents (red big one Feeder 1, green small one Feeder 2)

Regarding this condition it is possible to observe that:

- Distorted waveforms are not desired in an electric system, given that they generate non-active powers and can cause resonances associated to their non-linear behavior.
- The Load's non-linear behavior is unavoidable, current waveform distortion belongs to its nature. On the other hand, the customer has the right of using the suitable electric devices to carry out his economic activity, such element must accomplish power quality requirements, but acceptable conditions for risky devices depend not only on the devices themselves but also on the feeding network.
- Distorted waveforms can be tolerated as long as they do not exceed distortion limits. However, undesirable distorted components are present and their identification may be required to prevent or forecast the occurrence of intolerable conditions.
- This simple test case shows the flow of non-linear currents across the system, as depicted on Figure 1.2, where the feeder currents are distorted as well.
- If the currents were not tolerable, it may be said that both customers are responsible for distorting the currents. However, in that case the short circuit impedance could not be low enough, so that any non-linear load is able to reach current distortion over the limits. Thus, the Utilities are responsible for not providing a suitable network, and the responsibility for disturbing the system should be distributed among customers and utilities.

Once the capacitor is switched on in parallel to the Load 1, current waveforms of both feeders and Load 1 get highly distorted, current of Load 2 does not present an appreciable change, current waveforms are displayed on Figure 1.3.



(a) Loads currents

(b) Feeders currents

FIGURE 1.3: Current waveforms with the capacitor switched on. Left: Load currents (green undistorted one Load 2, red distorted one Load 1). Right: Feeders currents (red big one Feeder 1, green small one Feeder 2)

Some observations regarding this new condition are the following:

- By connecting the capacitor nearby the Load 1, a resonance takes place. The current absorbed at the Point of Common Coupling 1 and the currents of both feeders become highly distorted, such situation may be seen on Figure 1.3. It is noteworthy that the current of Load 2 remains undistorted.

- Given that the customer of Load 1 incorporated the capacitor, which caused the resonance, it might be said that Customer 1 should assume the responsibility for disturbing the current provoking an undesirable and risky power quality condition.

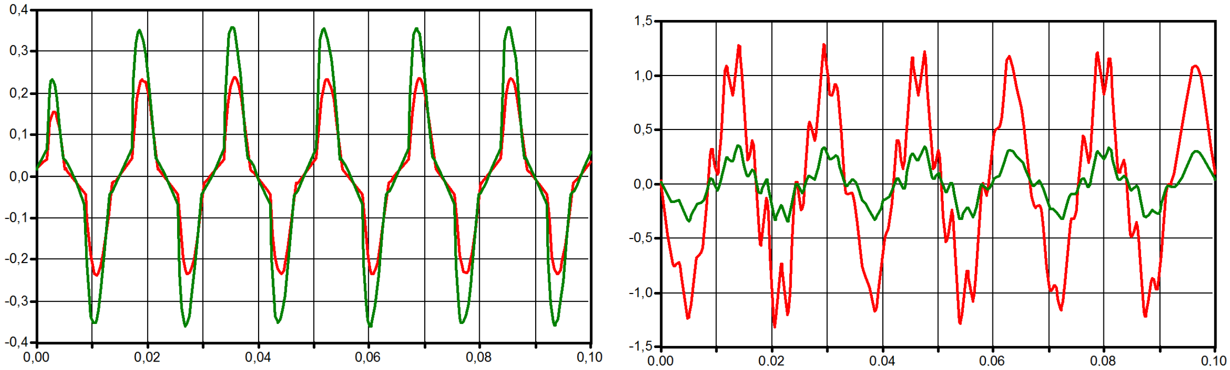
- The cause of the resonance is the concurrence of three elements simultaneously: a compensating capacitor without a filter inductance, a non-linear load and a network impedance. The network impedance is synthonized at the frequency components of the non-linear load when a capacitor is connected.

- The origin of the resonance can be easily identified, given that the amplified resonant currents flow from both feeders towards the point of common coupling of Load 1, where two of the causing elements concur.

- Once again, the utility's role should be considered. Would it be possible for the utilities to avoid the occurrence of resonances caused by the concurrence of non-linear devices and compensating capacitors by means of suitable short circuit impedances or by means of rules for the installation of any compensating device?

- Both feeder currents become distorted, if the responsibility is assigned to the Customer 1, how should the Utilities be compensated? How should the compensation be distributed between the Utilities?

Let us contemplate another possibility. If the utility decides to compensate power factor and voltage drop employing a capacitor in the feeding system, for example at the point marked as $U1$ on Figure 1.1, the current of the feeders and the loads behave as depicted on Figure 1.4.



(a) Loads currents

(b) Feeders currents

FIGURE 1.4: Current waveforms with the capacitor switched on. Left: Load currents (green big one Load 2, red small one Load 1). Right: Feeders currents (red big one Feeder 1, green small one Feeder 2)

The following observations can be listed:

- The Customers currents do not present any waveform deviation beyond their normal non-linear acceptable behavior.
- Feeders' currents present resonance, quite more intense in comparison to the previous cases.
- There exist only non-linear loads able to activate a resonance at the customers side, therefore the utilities may suspect that the activating cause of the resonance is located anywhere downwards. Nevertheless, measurements shall not reflect any current similar to those present at the feeders. Moreover, the customers currents remain unchanged after the resonance's activation.
- Although there are reasons to think the resonance is caused by any non-linear element downwards, would it be fair to judge the customers when the responsibilities assignment cannot be performed using measurements?
- Having in mind that the utility decided to install the compensating capacitor, and taking into consideration that the customers responsibility cannot be established by means of measurements, would it be fair to assign completely the responsibility to the customers?
- The Utility has not switched on the capacitor to disturb the power quality, not purposely, but before the connection the power quality was acceptable. Even though the resonance was activated by the non-linear frequency components, the connection of the capacitor was tha main cause of the resonance, then a new question arises: The Utility is in fact responsible of disturbing the power quality, should this responsibility be assigned to the Utility only?

The preceding reflections are aimed to highlight some facts with regard to the location and the cause of a disturbance source. In some cases the disturbance source may be identified from measurements easily, however the measurements themselves do not contain all information about all involved parts. Regrettably, as stated in the condition depicted by Figure 1.4, there exist also cases in which the disturbance cause cannot be identified by any chance from direct measurements. Thus, additional analytical procedures are required to search for any apparently hidden information inside the currents and voltages, which may lead to a more precise establishment of responsibilities given an identified non-desirable power quality state.

It is noteworthy to highlight that the determination of the cause of power quality disturbances has many contrasts regarding aspects like:

- What *conjunction* or *combination* of elements provoke an intolerable power quality condition.
- What sequence of events led to undesired PQ conditions.
- Have the conditions and element met purposely or accidentally?
- Could any involved part avoid the occurrence of the undesired disturbance?
- Is it possible for any case to avoid undesired disturbances?

The previous examples revealed that the conjunction of various triggering elements is the actual cause of the undesired disturbance. Thus, assigning responsibilities to only one part would be unfair. The location of a disturbance might not be unique, it may imply several elements and conditions, then the primary cause and origin of undesired power quality conditions should be shared in many cases.

1.1.2 All parts involvement

Electric energy flows through electric systems almost without any restriction. Transformers, distribution lines, capacitors and other elements act sometimes as electric borders and sometimes attract the disturbances around them. It is very important to take into account that all existing elements in a network interact with each other. Such interaction can benefit, damage or be negligible, the only truth is that the interaction among all elements will be always present.

The next example is similar to the case presented in the previous title. Now the network is composed by a medium voltage feeder and two customers connected at low voltage by means of transformers, as depicted in Figure 1.5. Once again, the conditions for an undesirable situation to happen are set. A non-specific non-linear load is supposed at one of the customers. The second customer has a linear load, which needs reactive power compensation. The utility can install a compensation capacitor bank in the medium voltage network as well.

The first condition to analyze is when the utility supplies reactive power by means of a capacitor bank connected at the **POS1** location, shown in the left side of Figure 1.5. It is possible to foresee that:

- A resonance may occur between the feeder's short circuit impedance and the capacitor bank, excited by the non-linear load through the transformer. Similar to the previous example, the excitation provoked by the non-linear load can possibly not be identified by measurements, or the signals can become less distorted in comparison to the resonant circuit.

- In this case, measurements cannot lead to the identification of the disturbance's sources nor the assignment of responsibilities either. It is possible to consider the assignment of the responsibility completely to the utility, because a suitable analysis should have been performed in advance to avoid any possible risk of resonance.

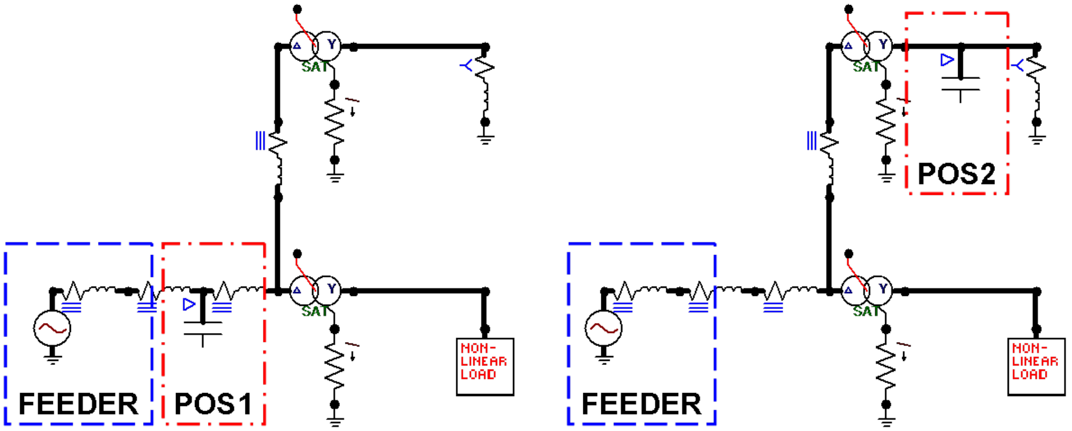


FIGURE 1.5: Responsibilities assessment example

The second condition consist of another location of the capacitor compensator, at the point **POS2** sketched at the right side of Figure 1.5. The following annotations are listed:

- With the capacitor bank at point **POS2**, the resonance will be excited by the non-linear load again, but the current amplification will take place between the linear loaded customer and the feeding network.

- Unfortunately, the exciting signal may be weaker compared to the resonant signals, then the responsibilities would be almost surely assigned to the linear load customer. This assignment would be clearly unfair.

- The activation of the resonance is in this example caused by the non-linear load. However, the utility is partially responsible because the network should be strong enough to reject resonances, or it should be capable of absorbing them. Additionally, the utility must establish rules and standards to avoid risky situations, in particular when a third part can endanger the existing equipment.

This case remarks the fact that not only additional analytic resources are required to analyze a responsibilities problem, all elements conforming the network ought to be involved in the responsibilities determination, i.e., all customers, utilities, compensating facilities, the network itself should be taken into account to find out the sources of power quality disturbances. The example shows that future new loads, compensation devices, changes in topology, etc., must be considered in advance for assessing responsibilites.

1.1.3 Non-prior determination of location

The preceding examples revealed situations where an *a priori* judgment may prejudice a non-responsible customer or utility. From the utility's viewpoint, the customers are the most frequent cause of power quality detriment, specially those customers with recurrent complains for failures in the service. From the customer's perspective, the utility has to provide energy with the highest quality standards, regardless what kind of loads the customer belongs and it does not matter what neighbors are connected nearby either.

Both perspectives need to be conciliated, it does not mean that no one is right, it does not mean that everyone is wrong either. Both positions are partially correct, but it is very important to recognize that a judgment cannot be made in advance without the proper investigation, such investigation requires the examination of all involved parts in detail.

The location of a disturbance source cannot be carried out without the analysis of measurements performed at all the elements connected to a network. Currently, most of the systems comprise several customers, compensating facilities and network configuration devices, which are capable to influence the electric energy flow and the power quality correspondingly. All elements must be considered and measured.

1.1.4 Time variation of disturbances

Currently it is not necessary anymore to describe in detail how the disturbances vary along time. Several efforts have been made to propose a suitable manner to deal with the dynamics of power quality such as [BBC+98][OXB03][Xu05]. Nowadays, all power quality international standards recognise the time variation of disturbances, this is the main reason to evaluate power quality along the time during days, weeks or even longer.

Disturbances depend on the network's electric characteristics, on the loads' size and behavior. Disturbances change according to modifications in frequency response of the systems due to topology changes, inception of compensating facilities, new power sources, load rejection, etc., contributions like [BBC+02][TCL02] have discussed and proposed methodologies to deal with these conditions. Moreover, all the previous listed conditions may happen simultaneously in a time scale of minutes, hours, even days, and the precise moment at which they will take place cannot be established in advance. In most cases, statistical analysis are performed to investigate the time varying nature of power quality disturbances [iee93][CEN00].

As it was described, disturbances change in time, therefore responsibilities change in time correspondingly. Analytic procedures can be applied to series of measurements, such procedures must be reliable and applicable to any condition, even more they need to be efficient as well. The amount of information to be handled seems to grow considerably as the number of involved elements becomes greater, then it is necessary to develop efficient methods to assess responsibilities. Without efficient method to assess location, the origin of disturbances will be nothing else than a theoretical and academic matter.

1.1.5 Distribution of responsibilities

The above mentioned examples highlight several reflections regarding the determination of responsibilities. Reviewing the Figures 1.3 and 1.4 another question arises. Let us suppose that the location of the disturbance has been already determined, thus a responsibility has been assigned to someone, in the example to the nonlinear loads.

Once the cause of the disturbance has been located, a legal and technical process comes up. The affected parts demand a compensation for the damages produced by the unsuitable power quality. Then, how can be determined how much should pay the Customer 1 and the Customer 2. Moreover, how much should receive the Utility 1 and the Utility 2?

Previously it has been clarified that all involved elements can influence the disturbance propagation, some parts excite and exacerbate the undesirable situation, some parts tend to receive damage and sometimes help to damp the disturbances. As supposed above, once the location of disturbances has been already established, the concerning parts may be classified into two groups.

CAUSING AGENTS Parts contributing to increase the undesirable power quality condition. These parts take part actively in the disturbance amplification or may be the main disturbance cause.

RECEIVING AGENTS Parts experiencing disturbances produced by the causing agents, these parts may interact passively with the disturbance, contributing to damp and limit the disturbance propagation.

The term **agent** is used for the first time here and will be explained in the following paragraphs. When the parts involved in the problem have been classified, a method to quantify the amount of disturbance of each group must be used, in [DEP00b][PST10] some methods to quantify and distribute responsibilities can be found.

1.1.6 Definition of the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$

According to the preceding characteristics, the Responsibilities Assignment Problem - $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ in Power Quality can be defined as the qualitative and quantitative determination of the contributions to specific detrimental or improving Power Quality conditions caused by each part belonging to an electric system. The assignment of responsibilities requires the investigation of all parts connected to a network by means of measurements. This definition has been presented for the first time in [PST08].

It has been highlighted that the traditional power quality evaluation procedures may not suffice the needs of the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$. Additional analytic procedures must be developed and employed to determine the disturbances origin and interaction, the quantification of each part's contribution needs the development of a new procedure as well. As the investigation of responsibilities requirer the definition of an agent in order to treat fairly all involved parts, the next section is dedicated to describe and define an agent in this context.

1.2 Agents in Responsibilities Assignment

Currently the electric energy is handled as a product, which must be treated using different kinds of contracts. The contractual terms are defined according to the customer's necessities and the possibilities of the delivering utilities. Of course, the violation of any term by any of the involved parts may have implications. The price of the delivered product is in most cases related to the primary resource, transmission system and distribution network usage, electric system constrains, management, revenue, customer service, among other commercial related issues.

Any detriment on the quality of voltages or currents has technical implications financial ones too. The technical implications depend on the strength of the disturbances and on immunity of the equipment to those disturbances, implications from shutting down, recoverable failure or resetting programs to partial or total damage may happen. Technical implications represent costs due to equipment damage or lost, but the costs related to process failures are in most cases more significant [Bol00].

The financial impact of a poor quality of power is reflected by the increase of production costs, the loss of materials, the fail of committed production with the corresponding detriment on the producer's image and trust. These effects have a substantially higher cost for the user than the not delivered energy nor the energy not used during the failure caused by a poor power quality. The quality of the electric power is not commonly considered as a defining characteristic of the energy price. Nevertheless, when power quality problems arise, their implications usually cost much more than the delivered energy.

As long as the analysed disturbances may implicate a detriment on equipment of customers or utilities, the definition of responsibilities has technical and contractual implications. Therefore, when methods to assess responsibilities are under study or development, a fair treatment of all entities involved in the assessment is required. Depending on the viewpoint, someone might be responsible for deteriorating the power quality. For example, let us inspect two particular viewpoints:

- **Utility** The system provides a perfectly sinusoidal, symmetrical electric energy service. The service attains a high availability, given that the utility operates the system under optimal conditions. In the moment the users take the energy, the system deviates from the optimal delivered characteristics and becomes distorted.
- **Customer** Customer's installation is designed and constructed in such a manner that the energy is taken from the electric grid causing the minimal negative impact on voltage and current. Nevertheless, disturbances come from the system and harm its production and equipment.

Both perspectives are neither wrong nor right. The utility is unable to provide such perfect system quality conditions, the system has naturally asymmetry and distortion, the interruptions cannot be avoided completely either. On the contrary, the customers may disturb the system not purposely, but their devices are in many cases capable of harming the electric energy quality in different manners and in different amounts.

Let us think about a particular case. A particular condition appears in a system, a customer and its energy delivering utility are affected by a disturbance generated by a third part, the disturbance is harmful for the customer and for the utility as well. Either the utility or the customer are not able to recognise where the problem comes from, nor who is that third part causing the disturbance. Once the problem appears, customer and utility will complain and try to demonstrate that the other one is responsible. According to the two "predetermined" perspectives listed above, each one is responsible from the other's point of view. It is obvious that anyone before a conflict tries to release any responsibility resorting to technical or contractual arguments, the first resource that each part has is to think that *the other is responsible, not me.*

Once again, this perspective is obvious and natural. The intrinsic problem of having in mind this kind of thought is that it might be reproduced widely, even when no one of the involved parts has actually the responsibility for causing the problem. For avoiding this *technical prejudice*, it is proposed to employ the term **AGENT** instead of **CUSTOMER** or **UTILITY** when dealing with responsibilities assignment.

In the context of responsibilities assignment in power quality, an **agent** may be defined as a customer or utility connected to an electric system, having the following characteristics:

- Every agent has the capability of absorbing, delivering or generating electric energy. The possibility of generating electric energy at the distribution level is a widespread option nowadays, specially due to the usage of smart grids and alternative energy resources.
- Each agent has a Point of Common Coupling to the system, where the exchange of energy and the power quality conditions must be assessed.
- An agent is a subject of duties and rights in contractual and legal terms.
- An agent is a subject able to use the electric energy.
- An agent is able to improve, detriment or hold the power quality conditions.
- An agent is capable, at least from the technical viewpoint, to modify some of its operating conditions with the aim of changing the power quality conditions of the electric grid.

The definition of agent in the context of the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ is aimed mainly to found in the reader's mind an impartial way of thinking about any part involved in the analysis of disturbances origin. An advantage of stating an **agent** is that a set of expected or desirable operating conditions can be defined as well. As it has been presented in the preceding section, a manner to assess responsibilities is comparing any agent's electric signals to a set of reference conditions, any deviation from the acceptable behavior can be identified, measured and assessed. If the deviation is over the tolerable disturbance limits, then a measure needs to be taken. In the following section presents a set of reference conditions to assess responsibilities is presented.

1.3 Reference Conditions to assess responsibilities

In preceding paragraphs three widely used criteria to assess responsibilities were presented:

- Impedance characteristics
- Power flow
- Comparison to reference or ideal conditions

Each criterion appeals to physical and technical principia in order to identify how disturbances flow. Then, any deviation from the expected behavior or from the presence of desired signals in the system would mean that disturbances are present. The criteria may provide information about origin and magnitude of disturbances as well, in some cases additional criteria ought to be considered to acquire information about location and size of power quality deviations.

In the previous sections the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ was presented, the involvement of all agents in the disturbance condition was explained. Special emphasis was put on the fact that all agents need to be taken into account. Hence, single point measurements may provide information on the power quality condition of a particular agent, however they hardly shall provide sufficient data to assess and assign responsibilities. The currently available methods to assess responsibilities using a single point measurement, like those presented in [XL00][CLK$^+$04], can likely commit mistakes because no enough information is registered as explained in [DEP00a]. Thus, measurements on multiple points are always recommended to assess responsibilities to avoid loss of relevant information and to account for all agents fairly, several methods have presented alternatives to deal with these kind of measuring campaigns [DEP00b][DC03][PST10].

In this thesis a set of reference conditions is proposed to identify an undesired power quality behavior. These reference conditions lead to a current decomposition, whose parts contain information on each stationary disturbance considered in the thesis, i.e., phase displacement, asymmetry and waveform distortion.

In order to introduce the reader in the need for definition of reference conditions, an example is presented in the following subsection.

1.3.1 An example of responsibilities assignment

In the decade of 1920 several contributions to the understanding of electric power were published. Charles Fortescue, the author of the symmetrical components theory, proposed a method to measure power in polyphase circuits [For23], in the discussion to this paper an illustrative example with regard to responsibilities written by Vladimir Karapetoff was presented. Let us suppose water is pumped from from an intake E using three pumps a, b and c through three lines A, B and C to the reservoir D, as depicted on Figure 1.6.

The consumer requires $24 + 16 + 2 = 42$ gallons per minute, but the consumer instead of opening the three valves to provide a rate of $42/3 = 14$ gallons per minute, each pump takes a different amount of water, the line A has a water flow of $24 gall/\text{min}$, B $16 gall/\text{min}$ and C $2 gall/\text{min}$. It can be observed that:

- The water required by the consumer is delivered, but he is taking it asymmetrically.
- Supposing that this system should operate symmetrically, a question arises: Is the customer responsible for taking the water improperly or is the water utility responsible for delivering it asymmetrically? How this responsibility may be determined?

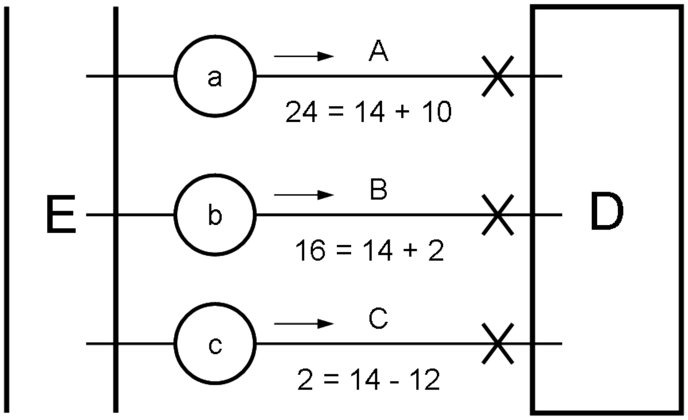


FIGURE 1.6: Hydraulic analogy to unbalanced conditions

- Let us suppose the customer is able to control the water flow, then he is responsible. The needed amount of water is $42gall/\mathrm{min}$, which can be split into $42/3 = 12gall/\mathrm{min}$. This flow of water would be the ideal flow condition, given that the water is supposed to be symmetrically delivered. Each actual line's flow can be computed as $24 = 14 + 10$, $16 = 14 + 2$ and $2 = 14 - 12$, quantities equivalent to the real ones, as shown on Figure 1.6. An interpretation for the last calculation may be: the asymmetrical water consumption of the customer takes the demanded water but causes a water circulation among pipes, which do not contribute to the total water flow but compels a higher effort in some pipes.

- Considering that the expected flow, in other terms, the nominal flow per pipe, would be $14gall/\mathrm{min}$, yielding a nominal maximal flow of $42gall/\mathrm{min}$. Then, a re-dimensioning of two pipes is necessary to meet the customer's needs, yielding a new nominal maximal flow of $24 \times 3 = 72gall/\mathrm{min}$, which would be less efficient and more expensive.

- In the case that each pipe's flow needed to be different (for example if each pipe has a different diameter, the pumps have different capacities, etc.), and the nominal flow per pipe were 24,16 and $2gall/\mathrm{min}$, then the customer's water consumption is optimal. Even more, the maximal water flow is the one taken by the customer. Given such conditions, if the customer had to be assessed supposing a symmetrical flow, he would be evaluated unfairly.

The engineering common sense would judge the previous example in a simple manner, the customer must be penalized for taking the water in such a careless manner. Nevertheless, the reason for highlighting two consumption conditions, a symmetrical and an asymmetrical one is to pay attention on the fact that depending on the viewpoint, an agent can be assessed as harmful or harmless. Thus the definition of reference conditions is more important indeed. In the next paragraphs the reference conditions proposed in this thesis will be explained.

1.3.2 Desired and undesired behavior

The definition of reference conditions requires the consideration of what is expected from customers and utilities. Once the expected behavior has been defined, deviations from it will lead to the identification of unexpected or undesired behavior. Regarding desired and ideal behavior of customers and utilities, some characteristics can be listed:

Utilty

- A *pure* sinusoidal voltage is provided.
- An ideal behavior for an utility is to deliver a non-distorted, perfectly symmetrical always available voltage signal able to feed any power demanded by the customers.
- The utility provides (generates) a purely sinusoidal positive sequence system of voltages.
- The feeding short circuit impedance as low as possible. This impedance should be in some manner capable to avoid any interaction with the customers, which may risk the provided service.
- The utility's network should be able to absorb any disturbance, either transient as stationary, that may be produced by the customers or any other source.

Customer

- The user has always perfectly balanced non commutated resistive loads.
- If any inductive load is present, such load does not absorb any reactive power causing power factors under 0.9.
- The load does not cause any negative or zero sequence current.
- The load does not generate current or voltage waveform distortion, consequently the load should not generate any non-active power.

If the previous conditions would exist in an electric system, the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ would be solved easily:

- If the utility always delivers *ideal* energy and the customers take it ideally, there will not be any responsibility to assign.
- If the utility always delivers *ideal* energy and the customers fail in any of the listed ideal conditions, the customer is responsible.
- If the utility fails in providing the ideal energy and the customer behaves as ideal anyway, the utility is responsible.
- If as the utility as the customers fail to accomplish the ideal behavior, either no responsibilities is assigned or the responsibility is distributed.

Such ideal conditions happen quite rarely, if never at all. The normality of the electric systems is to present deviations from the above listed ideal characteristics, therefore the previous list of responsibilities assignment cases cannot be employed. An ideal behavior is hard to be accomplished, then a behavior corresponding to the actual conditions would be more realistic. Let us itemize some desirable and undesirable behavior characteristics.

Desirable

- **Ideal**: rated frequency, purely resistive, non inductive nor capacitive, non distorted voltage and current waveforms, and pure positive sequence system.
- If voltage is already distorted, current must be distorted correspondingly.
- Power should be uniformly distributed among power line conductors, proportionally to the squared rms voltage values.
- Loads must be purely resistive and symmetric.
- The interaction medium for all agents interact is the electric network. In terms of electric circuits, this interaction is made through the short circuit impedances. Short circuit impedances should be low enough to avoid intolerable voltage drops and to absorb any voltage deviation caused by load changes.
- The load should not generate any non-active power, e.g. reactive power, phase displacement, asymmetric components or waveform distortion.

Undesirable

- Distorted, phase displaced and distorted current or voltage waveforms.
- Non-active power flows across the system, it does not matter which agent generates it.
- Agents take and provide energy asymmetrically.
- The utility's network structure is more unbalanced as tolerable.

The last listed characteristics are closer to the reality of a conventional electric system and allow the definition of how the agents should behave to operate compatibly to each other. Once the expected behavior is defined, the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ may be dealt as follows:

1. Ideal behavior or reference conditions must be defined in terms of procedures to analyze electric signals.

2. Electric signals processing must lead to a decomposition of the signals. All electric signals for the assessment of responsibilities must be measured.

3. Each considered stationary disturbance must be associated to a specific current or power component, in such a manner that it is treated separately from the other disturbances and from the desired components.

4. Once the signals are decomposed and each component is associated to a specific disturbance, the components of all agents must be analyzed together to determine the origin and amount of disturbances.

In this thesis the following reference conditions are proposed:

Voltage reference signal The signals decomposition require a signal, with respect any other may compared and decomposed.

Resistive ideal behavior Loads should be purely resistive.

Active Power direction The active power flows in one single direction.

Symmetrical behavior The power should be distributed uniformly and the effective voltages should be equal to each other.

These reference conditions have been published in [PST10] and will be detailed in the following paragraphs.

1.3.3 Voltage as reference signal

Electric systems are built in a parallel structure. This construction topology allows a more reliable energy delivery, permitting the presence of a common voltage within a suitable range for the most of the users. If the system would be constructed to operate in series, any load desconnexion might affect the remaining users and the quality of service would suffer significant detriments constantly.

Given the parallel structure of the electric systems, it can be accepted with no further discussion that the voltage signal is expected to be the same for all agents, whose points of common coupling are electrically close to each other. Nevertheless, some aspects must be detailed in order to reinforce this assumption. The expression *electrically close* has the following meanings:

- Any voltage difference among a group of agents is within a suitable percentage of the rated voltage. If the voltage is expected to be the reference signal, it has to be common to all agents, then only agents connected through line conductors may be analyzed at the same time.
- There is no isolation media among the concerning agents. The transformers change either the voltage level as the impedances of the systems, these devices isolate and separate the electric systems, the disturbances are affected due to the presence of transformers strongly. Therefore, responsibilites analysis using the voltage as reference signal must be performed at a specific voltage level.
- Responsibilities analysis among agents connected at different voltage levels may be performed taking into account the signals at a common voltage level.

It is also worth to remark that the voltage as reference signal has some important common properties for the most of the electric distribution systems, there exist always a minimal waveform distortion and asymmetry level.

Electric rotating machines are constructed to generate minimal harmonic frequency components, but they cannot be suppressed completely. The voltage distortion of distribution systems is almost always caused by non-linear and unbalanced loads. But even if only linear balanced resistive loads would be fed, a minimum harmonic distortion would persist. Taking into account the previous reflexion, one can say that the waveform distortion itself is not the problem, the problem appears when waveform distortion increases beyond the tolerable levels.

Asymmetry cannot be suppressed completely either. Electric machines do generate a symmetric voltage system, the transmission and distribution networks are constructed as symmteric as possible, but there will always exist a minimal unbalanced behavior, which will be seen at the connection point of all users as a minimal asymmetry level.

Accounting for the preceding reflexions, the reference condition may be complemented as: **the voltage signals will be used as reference signals to identify disturbances. They shall be employed as they are measured at the corresponding point of common coupling, regardless of any waveform distortion or asymmetry these voltages may contain**.

Many power theories and compensation procedures resort to the voltage as reference signals. Some of those theories are the following:

- Stanisław Fryze proposed a current decomposition taken the voltage as reference signal [Fry32], current might have been used as reference too, but given the previous analysis it is very reasonable to employ the voltage instead of the current.

- In the $p - q$ power theory proposed by Hirofumi Akagi et.al. [AKN83][AKN84] the currents are compared and decomposed with respect to the voltage in order to identify active and non-active current and power components.

- The FBD power theory, elaborated by Manfred Depenbrock [Dep79][Dep93], defines active currents, which contain active power. An active current is the portion of the total current with the same waveform of the voltage and contains the whole active power related to the total current and the voltage.

- Paolo Tenti et.al. has been proposed another current decomposition procedure [TM04], where the so called homopolar components are calculated as differential, integral and proportional functions of the feeding voltage, this idea comes from Fryze's active current.

- Leszek Czarnecki has proposed another electric power theory [Cza88][Cza08], his theory is based on Fryze's principles and uses the voltage as reference too.

- Finally, Alexander Emanuel has proposed a power decomposition procedure in the IEEE Standard 1459 [IC10], this procedure requires the definition of power quantities that resort to a common voltage to be calculated.

There are still more power theories. This brief revision serves to support the proposal of using the voltage as reference signal as well.

1.3.4 Resistive ideal behavior

The resistive behavior of an electric load, valued as an ideal one, may be traced back several years ago. For example, in [Smi33] it has been mentioned that the maximal active power in a determined circuit can be reached only when the load is composed by a star connected set of resistances. Such statement has a direct relationship to the definition of apparent power, which is the maximal power to be delivered or demanded given the voltage and current rms values. It is easy to demonstrate that a purely resistive load allows the maximal usage of electric energy. Figure 1.7 shows a resistive linear network feb by a three-phase set of voltages, which might be distorted or not. Common mode voltages and currents are not taken into consideration ($i_n = 0$,$u_{an} + u_{bn} + u_{cn} = 0$).

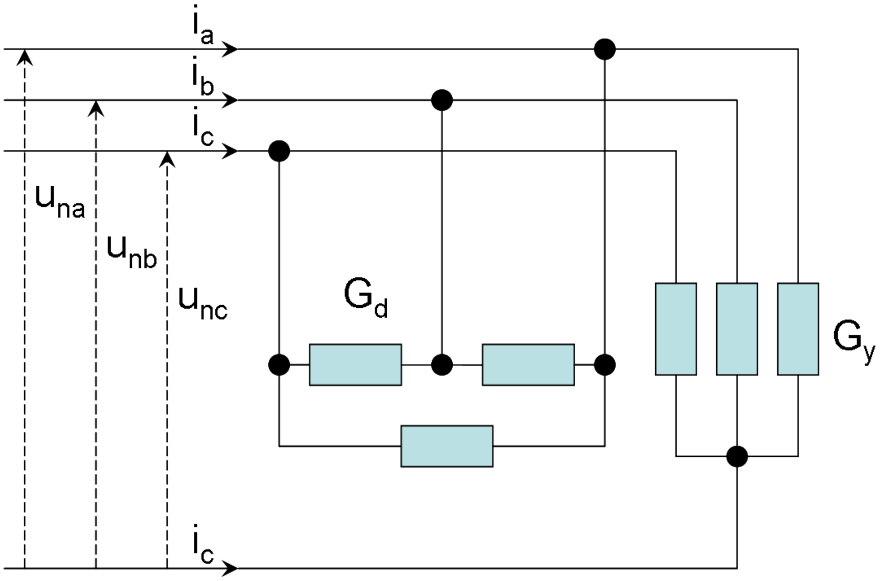


FIGURE 1.7: Ideal resistive network

In the Figure 1.7 G_y and G_d represent the resistive linear admittances of the star and delta networks, respectively. The line currents are calculated as:

$$\begin{aligned}
\mathbf{i}_{abc} &= \mathbf{G}_{abc}\mathbf{u}_{abc} \\
\begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^t &= \mathbf{G}_{abc}\begin{bmatrix} u_{an} & u_{bn} & u_{cn} \end{bmatrix}^t \\
\mathbf{G}_{abc} &= \begin{bmatrix} G_y + 2G_d & -G_d & -G_d \\ -G_d & G_y + 2G_d & -G_d \\ -G_d & -G_d & G_y + 2G_d \end{bmatrix} = \begin{bmatrix} G_0 & G_m & G_m \\ G_m & G_0 & G_m \\ G_m & G_m & G_0 \end{bmatrix}
\end{aligned} \tag{1.1}$$

where t is the vector or matrix transpose. The instantaneous power in phase coordinates p_{abc} and its corresponding active power P_{abc} are:

$$\begin{aligned}
p_{abc} &= \mathbf{i}_{abc}^{t}\mathbf{u}_{abc} \\
p_{abc} &= (G_y + 3G_d)\left[u_{an}^2 + u_{bn}^2 + u_{cn}^2\right] \\
U_{\Sigma}^2 &= \langle \mathbf{u}_{abc}, \mathbf{u}_{abc} \rangle = U_{an}^2 + U_{bn}^2 + U_{cn}^2 \\
P_{abc} &= \langle \mathbf{u}_{abc}, \mathbf{i}_{abc} \rangle \\
P_{abc} &= (G_y + 3G_d)U_{\Sigma}^2
\end{aligned} \tag{1.2}$$

where U_{Σ} is the collective effective value of voltage, U_{an} the rms value of line-to-neutral voltage, $\langle \mathbf{u}_{abc}, \mathbf{i}_{abc} \rangle$ is the inner product of the voltages and the currents yielding the active power. In order to understand the effect of different disturbances, Clarke and symmetrical components transformation will be applied to (1.1). First it is necessary to determine expressions for active power in the different coordinates.

$$\begin{aligned}
\mathbf{i}_{abc} &= \mathbf{G}_{abc}\mathbf{u}_{abc} \\
T_C\mathbf{i}_{0\alpha\beta} &= \mathbf{G}_{abc}T_C\mathbf{u}_{0\alpha\beta} \\
\mathbf{i}_{0\alpha\beta} &= T_C^{-1}\mathbf{G}_{abc}T_C\mathbf{u}_{0\alpha\beta} = \mathbf{G}_{0\alpha\beta}\mathbf{u}_{0\alpha\beta} \\
\mathbf{G}_{0\alpha\beta} &= T_C^{-1}\mathbf{G}_{abc}T_C \\
\mathbf{G}_{0\alpha\beta} &= \begin{bmatrix} G_y & 0 & 0 \\ 0 & G_y + 3G_d & 0 \\ 0 & 0 & G_y + 3G_d \end{bmatrix} = \begin{bmatrix} G_0 + 2G_m & 0 & 0 \\ 0 & G_0 - G_m & 0 \\ 0 & 0 & G_0 - G_m \end{bmatrix}
\end{aligned} \tag{1.3}$$

the instantaneous and active power in $\{0\alpha\beta\}$ coordinates is:

$$\begin{aligned}
p_{0\alpha\beta} &= \mathbf{i}_{0\alpha\beta}^{t}\mathbf{u}_{0\alpha\beta} \\
p_{0\alpha\beta} &= G_y u_0^2 + (G_y + 3G_d)\left[u_{\alpha}^2 + u_{\beta}^2\right] \\
U_{\Sigma}^2 &= \langle \mathbf{u}_{0\alpha\beta}, \mathbf{u}_{0\alpha\beta} \rangle = U_0^2 + U_{\alpha}^2 + U_{\beta}^2 \\
P_{0\alpha\beta} &= \langle \mathbf{u}_{0\alpha\beta}, \mathbf{i}_{0\alpha\beta} \rangle \\
P_{0\alpha\beta} &= G_y U_0^2 + (G_y + 3G_d)\left[U_{\alpha}^2 + U_{\beta}^2\right]
\end{aligned} \tag{1.4}$$

Similar results can be obtained using the symmetrical components transformation:

$$\begin{aligned}
\mathbf{G}_{012} &= S^{-1}\mathbf{G}_{abc}S \\
\mathbf{G}_{012} &= \begin{bmatrix} G_y & 0 & 0 \\ 0 & G_y + 3G_d & 0 \\ 0 & 0 & G_y + 3G_d \end{bmatrix} = \begin{bmatrix} G_0 + 2G_m & 0 & 0 \\ 0 & G_0 - G_m & 0 \\ 0 & 0 & G_0 - G_m \end{bmatrix} \\
\mathbf{G}_{012} &= \mathbf{G}_{0\alpha\beta}
\end{aligned} \tag{1.5}$$

in this case, the admittance matrix $\mathbf{G}_{0\alpha\beta}$ and $\mathbf{G}_{012}$ are identical. The active power calculation in $\{012\}$ coordinates yields:

$$\begin{aligned}
U_{\Sigma}^2 &= \langle \mathbf{U}_{012}, \mathbf{U}_{012} \rangle = \mathbf{U}_{012}^{T}\mathbf{U}_{012} = U_{(0)}^2 + U_{(1)}^2 + U_{(2)}^2 \\
P_{012} &= real\{\langle \mathbf{U}_{012}, \mathbf{I}_{012} \rangle\} = real\{\mathbf{I}_{012}^{T}\mathbf{U}_{012}\} \\
P_{012} &= G_y U_{(0)}^2 + (G_y + 3G_d)\left[U_{(1)}^2 + U_{(2)}^2\right]
\end{aligned} \tag{1.6}$$

The comparison of the three coordinates system representations requires the apparent power calculation too. Collective effective voltages have been already calculated for all coordinated systems, current effective voltages must be calculated. For the sake of simplicity, the zero sequence components will not be shown.

$$\begin{aligned} \mathbf{i}_{abc} &= \mathbf{G}_{abc}\mathbf{u}_{abc}, & I_{abc} &= \sqrt{\langle \mathbf{i}_{abc}, \mathbf{i}_{abc}\rangle} = (G_y + 3G_d)\sqrt{U_{an}^2 + U_{bn}^2 + U_{cn}^2} \\ \mathbf{i}_{0\alpha\beta} &= \mathbf{G}_{0\alpha\beta}\mathbf{u}_{0\alpha\beta}, & I_{0\alpha\beta} &= \sqrt{\langle \mathbf{i}_{0\alpha\beta}, \mathbf{i}_{0\alpha\beta}\rangle} = (G_y + 3G_d)\sqrt{U_{\alpha}^2 + U_{\beta}^2} \\ \mathbf{I}_{012} &= \mathbf{G}_{012}\mathbf{U}_{012}, & I_{012} &= \sqrt{\langle \mathbf{I}_{012}, \mathbf{I}_{012}\rangle} = (G_y + 3G_d)\sqrt{U_{(1)}^2 + U_{(2)}^2} \end{aligned} \tag{1.7}$$

$$\begin{aligned} P_{abc} &= (G_y + 3G_d)\left[U_{an}^2 + U_{bn}^2 + U_{cn}^2\right] = U_{\Sigma} I_{abc} = S_{abc} \\ P_{0\alpha\beta} &= (G_y + 3G_d)\left[U_{\alpha}^2 + U_{\beta}^2\right] = U_{\Sigma} I_{0\alpha\beta} = S_{0\alpha\beta} \\ P_{012} &= (G_y + 3G_d)\left[U_{(1)}^2 + U_{(2)}^2\right] = U_{\Sigma} I_{012} = S_{012} \end{aligned} \tag{1.8}$$

Comparing Eqs. (1.2), (1.4), (1.6) and (1.8), when no zero sequence components exist, the following observations can be listed:

- For balanced load conditions, active power is equal to the apparent power. Given that the apparent power is the maximal active power constrained to the collective values of voltage and currents, then the presence of linear balanced resistive loads yields to an optimal usage of the electric energy.

- Given that conductance matrices in $\{0\alpha\beta\}$ and $\{012\}$ coordinates are diagonal matrices, the currents are proportional to the corresponding voltages. If any component of the load braches would not be equal to each other, the conductance matrices of (1.4) and (1.5) would not be diagonal. In that case, the currents would be composed by a linear combination of α and β voltages or by positive and negative sequence components. Such crossed components cause the active power to decrease because different coordinates components are not proportional, then their inner product may yield negative or zero values. When the load is unbalanced, crossed components do not contribute to increase the active power, but the effective current does increase, then the apparent power becomes higher. Therefore, for unbalanced load conditions, active power is always lesser than the apparent power, the electric energy usage is not optimal.

- For balanced loading, the active and apparent power are proportional to the collective effective voltages, regardless of the presence of negative sequence components, as shown in (1.6). Thus a balanced load is able to use the electric energy in an optimal way, even if the feeding voltage is not balanced. From (1.2) and (1.4) a similar conclusion can be extracted, the active power is proportional to the sum of the squared values of the effective voltages, it does not matter that any of this effective voltage differ from each other, this reinforces the previous conclusion.

- Considering the previous observations, if the load is symmetrical, the feeding voltage may be asymmetrical and the energy usage will be optimal, i.e., the active power shall have the same value of the apparent power, as show also in [Sta00], as long as the load is resistive and balanced.

Let us assume that the collective currents may be fixed at a constant value, so as the collective voltage, even if the load structure changes. Under such conditions, the form of the collective current (1.7) would vary. Changes in the currents may occur due to:

- The conductances become unbalanced, as explained previously, causing negative sequence currents which decrease the active power absorption capability. Reactive elements may produce also asymmetrical components, their effect would be similar, the active power will reduce even more.
- Presence of linear coils and capacitors, contributing to non-active power, then decreasing the active power.
- Non-linear elements with frequency components different to the voltage components, thus they modify the waveform and, depending on its relative effective value, the active power will sink correspondingly.

The aforementioned analysis has been carried out taken into account the apparent power is calculated as the product of collective voltage and current. It is worth to note that either the active power as the apparent power calculation depend strongly on how the voltages are measured. In [WGE05] a comparison between the IEEE 1459 effective power and the apparent power proposed in the standard DIN 40110 [DIfN96] is presented, the latter power quantity is based on the FBD power theory [Dep93]. The presence of zero sequence components affects significantly both methods, however it has been chosen in this thesis to resort to the FBD based apparent power because it requires less information about the system impedance. It needs only the waveforms and it is in many senses more practical. Furthermore, zero sequence components do not contribute significantly to active power, in many cases and it can be treated separately, then the analysis presented previously is still valid.

The previous analysis has been made without mentioning that the voltages may have an arbitrary waveform. As long as the conditions $u_a + u_b + u_c = 0$ and $i_n = 0$ are held, the waveforms may be highly distorted and the conclusions would remain unchanged. Moreover, taking into account the last paragraph, the zero sequence or common mode components can be handled separately without affective the validity of the reference condition.

The previous presentation allow to summarise the reference condition: **any linear balanced load behaves optimally and would absorb energy of the feeding source regardless any asymmetry of waveform distortion is present**.

1.3.5 Active power direction

Several methods to assess the origin of disturbances are based on the direction of harmonic active power components. Among them, the following can be listed [Mus98][SvWC94][CF94] and [FSF91]. The proposed principle to locate the origin of disturbances, in this particular case the origin of harmonic sources, is that *any harmonic active power component is positive for agents absorbing power and negative for agents delivering power.* Let us suppose an **AGENT B** is fed by an **AGENT A**, as depicted on Figure 1.8, a voltage $u(t)$ at the point of common coupling is applied and the current $i(t)$ flows from **AGENT A** to **AGENT B**. Voltage and current can be expressed in terms of Fourier components as:

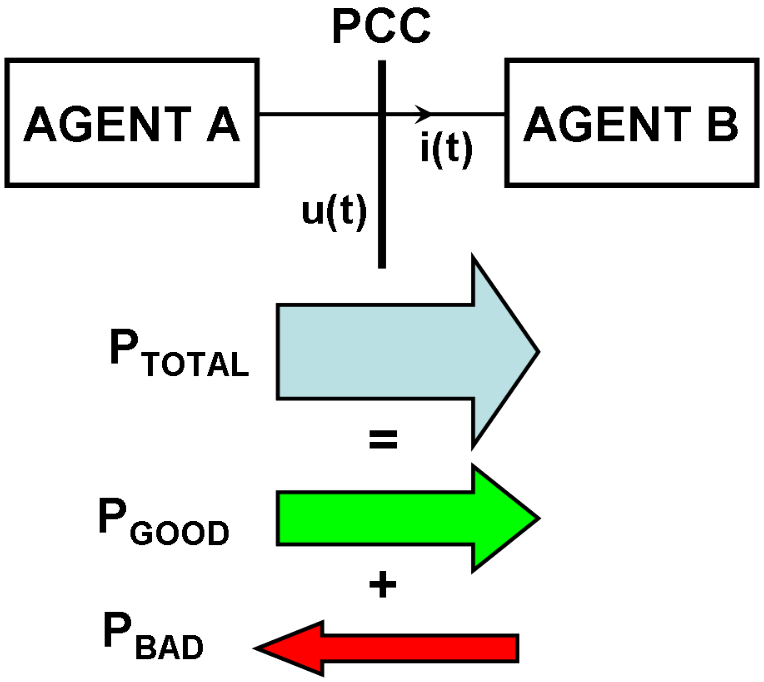


FIGURE 1.8: Harmonic active power direction

$$\begin{aligned} u(t) &= \sum_{k=1}^{N} \sqrt{2} U_k \cos(k w_0 t + \alpha_k) \\ i(t) &= \sum_{k=1}^{N} \sqrt{2} I_k \cos(k w_0 t + \beta_k) \end{aligned} \tag{1.9}$$

where U_k and I_k are the rms values of voltage and current, α_k and β the phase angle of each frequency component, k the harmonic order and w_0 the fundamental or rated frequency. The active power flowing from **AGENT A** to **AGENT B** results from:

$$\begin{aligned}
P_{TOTAL} &= \langle u(t), i(t) \rangle = \frac{1}{T}\int_{t=0}^{T} u(t)i(t)dt \\
P_{TOTAL} &= \sum_{k=1}^{N} U_k I_k \cos(\alpha_k - \beta_k) \\
P_{TOTAL} &= \sum_{k=1}^{N} P_k \\
P_{TOTAL} &= \sum_{k \in GOOD} P_k - \sum_{k \in BAD} P_k = P_{GOOD} - P_{BAD}
\end{aligned} \tag{1.10}$$

The active power represents the energy flow. Regardless of the presence of distortion or asymmetry in the source or the load, active power shows how the electric energy flows from one site to another. In the example, energy flows from **AGENT A** towards **AGENT B**. In (1.10) the terms $P_k = U_k I_k \cos(\alpha_k - \beta_k)$ are presented, these terms are the harmonic active power components, which can be positive, negative or zero. Additionally it is supposed the harmonic active power components may be grouped into two parts, one flowing in the same direction of the total power called *GOOD* and another one flowing in the opposite direction called *BAD*. The terms *GOOD* and *BAD* are used only as a matter of example, they do not represent any kind of valuation.

According to the harmonic active power flow principle, all frequency components belonging to the group *GOOD* has the same direction of the active power and operates as it would be expected, this is, from the source towards the load. Additionally, they are generated where they are expected, then the frequency components of the *GOOD* group are considered as desirable. On the opposite, the frequency components of the group *BAD* do not operate as it is expected, they come from the load and flow back to the source. They are generated where the energy is expected to be consumed. As long as they are not in agreement with the usual statement, they are undesirable components.

In order to analyze the previous example, let us suppose that **AGENT B** has a resistive linear load of conductance G. Hence, the current across the point of common coupling would be $i(t) = Gu(t)$, a current with the same waveform of the voltage but different magnitude. The expression (1.10) would be:

$$\begin{aligned}
P_{TOTAL} &= \langle u(t), Gu(t) \rangle = \frac{1}{T}\int_{t=0}^{T} Gu^2(t)dt \\
P_{TOTAL} &= \sum_{k=1}^{N} GU_k U_k \cos(\alpha_k - \alpha_k) = \sum_{k=1}^{N} GU_k^2 \\
P_{TOTAL} &= \sum_{k=1}^{N} P_k \\
P_{TOTAL} &= \sum_{k \in GOOD} P_k = P_{GOOD}
\end{aligned} \tag{1.11}$$

For a resistive load, all harmonic active power components are positive, flow in the same direction and no backwards flowing components appeared. This means that for an ideal resistive load, total active power flows in one single direction and its harmonic frequency components flow in the same direction as well.

Non-linear loads are able to generate non-active currents and powers, which may cause the presence of harmonic active power components with negative, null and positive values. If **AGENT B** is a non-linear load without any energy storage capacity, it cannot generate active power capable to flow towards the **AGENT A**. The **AGENT B** operates as long as **AGENT A** applies a voltage and a current flow. If any energy can be generated within the **AGENT B**, **AGENT A** could be turned off and power would flow into it, of course this phenomenon will not happen.

Several studies have been carried out to analyze whether the harmonic active power is a useful quantity to identify the origin of disturbances or not [Ema95][RS01][XLL03]. Among others, the following conclusions have been extracted:

- Non-linear loads absorb active power, as it is expected from any load, but negative harmonic active power components may appear. This negative components hold any any value, nevertheless the total sum of all power components coincides with the total power.

- Non-linear loads and their feeding facilities may interact in such a manner that the harmonic active power can have positive or negative values under certain conditions. Furthermore, harmonic active powers related to the same loads can switch their signs under new conditions. These harmonic *active* power components are not really active, they are simply non-active power components.

- Moreover, when non-linear and linear loads are fed by the same source it can happen that the linear load seems to have negative harmonic active power components.

- As explained above, only for resistive linear loads all frequency power components are either positive or negative, depending if an energy source or a consuming facility is being analyzed.

- The presence of distributed generating resources in the load's side would cause any kind of power flow from the loads towards other loads and the feeding source. Although the energy does not flow normally from the loads to the feeders, this energy can be generated suitably and properly, then it cannot be considered as undesirable.

The previous observations lead us to conclude that the active power frequency components criterion cannot be used to assess the origin of disturbances in any case, when non-linear devices are present this quantity may be misleading. Additionally, it has been proved that the measurement of harmonic active power components causes higher inaccuracies [XLL03][Fer06].

Active power may also be affected by the presence of asymmetry. In (1.6) three power components can be extracted:

$$\begin{aligned} P_{012} &= G_y U_{(0)}^2 + (G_y + 3G_d)\left[U_{(1)}^2 + U_{(2)}^2\right] \\ P_{012} &= P_{(0)} + P_{(1)} + P_{(2)} \end{aligned} \tag{1.12}$$

called zero, positive and negative sequence active power components. Under normal conditions, positive sequence power would be the bigger component and should flow from sources to loads, negative and zero sequence power components may be have any value. Under ideal conditions, neither negative nor zero sequence component would exist, they are completely undesirable but cannot be avoided either. Given that an ideal load and an ideal source have all power components with the same sign, even under unbalanced conditions, the active power and all its components shall flow in the same direction.

According to the considerations presented, the example and the cited conclusions, the reference condition may be defined as: **Active power represents the energy exchange, it flows in one single direction regardless the presence of waveform distortion or asymmetry. All components of the active power flow in the same direction.**

1.3.6 Symmetrical behavior

The previous sections have presented three reference conditions, another condition regarding symmetrical behavior remains to be defined. The most commonly used method to identify any asymmetry is the Fortescue's symmetrical components transformation [For18]. In Equations (1.6) to (1.8), the computation of active power in symmetrical coordinates for a perfectly balanced load was presented. From this presentation, it has been shown that a balanced resistive load absorbs electric power optimally, regardless of the presence of waveform distortion or asymmetry. Additionally, when all line-to-neutral and line-to-line rms voltages are equal, then the active power will be distributed uniformly among all phase conductors. Any deviation from an uniformly distribution of power implies either unbalanced source voltages or unbalanced loading. Therefore, to identify an asymmetrical behavior two aspects must be assessed:

Load Symmetry

The ideal load's behavior comprises the connection of linear resistive balanced elements to all phase conductors, this condition is not only optimal in terms of power consumption, but also allows a symmetrical power usage.

Source Symmetry

The source's ideal consists of voltages with equal rms values and equal line impedances. Equal rms voltages avoid the presence of negative or zero sequence components, identical line impedances permit an uniform absorption of power.

Several method exist to identify and measure the presence of asymmetry in loads and sources. In the IEEE Standard 1459 [IC10] the unbalance is assessed at the fundamental frequency. The computation of positive sequence active and reactive powers allows the calculation of unbalanced power components, which are used as an asymmetry measure.

A purely positive sequence system of voltages implies that all line-to-neutral voltages have the same waveform but phase displaced $2\pi/3$ among each other. For the currents the same criteria is used. To identify the asymmetry origin some consideration must be taken:

- Unbalanced voltage components can cause unbalanced load currents.
- Asymmetric loads are able to produce unbalanced currents.

- Unbalanced load currents may be produced by unbalanced load composition or by un asymmetrical feeding voltage.
- Unbalanced voltages may be caused by asymmetrical loading or by asymmetry in the source. A source may be unbalanced due to unbalanced short circuit impedances or by unequal line-to-neutral rms voltages.

According to this, the assessment of asymmetry must be performed taking into account voltages and currents, because the separated evaluation of voltage and current are insufficient and may lead to wrong conclusions.

In the DIN Standard 40110-2 [DIfN96], the asymmetry is evaluated comparing the active power distribution among all conductors. The power distribution is proportional to the squared rms voltage of each line. This evaluation requires three stages: the calculation of rms values of all voltages, the calculation of all active powers and a current decomposition based on the preceding values. The current decomposition provides a current components containing information about the asymmetry. This procedure accounts for the source and load asymmetry evaluation as a whole, its application will be presented in a posterior chapter.

The reference condition to assess responsibilities regarding symmetry is: **A poly-phase system behaves symmetrically if all rms voltages (line-to-neutral and line-to-line rms voltages) have the same value and when the exchanged active power is equally distributed among all phase conductors.**

1.4 Summary of the Chapter

In this chapter the problem of responsibilities assignment has been presented and described. The $\mathcal{R_A P}$ was explained resorting to its general characteristics, which lead to define it as the qualitative and quantitative determination of contributions to the detriment or improving of power quality in a system caused by all involved agents. The term agent has been introduced to promote an egalitarian and fair treatment of all parts involved in the responsibilities assignment. Finally, reference conditions to assess the $\mathcal{R_A P}$. The reference conditions contain technical criteria to identify and evaluate the presence of the stationary disturbances, these conditions found the principles to review any available responsibilities method, new methods may be develop from these conditions as well. The previously presented ideas have been already published, the reader may see these references for details [PST08][PST09][PST10].

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CHAPTER 2

Electric power definitions

I sell here, Sir, what all the world desires to have - Power.

Matthew Boulton, speaking at the Boulton-Watt works in 1776
Museum of Science and Industry, Manchester, UK

The quality of the electric energy can be analyzed according to two perspectives:

- Continuity and Reliability, related to the presence of the energy when a customers demands it and how likely can the energy be present.
- Power Quality, the set of characteristics of the energy at some point and moment in the operation of a system to satisfy the customer's necessities.

The electric power absorbed by a customer or delivered by an utility presents characteristics related to the manner in which the electric energy is employed, these characteristics are related to different physical phenomena. In order to describe, quantify and describe those phenomena, it is necessary to account for definitions and mathematical operations to extract information from electric signals. This information will serve for judging whether the quality is in a suitable condition or not.

The study of power flow and electric phenomena characterization has been carried out from the beginnings of electric systems. In 1933 a discussion on the definition and analysis of reactive power power took place. One of those discussions [Kno33] began with the following text, that I cite here to motivate and introduce the review of power definitions.

> *If all electrical iron could by divine decree or presidential proclamation be straightened into uniform permeability over its whole range of magnetization there would be less occasion to raise the question of adequacy of our prevailing concepts of reactive power and power factor. If all synchronous machine windings under all conditions of loading could have flux distribution in strict*

> *conformity with symmetrical sinusoidal generation there would be still less. Moreover, the excuse would nearly vanish if polyphase circuits could always be held to rigid balance of impedances on their lines and loads. With these factors eliminated the residue of doubt, if any, would be a topic to intrigue only the academic and metaphysical minds.*
> *Archer Knowlton in Reactive Power Concepts in need of Clarification - 1933*

Although power quality is a concept developed in the last decades, it has been a concern for electricians since the beginning of the 20th century. Furthermore, the questioning on the origin of disturbances has been tackled in the 20s and 30s. Many solutions were proposed, nowadays electricians have more powerful tools and equipment to solve what still remains unsolved.

In the previous chapter, the concepts related to the analysis of responsibilities in power quality were presented. The analysis of measurements requires a set of technical tools to extract information from voltages and currents. In this chapter a description of the power quantities involved in the analysis of responsibilities is presented. The zero sum quantities are used with the aim of ordering voltages and currents in poly-phase systems. These quantities with the usage of inner product allows the mathematical definition of quantities like apparent power and supports the interpretation of other power quantities.

2.1 Voltages and Currents

2.1.1 Zero sum Quantities

With the aim of defining a procedure to calculate the power, some fundamental concepts must be presented. First, the power is the rate of energy exchange through a particular boundary inside an electric system [CS35]. The boundary defines a closed region, where the energy flows to or comes from. The content of this region may be a customer, an energy source, a compensating facility, etc. This region allows also the definition of an equipotential region, where currents and voltages ought to be measured. The circuit enclosed by the region is connected to the rest of the system by means of a set of n-terminals, for the general case.

The enclosing region must satisfy some characteristics, as it is described in [Sta02]:

- Only conductive couplings are allowed, no radiated energy is considered.
- All current contributions must be lumped at any place of the system, it is not allowed the presence of distributed quantities e.g. current densities.
- Not only conductors transporting electric power pass through the enclosing region, measuring and protective terminals, communication and control lines penetrate the region, among others. Only the main power conductors ought to be considered, this includes the neutral conductor but it does not include the grounding protective conductors.

The enclosing region intercepts the n-terminals, defining the place where currents and voltages must be measured. This place is also known as the *Point of Common Coupling - PCC*, in the standard IEEE 519 [iee93] it is defined as the point where only one

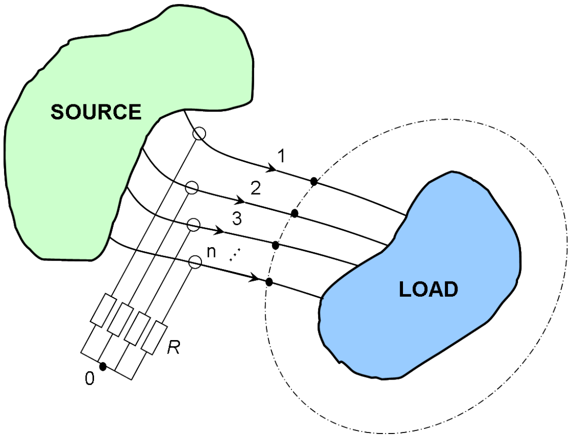


FIGURE 2.1: Point of common coupling for an n-terminals circuit

customer can take energy from the grid, this concept accomplishes the above mentioned characteristics too, therefore both definitions will be considered equivalent. The Figure 2.1 illustrates the point of common coupling for a load fed by an energy source, the place where the enclosing envelope cuts the n-terminals is the PCC.

When only the main power conductors are considered, the Kirchhoff's law for currents in a n-terminals circuit implies that their currents sum up to zero for any time instant, as depicted on (2.1).

$$\sum_{\mu=1}^{n} i_{\mu}(t) = 0, \mu \in \{1, 2, 3, \ldots, n\} \tag{2.1}$$

Quantities like (2.1) are called **zero sum quantities**. Evidently in (2.1) only $n-1$ currents are linearly independent, thus knowing $n-1$ currents suffices to determine the n-th current and to characterize all the currents of the agent.

The n voltages of each conductor at the PCC may be measured with respect to an arbitrary voltage reference point. The most common practice is to use one of the terminals as reference, for a three-phase four-conductor system the neutral conductor is used as reference, then only $n-1$ voltages need to be measured. The measured voltages should have the same characteristic as the currents (2.1), they should be zero-sum quantities. This requires, for mathematical treatment, a special voltage reference point, the virtual star point [Sta00][DIfN96][Fer98]. Voltages against the virtual star point can be derived mathematically from any set of voltages measured against an arbitrary reference. No extended measuring effort is needed.

Once all voltages are measured against the virtual star point, the following condition is accomplished:

$$\sum_{\mu=1}^{n} u_{\mu 0}(t) = 0, \mu \in \{1, 2, 3, \ldots, n\} \tag{2.2}$$

where 0 designates the virtual star point. The virtual star-point can be realized using n equal star connected resistors R, as depicted on Figure 2.1. The star point of the n

resistors, according to Kirchhoff's currents law, has a zero voltage, which is the previously mentioned condition.

As already stated above, the set of zero sum voltages can be calculated from other measured voltages, for example from the terminal-to-terminal voltages as explained in [DIfN96]:

$$\begin{aligned} u_{\mu 0} &= \frac{1}{n}\sum_{k=1}^{n} u_{\mu k}(t), \mu \in \{1,2,3,\dots,n\} \\ u_{\mu 0} &= u_{\mu\rho} - \frac{1}{n}\sum_{k=1}^{n} u_{k\rho}(t), \rho \in \{1,2,3,\dots,n\} \end{aligned} \tag{2.3}$$

where $u_{\mu k} = -u_{k\mu}$ and $u_{\mu\mu} = 0$. For instance, in the case of $n = 4$ the zero sum quantities can be calculated as follows:

$$\begin{aligned} i_4 = i_N &= -(i_1 + i_2 + i_3) \\ u_{10} &= \frac{1}{4}\left(u_{12} + u_{13} + u_{1N}\right) = u_{1N} - \frac{1}{n}\left(u_{1N} + u_{2N} + u_{3N}\right) \\ u_{20} &= \frac{1}{4}\left(u_{21} + u_{23} + u_{2N}\right) = u_{2N} - \frac{1}{n}\left(u_{1N} + u_{2N} + u_{3N}\right) \\ u_{30} &= \frac{1}{4}\left(u_{31} + u_{32} + u_{3N}\right) = u_{3N} - \frac{1}{n}\left(u_{1N} + u_{2N} + u_{3N}\right) \\ u_{40} &= \frac{1}{4}\left(u_{N1} + u_{N2} + u_{N3}\right) = \qquad -\frac{1}{n}\left(u_{1N} + u_{2N} + u_{3N}\right) \end{aligned} \tag{2.4}$$

The zero sum voltages (2.4) can be expressed in matrix form:

$$\begin{bmatrix} u_{10} \\ u_{20} \\ u_{30} \\ u_{40} \end{bmatrix} = \frac{1}{4}\begin{bmatrix} 3 & -1 & -1 \\ -1 & 3 & -1 \\ -1 & -1 & 3 \\ -1 & -1 & -1 \end{bmatrix}\begin{bmatrix} u_{1N} \\ u_{2N} \\ u_{3N} \end{bmatrix} \qquad \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -1 & -1 \end{bmatrix}\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \tag{2.5}$$

2.1.2 Collective effective values

For stationary or quasi-stationary conditions the instantaneous values of currents and voltages can be employed, but their effective or root mean square values [IEC] are also necessary, either for single-phase as for polyphase systems. Considering the periodic signals under analysis with period T, the inner product between any pair of signals f and g is calculated as [KF61]:

given that:

$$f(t) = f(t-T) \qquad g(t) = g(t-T)$$

$$\langle f, g\rangle = \langle f(t), g(t)\rangle = \frac{1}{nT}\int_{\tau=t_0}^{\tau=t_0+nT} f(\tau)g(\tau)d\tau \tag{2.6}$$

When several periods of the signals are analyzed, the methodology suggested in the IEC standards 61000-4-7 [IEC02] and 61000-4-30 [IEC08] can be used. Currently a time window of 200ms length is proposed in the international standards to measure all stationary parameters like effective values of currents and voltages, powers, harmonic and interharmonic frequency components.

The effective or root mean square - rms value of a voltage u or a current i is determined as follows:

$$\begin{aligned} U &= \sqrt{\langle u, u\rangle} = \sqrt{\frac{1}{nT}\int_{\tau=t_0}^{\tau=t_0+nT} u(\tau)^2 d\tau} \\ I &= \sqrt{\langle i, i\rangle} = \sqrt{\frac{1}{nT}\int_{\tau=t_0}^{\tau=t_0+nT} i(\tau)^2 d\tau} \end{aligned} \tag{2.7}$$

From now on, the effective value of a single phase voltage or current will be called rms value. The inner product operation and notation defined in (2.6) and (2.7) shall be utilized to calculated power quantities in the next sections.

When dealing with polyphase circuits, collective quantities and values are sensible [Fer98][Sta00]. A voltage and current vector notation can be used for the sake of simplicity.

$$\mathbf{u}_0 = [u_{10}, u_{20}, u_{30}, u_{40}]^T \qquad \mathbf{i} = [i_1, i_2, i_3, i_4]^T \tag{2.8}$$

Instantaneous and rms quantities are needed to analyze power exchange. Given that stationary power quality disturbances comprise the principal concern of this thesis, special emphasis on rms values extracted from periodic signals is going to be made. The collective rms values, or simply named collective values of $\mathbf{u}_0$ and $\mathbf{i}$ are calculated using the inner product too.

$$\begin{aligned} U_\Sigma^2 &= \langle \mathbf{u}_0, \mathbf{u}_0\rangle = \frac{1}{nT}\int_{\tau=t_0}^{\tau=t_0+nT} \mathbf{u}_0^T \cdot \mathbf{u}_0 d\tau \\ U_\Sigma^2 &= \langle \mathbf{u}_0, \mathbf{u}_0\rangle = \sum_{\mu=1}^{n}\langle u_{\mu 0}, u_{\mu 0}\rangle = \sum_{\mu=1}^{n} U_{\mu 0}^2 \\ I_\Sigma^2 &= \langle \mathbf{i}, \mathbf{i}\rangle = \sum_{\mu=1}^{n}\langle i_\mu, i_\mu\rangle = \sum_{\mu=1}^{n} I_\mu^2 \end{aligned} \tag{2.9}$$

Employing the inner product to operate on the signals under analysis, it is possible to determine the properties of the definitions previously presented and to extract information about the power quantities. The exchange of electric energy may be analyzed completely resorting to the currents and voltages, from which the energy flowing into a point of common coupling can be fully determined.

2.1.3 Representation using selected coordinate systems

Several coordinates transformation can be used to describe voltages and currents. Depending on the particular issue to be studied, a specific coordinate transformation can be resorted to. Three coordinates transformations are of special interest in this thesis, the symmetrical components transformation [For18], the Clarke and the Park transformation, explained for polyphase systems in [Wil69]. All these transformations have an initial and a normalized form, it is recommendable to employ normalized transformations to dispose of power invariant quantities, for symmetrical components as well as for the Clarke transformation.

2.1.3.1 Clarke Transformation

The Clarke transformation is a linear transformation from the phase components $\{a, b, c\}$ into the $\{0, \alpha, \beta\}$ coordinates, the Park transformation is a generalization of the Clarke transformation for rotating systems, in the context of this thesis only the Clarke transformation will be used.

$$T_C = \begin{bmatrix} \sqrt{1/3} & \sqrt{2/3} & 0 \\ \sqrt{1/3} & -\sqrt{1/6} & \sqrt{1/2} \\ \sqrt{1/3} & -\sqrt{1/6} & -\sqrt{1/2} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sqrt{2}/2 & 1 & 0 \\ \sqrt{2}/2 & -1/2 & \sqrt{3}/2 \\ \sqrt{2}/2 & -1/2 & -\sqrt{3}/2 \end{bmatrix} \tag{2.10}$$

The Clarke transformation is a linear operation, whose matrix (2.10) is an orthonormal matrix, then its inverse results transposing it.

$$T_C^{-1} = \begin{bmatrix} \sqrt{1/3} & \sqrt{1/3} & \sqrt{1/3} \\ \sqrt{2/3} & -\sqrt{1/6} & 1\sqrt{1/6} \\ 0 & \sqrt{1/2} & -\sqrt{1/2} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{2.11}$$

The Clarke transformation may be used in the following manner:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = T_C \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix}, \qquad \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = T_C^{-1} \begin{bmatrix} i_a \\ i_b \\ i_b \end{bmatrix} \tag{2.12}$$

where a, b, c are the phase components, 0, α and β are the Clarke domain components.

2.1.3.2 Symmetrical components transformation

The symmetrical components normalized transformation, also known as symmetrical coordinates normalized transformation, is carried out using the following transformation matrix:

$$S^{-1} = \sqrt{\frac{1}{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}, \qquad S = \sqrt{\frac{1}{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \tag{2.13}$$

where $\alpha = e^{j2\pi/3}$, this transformation is orthonormal too, then transposing (2.13) the inverse transformation matrix is obtained, it is worth to note that S is a complex matrix, then the transposition implies to conjugate each component of the matrix. The symmetrical components transformation can be used only at each frequency component, because it operates on phasors, then only a single frequency component may be analyzed at the same time.

The Fortescue's symmetrical components transformation may be used in the following manner:

$$\begin{bmatrix}\hat{I}_a\\ \hat{I}_b\\ \hat{I}_c\end{bmatrix} = S\begin{bmatrix}\hat{I}_{(0)}\\ \hat{I}_{(1)}\\ \hat{I}_{(2)}\end{bmatrix}, \qquad \begin{bmatrix}\hat{I}_{(0)}\\ \hat{I}_{(1)}\\ \hat{I}_{(2)}\end{bmatrix} = S^{-1}\begin{bmatrix}\hat{I}_a\\ \hat{I}_b\\ \hat{I}_b\end{bmatrix} \tag{2.14}$$

where a, b, c are the phase components, (0), (1) and (1) are the zero, positive and negative symmetrical components. As this transformation can be used on complex numbers only, the Fourier transform is required to calculate the current or voltage phasor at each frequency component, $\hat{I}_a$ represents the current phasor of the line a at a specified frequency extracted from Fourier analysis. The symmetrical components theory [For18] was proposed to be applied on the fundamental frequency current and voltage components, its interpretation and most widely usage is related to this frequency, a generalization to any frequency component is possible [SvWC96], but rarely used in practice.

2.2 Active Power

Active power represents the rate of electric energy consumption or delivery, depending on whether the energy is being absorbed by a consumer or provided by an generating facility. Among all the electric power related definitions, active power is the only truly physical power quantity, therefore it has reached a global agreement. Although many significant efforts have been made in the last ninety years to provide physical and mathematical meaningful definitions, other power quantities like apparent power, power factor and reactive power remain under discussion.

2.2.1 Definition and physical meaning

Electric potential difference or voltage may be interpreted as the amount of energy that an electric field can provide to an electric charge. When this charge is moving due to the action of the mentioned electric field, an electric current is produced. The rate at which the electric charge receives energy at any time instant t is determined by the product of the current $i(t)$ and the voltage $u(t)$, this quantity is called instantaneous power.

$$p(t) = u(t)i(t) \tag{2.15}$$

If the instantaneous power (2.15) is integrated over a time interval of length nT, the integral represents the energy provided by the above mentioned electric field.

$$\int_t^{t+nT} p(t)dt = \int_t^{t+nT} u(t)i(t)dt = W_e \tag{2.16}$$

The mean value of the instantaneous power during the time interval of length nT ought to be calculated using the same integral (2.16) dividing it by nT. This new quantity is the **Active Power** [DIfN94], also known as real power [IC10], average power [Fer98], it represents the average value of electric energy flow. Referring to the definition of inner product (2.6), a mathematical definition of active power can be established as the inner product of a voltage an its corresponding current.

$$\frac{1}{nT}\int_{t}^{t+nT} p(t)dt = \frac{1}{nT}\int_{t}^{t+nT} u(t)i(t)dt = \langle u(t), i(t)\rangle = P \tag{2.17}$$

In this document, the quantity defined in (2.17) will be named as **active power** and represented by the symbol P. Its physical meaning again, which is the mean flow of electric energy provided by a source. If the potential difference or voltage is periodic, the mean value of the instantaneous power can be calculated over one or n periods.

For polyphase systems, the voltage and current vectors (2.8) can be used to define the instantaneous polyphase power as follows:

$$\begin{aligned} p_\Sigma(t) &= u_{1N}i_1 + u_{2N}i_2 + u_{3N}i_3 \\ p_\Sigma(t) &= u_{10}i_0 + u_{20}i_2 + u_{30}i_3 + u_{40}i_4 = \mathbf{u}_0^T\mathbf{i} \end{aligned} \tag{2.18}$$

In (2.18) the instantaneous power calculated from voltages measured against the neutral or from zero sum voltages are identical. Once the instantaneous power has been established, the total active power for the polyphase system can be derived:

$$\begin{aligned} P_\Sigma &= \langle u_{1N}, i_1\rangle + \langle u_{2N}i_2\rangle + \langle u_{3N}i_3\rangle \\ P_\Sigma &= P_{1N} + P_{2N} + P_{3N} \\ P_\Sigma &= \langle u_{10}, i_0\rangle + \langle u_{20}, i_2\rangle + \langle u_{30}, i_3\rangle + \langle u_{40}, i_4\rangle = \langle \mathbf{u}_0, \mathbf{i}\rangle \\ P_\Sigma &= P_1 + P_2 + P_3 + P_4 \end{aligned} \tag{2.19}$$

2.2.2 Active and non-active currents definition

The analysis of power quality disturbances for responsibilities assignment purposes needs the decomposition of the signals. The decomposition must reflect the energy exchange, the phenomena affecting the power factor and the power quality stationary disturbances.

In this thesis, a current decomposition will be employed. As it was explained in the previous chapter, voltages will be used as reference signals. Hence, the currents are decomposed into signals that reflect every phenomenon.

The first component is the active current. This current component is a current with the same waveform of the voltage and contains the whole active power. The active current i_a is therefore proportional to the voltage signal. The proportional constant is the so called active conductance G. The active current is calculated as follows:

$$\begin{aligned} G &= \frac{P}{U^2} = \frac{\langle u, i\rangle}{\langle u, u\rangle} \\ i_a(t) &= Gu(t) \end{aligned} \tag{2.20}$$

The active current was first proposed by Fryze [Fry32] and has been taken into account by others in several power theories like Depenbrock's FBD theory [Dep79][Dep93][Sta08], Czarnecki's CPC theory [Cza08], Tenti's theory [TM04][TTTM09] and others. The active current has the following properties:

- Active current has the same waveform of the voltage.
- The power transported by the active current equals the power transported by the total current

- Instantaneous power computed using active currents, called earlier as intrinsical instantaneous power [Ema90], has either positive values or negative ones throughout.
- All the active power harmonic components calculated using the active current have the same sign, if power is being delivered all harmonic active power components are positive and if the power is being generated all components are negative.

The active power can be calculated form active the current as follows:

$$\begin{aligned} \langle u, i \rangle &= P \\ \langle u, i_a \rangle &= \langle u, Gu \rangle = GU^2 = P \end{aligned} \tag{2.21}$$

The active current allows the calculation of the non-active current [Dep79][Sta00], a current component whose corresponding power was named previously as Fictitious power [Smi33][MvW91]. Fictitious power and current are defined as the part of the apparent power or the total current not contributing to the active power. When sinusoidal conditions prevail, the fictitious power comprises nothing else than the reactive power. In this thesis, the term non-active power will be used, as it has been proposed in [SW04][Sta08][IC10]. The non-active current i_x results out of subtracting the active current from the total current:

$$\begin{aligned} i_x(t) &= i(t) - i_a(t) \\ i_x(t) &= i(t) - Gu(t) \end{aligned} \tag{2.22}$$

It can be proven that the non-active current does not contain any active power:

$$\begin{aligned} \langle u, i_x \rangle &= \langle u, i - i_a \rangle \\ \langle u, i_x \rangle &= \langle u, i \rangle - \langle u, i_a \rangle = P - P = 0 \end{aligned} \tag{2.23}$$

The non-active current has the following properties:

- Non-active currents do not contribute to active power but do increase the effective value of total current.
- Non-active currents and active currents are orthogonal functions, then non-active currents and voltages are orthogonal accordingly.
- Non-active currents may have any waveform in comparison to the voltage and the active current.
- The mean value of the instantaneous powers calculated from non-active currents are always zero, resulting from the fact that non-active currents do not contain any active power at all.

In later sections, the non-active current and power will be described in detail.

2.2.3 Representation of active power in different reference frames

Depending on the analysis to be performed, power can be represented in different reference frames. In the following three representations will be briefly described: frequency domain, Clarke's $\{0, \alpha, \beta\}$ an Fortescue's $\{(0), (1), (2)\}$ coordinate systems.

2.2.3.1 Frequency domain representations

Regarding the assessment of responsibilities, many authors have proposed methods based on the analysis of frequency components of the active power, for example in [CF94] [Mus98]. Among others, active power frequency components have been employed in different ways providing criteria to determine where the disturbances come from. Not only for disturbances allocation it is useful to know the frequency domain representation of active power, but also to observe if power quality complies with distortion standards. Hence, a brief development of power in frequency components is presented.

In order to study the signals in frequency domain the Fourier transform is used. Given that only periodic signals will be taken into account, the frequency representation of the signals by means of Fourier transform yields a series of complex numbers. The Fourier transformation of a signal $u(t)$ is the following:

$$\mathbf{F}\{u(t)\} = \{\cdots \hat{U}_{-N}, \cdots, \hat{U}_{-k}, \cdots, \hat{U}_{-1}, \hat{U}_0, \hat{U}_1, \cdots, \hat{U}_{-k}, \cdots, \hat{U}_N, \cdots\} = \mathbf{U} \tag{2.24}$$

This series has positive and negative frequency components. For an arbitrary periodic signal, the Fourier series expansion has an infinite number of components, if the signal is sampled in time domain, then the Fourier series will have a finite number of frequency components [OS89], in (2.24) it is supposed that N frequency components are available.

Active power is computed from frequency components as:

$$\begin{aligned} P &= \langle u, i\rangle \\ P &= \langle \mathbf{U}, \mathbf{I}\rangle = \mathbf{I}^T\mathbf{U} = \sum_{i=-N}^{N} real\{\hat{U}_i \hat{I}_i^*\} \\ P &= \sum_{k=0}^{N} U_k I_k \cos(\alpha_k - \beta_k) = \sum_{k=0}^{N} U_k I_k \cos(\phi_k) \end{aligned} \tag{2.25}$$

where $\mathbf{I}^T$ is the transposed conjugate of the vector $\mathbf{I}$, $\hat{I}^*$ is the conjugate of $\hat{I}$. The result of (2.25) is valid for each conductor, consequently for a three-phase system the following development for the active power can be used:

$$\begin{aligned} P_\Sigma &= \sum_{i\in\{a,b,c\}} \sum_{k=0}^{N} U_{i,k} I_{i,k} \cos(\phi_{i,k}) \\ P_\Sigma &= \sum_{i\in\{a,b,c\}} P_i = P_a + P_b + P_c \end{aligned} \tag{2.26}$$

2.2.4 Representation using different coordinate systems

Taking into account the Clarke and Symmetrical components reference frames, the active power in three-phase systems can be split into components, a short explanation of those components and its equivalence to the total active power is given in the next paragraphs.

2.2.4.1 Instantaneous and active power in Clarke transformation components

If the instantaneous power is calculated as it has been done in (2.18) using the Clarke components, it yields:

$$
\begin{aligned}
p_\Sigma(t) &= \mathbf{u}_{abc}^T \mathbf{i}_{abc} \\
p_\Sigma(t) &= \begin{bmatrix} u_a & u_b & u_c \end{bmatrix} \cdot \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^T = p_a + p_b + p_c \\
p_\Sigma(t) &= \left[T_C \mathbf{u}_{0\alpha\beta} \right]^T \left[T_C \mathbf{i}_{0\alpha\beta} \right] \\
p_\Sigma(t) &= \mathbf{u}_{0\alpha\beta}^T T_C^{-1} T_C \mathbf{i}_{0\alpha\beta} \\
p_\Sigma(t) &= p_0 + p_\alpha + p_\beta \\
P_\Sigma &= P_0 + P_\alpha + P_\beta
\end{aligned}
\tag{2.27}
$$

The instantaneous power can be averaged over one or several periods for periodic signals, obtaining the Active Power components in Clarke transformed domain P_0, P_α and P_β, it may also be obtained using the inner product operator as in (2.6).

2.2.4.2 Instantaneous and active power in symmetrical components

At a specific frequency component, the power in frequency domain is calculated using (2.26). Using the transformation (2.13) gives:

$$
\begin{aligned}
P_\Sigma &= \langle \mathbf{U}_{abc}, \mathbf{I}_{abc} \rangle = real\{ \mathbf{I}_{abc}^T \mathbf{U}_{abc} \} \\
P_\Sigma &= real\{ \left[S \mathbf{I}_{012} \right]^T \left[S \mathbf{U}_{012} \right] \} \\
P_\Sigma &= real\{ \mathbf{I}_{012}^T S^* S \mathbf{U}_{012} \} \\
P_\Sigma &= real\{ \hat{U}_{(0)} \hat{I}_{(0)}^* + \hat{U}_{(1)} \hat{I}_{(1)}^* + \hat{U}_{(2)} \hat{I}_{(2)}^* \} \\
P_\Sigma &= P_{(0)} + P_{(1)} + P_{(2)}
\end{aligned}
\tag{2.28}
$$

where $\mathbf{U}_{abc} = \left[\hat{U}_a, \hat{U}_b, \hat{U}_c \right]^t$, $\mathbf{I}_{abc}^T$ is transposed conjugate row vector of $\mathbf{I}_{abc}$. The power components $P_{(0)}$, $P_{(1)}$ and $P_{(2)}$ are zero, positive and negative sequence active power components, respectively. Note that only one single frequency has been used to calculate these power components. Hence, the power components calculated in (2.28) represent only a portion of the total active power, the meaning of these components will be discussed later.

The symmetrical components analysis is a powerful tool, its usefulness has been widely demonstrated along the last decades. In the case of power quality analysis and modeling it is very handy, however its usage may add complications to the analysis because of the fact that each frequency component needs to be analyzed separately. It is also worth to mention that the transformation into symmetrical components is not the only existing approach to assess asymmetrical conditions, other options have been proposed in [Sta00][Dep04] and [FSF91].

2.3 Apparent Power

Apparent power represents a fundamental quantity to determine the power exchange capacity of an electric circuit. If this capacity is not evaluated in a suitable manner, the circuits might be over or under sized. The study of the apparent power comes from the early years of 20th century, when contributions of engineers and scientists appeared for the first time to define what apparent power means and how it should be calculated. Although the apparent power has been deeply and widely discussed, an agreement with regard to its definition has not been reached yet.

2.3.1 Definition and interpretation

Conceptual definitions for the apparent power were given by Lyon [Lyo20] and Liénard [rou28], proposing that the apparent power is a dimensioning quantity. The apparent power is equal to the maximum value of active power when the rms values of current and voltage are fixed, even if their waveforms are changed in any possible manner. For single phase circuits the apparent power can be calculated as the product of voltage and current rms values (2.7). The Cauchy-Schwarz inequality [Tim04] allows to demonstrate that the maximum active power is the apparent power, given the effective values of current and voltage.

$$\begin{aligned} |\langle u,i\rangle|^2 &= |P|^2 \leq \langle u,u\rangle\langle i,i\rangle = U^2 I^2 \\ |\langle u,i\rangle| &= |P| \leq UI = S \end{aligned} \tag{2.29}$$

Buchholz and Goodhue [Buc22] [Goo33] proposed separately mathematical definitions for the apparent power in polyphase systems, using the line voltages and currents as follows:

$$S = \sqrt{U_a^2 + U_b^2 + U_c^2}\sqrt{I_a^2 + I_b^2 + I_c^2} \tag{2.30}$$

In the sixties and seventies, the contribution of Fryze [Fry32] and Buchholz [Buc22] were taken by Manfred Depenbrock [Dep79], who elaborated an extended power theory aimed to compensate non-active current components without energy storage. His contribution remained largely unknown for the scientific community outside Germany until 1993, when the Fryze-Buchholz-Depenbrock - FBD power theory was first published in English [Dep93].

In the FBD power theory, the apparent power for single phase systems is defined as the product of the rms values of current and voltage, for polyphase systems the collective values of voltage and currents (2.9) are used, as follows:

$$\begin{aligned} S_\Sigma^2 &= \langle \mathbf{u}_0, \mathbf{u}_0\rangle\langle \mathbf{i}, \mathbf{i}\rangle = U_\Sigma^2 I_\Sigma^2 \\ S_\Sigma &= U_\Sigma I_\Sigma \end{aligned} \tag{2.31}$$

The definitions presented previously allow to define the apparent power (2.31) and to demonstrate that it represents the maximal active power to be delivered (or generated), given the collective values of voltages and currents. In (2.19) the total active power was defined resorting to the inner product of the zero sum quantities $\mathbf{u}_0$ and $\mathbf{i}$. Analogously, it was proven in (2.29), that the apparent power is the maximal active power. For polyphase systems, it can be shown that the apparent power (2.31) is the maximal active power given the collectives quantities $\mathbf{u}_0$ and $\mathbf{i}$ as follows:

$$\begin{aligned} |\langle \mathbf{u}_0, \mathbf{i} \rangle|^2 = |P_\Sigma|^2 \leq \langle \mathbf{u}_0, \mathbf{u}_0 \rangle \langle \mathbf{i}, \mathbf{i} \rangle = U_\Sigma^2 I_\Sigma^2 \\ |\langle \mathbf{u}_0, \mathbf{i} \rangle| = |P_\Sigma| \leq U_\Sigma I_\Sigma = S_\Sigma \end{aligned} \tag{2.32}$$

The equality in (2.29) and (2.32) can be reached if and only if currents and voltage are proportional by a constant value. As it has been shown in [Sta00][Sta08], this condition is fulfilled when a linear resistive load is fed. An illustrative example was presented In Chapter 1. Equations (2.31) and (2.32) show the usefulness of the joint usage of zero sum quantities and the inner product. They provide a mathematical support to define the apparent power and enable the calculation of power using a procedure, whose mathematical interpretation is widely accepted.

Another definition of apparent power was proposed by the Working Group on Non-sinusoidal situations of IEEE, led by Alexander Emanuel. Some papers describe this proposal [Ema98][Wil04] and [WGE05]. In 2000 the IEEE 1459 standard was first published and recently updated [IC10].

In 1935 a document containing the definitions of power quantities was published [CS35], containing all the at that time available knowledge regarding electric power. With regard to apparent power, some properties were listed:

- It does not depend on which terminal or point is employed to measure voltages.
- Apparent power is equal to the maximum active power that can exist given the voltages and currents. Hence, it is directly related to the size of the required equipment, the generating and transmitting losses.
- The maximal active power can be determined regardless of the presence of reactive power, waveform distortion or unbalanced conditions.

In [CS35] other properties were proposed, currently they have been revised and some have been dropped. For the aim of this presentation they are not of relevance.

The second property has been mentioned as the conceptual definition of apparent power some paragraphs before, with a slight detail mentioned here. The apparent power has a relationship with the losses of the systems a customer is connected to. This characteristic of the apparent power is specially useful for design purposes. The losses are related to the rms values of line currents, including the neutral conductor, and to the rms values of line-to-line and line-to-neutral voltages. All these properties are accomplished by the apparent power definition of the standards DIN 40110-1 and 40110-2 [DIfN94][DIfN96].

The apparent power definition contained in [IC10] has been named **Effective Power** and takes into account the previously mentioned properties. Its definition requires the previous definition of the so called **effective** voltage and current. Effective voltage or current in the context of three-phase circuits should not be confused with rms value of a voltage or current, although they have a similar meaning. Effective power claims to include the effect on the electric losses of non-equal line impedances and the presence of voltage or current zero sequence components as well.

$$\begin{gathered}
I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2 + \rho I_n^2}{3}} = \sqrt{\left(I_{(1)}\right)^2 + \left(I_{(2)}\right)^2 + (1+3\rho)\left(I_{(0)}\right)^2} \\
U_e = \sqrt{\frac{3\left(U_a^2 + U_b^2 + U_c^2\right) + \xi\left(U_{ab}^2 + U_{bc}^2 + U_{ca}^2\right)}{9(1+\xi)}} = \sqrt{\left(U_{(1)}\right)^2 + \left(U_{(2)}\right)^2 + \frac{\left(I_{(0)}\right)^2}{1+\xi}} \\
S_e = 3U_e I_e
\end{gathered} \tag{2.33}$$

where $\rho = r_n/r$ is the ration to neutral line resistance to phase line resistance, I_e and U_e are the effective current and voltage. ξ is a parameter with values from zero to infinite, depending on the system configuration, if $\xi = 3$, (2.31) and (2.33) are equivalent. The effective power can be expressed in terms of the symmetrical components, as it is depicted on (2.33), of course a very detailed knowledge of the system structure is demanded.

The IEEE Standard 1459 claims to account for zero sequence component easily, comprising and attractive advantage for its usage. However, if any conductor different to the neutral is selected as reference, the effective voltage is strongly affected. Consequently, the apparent power is affected as well. Therefore, the effective power does not accomplish the property of not depending on which conductor is selected as reference, making the definition (2.33) weaker in comparison to (2.31). Although the IEEE standard 1459 represents an important contribution and moves forward the global knowledge on electric power, its correctness and global utilization remains under discussion yet.

2.3.2 Orthogonal current decomposition and power components

In the last section, two current components were introduced: active i_a (2.20) and non-active i_x (2.22) current components. Each component has specific properties, the orthogonality allows the decomposition of the total current rms value, given that $\langle i_a, i_x \rangle = 0$. In a single phase system, the rms value is calculated using (2.7). Considering the active and non-active current components, the current rms value looks like:

$$\begin{aligned}
I^2 &= \langle i, i \rangle \\
I^2 &= \langle i_a + i_x, i_a + i_x \rangle = \langle i_a, i_a \rangle + \langle i_x, i_x \rangle + \langle i_a, i_x \rangle \\
I^2 &= I_a^2 + I_x^2
\end{aligned} \tag{2.34}$$

Using the Cauchy-Schwarz inequality (2.29), it can be seen that the norm of the active power can be calculated as:

$$|P| = |\langle u, i_a \rangle| \leq U I_a = U(GU) = GU^2 = P \tag{2.35}$$

The apparent power has been defined according to (2.29) and (2.31). Now, using (2.34) yields:

$$\begin{aligned} S^2 &= U^2 I^2 \\ S^2 &= U^2 (I_a^2 + I_x^2) \\ S^2 &= (U I_a)^2 + (U I_x)^2 \\ S^2 &= P^2 + Q_x^2 \\ S &= \sqrt{P^2 + Q_x^2} \end{aligned} \tag{2.36}$$

The power quantity Q_x is the non-active power, it has been defined in [Fry32] [Dep79] and [Sta00]. It has been named in different ways in the last 80 years. This power quantifies the part of the apparent not being used for energy exchange. The non-active power can be attributed to several phenomena and will be described in detail in the subsequent sections.

2.3.3 Power factor

Two more definitions of apparent power were proposed in the twenties. A discussion was proposed on how the power factor oughted to be calculated in polyphase systems [rosjc20], for this calculation the apparent power must be calculated too, for this purpose two options were proposed:

1. Arithmetic apparent power. The volt-amperes or each phase must be arithmetical added, $S_A = U_a I_a + U_b I_b + U_c I_c = S_a + S_b + S_c$, yielding the polyphase volt-amperes, i.e., the apparent power.
2. Vector apparent power. The total active and reactive powers must be root mean square $S_V = \sqrt{P^2 + Q^2}$.

where U_a and I_a are the rms values of the line to neutral voltage and line current of the a phase conductor, P is the total active power and Q the total reactive power.

These definitions were discussed [Sil20][Lin20][Hol20], motivating decisive contributions like the apparent power definition of Lyon [Lyo20]. Subsequently these definitions were widely employed, being included in electric power definitions standards like [CS35] and currently [IC10]. Nowadays these definitions are still used to determine the power factor, the apparent power and to design electric systems. Arithmetic and vector power represent an important component among the fundamentals of electric circuits taught to engineering students.

The Apparent power definitions described in the preceding are equal only under the following conditions:

- Purely sinusoidal signals are present, or the waveform distortion is low.
- Voltage and current symmetry, or when the negative and zero sequence components are below certain tolerance levels.
- No reactive power is consumed or generated.

The power factor definition needs a definition of apparent power. Once active and apparent power are defined, the power factor results directly to provide information on how efficient the electric energy usage is.

Several discussions were also performed to define and calculate the power factor, contributing to define and quantify apparent power. In [rosjc20] the arithmetical and the vector apparent power were proposed to calculate the power factor. After discussing the implications of reactive power, asymmetry and waveform distortion on the these apparent definitions, it was found that arithmetical and vector apparent power did not accomplish the main requirement of the quantity, they do not represent the maximal active power given the voltage and current rms values.

As described in the previous section, the definitions proposed in the standards IEEE 1459 and DIN 40110-2 are the most suitable options to calculate the apparent power as well as the power factor.

If the apparent (2.31) and the effective (2.33) powers are taken into account ($\xi = 3$), for the most general case when asymmetry, waveform distortion and phase displacement are present, the power factor values calculated according to the above described apparent power definitions have the following relationships:

$$PF_{\Sigma} = PF_{e} \leq PF_{A} \leq PF_{V} \tag{2.37}$$

where $PF_{\Sigma} = P_{\Sigma}/S_{\Sigma}$ is the power factor calculated according to the standard DIN 40110, PF_e according to IEEE 1459, PF_A the arithmetic apparent power and PF_V the vector power. These relationships reveal that the usage of arithmetic or vector apparent power overestimate the efficiency of the system and does not show the presence of undesired power components. The power factor contains a general assessment of the energy usage efficiency, each phenomena affecting the efficiency cannot be differentiated by means of this index. The effect of each disturbance must be evaluated separately, then the affection of each disturbance on the efficiency can be calculated.

2.4 Non-active Power

Technicians and scientist in the 18th century made the first advances in identifying the electric phenomena, which do not contribute to energy exchange. The first contributions can be attributed to Maxwell and Steinmetz, among others. Great efforts were made to understand the origin and nature of non-active power components. The following physical phenomena were investigated:

- Phase displacement between voltage and current due to coils and capacitors.
- Magnetization currents in ferromagnetic coils.
- Hysteresis in ferromagnetic coils and circuits.
- Mercury Arc rectifiers.
- After the construction and usage of the first electric rotative machines, phase displacement among voltages and currents in synchronous and induction machines was also investigated.

In alternating current circuits, the presence of capacitors and inductors gave birth to the concept of Reactive Power. Reactive power represents electric energy oscillations between energy storage elements. Capacitor and coils store electric energy in electric and magnetic fields, respectively. A very good illustration of this concept can be found in [Ema90]. The presence of electric energy oscillations produces a phase displacement between voltage and current, this effect can be analyzed from two viewpoints:

- If the rms values of voltage and current remain unchanged, the active power reduces its value up to null as long as the phase shift approaches to $\pm\pi/2$.
- If the active power delivered (absorbed) by the circuit remains unchanged, there will be not only a phase displacement but also an increase in the rms values of current and voltage.

Both perspectives reveal a relationship among the phase displacement, active power and the apparent power. Taking into account other phenomena, several years ago the presence of non-active power components caused by unbalanced circuits was identified as an undesirable condition. In contributions like [For23], it has been shown how asymmetry is capable to reduce the power exchange efficiency, among other causes the following were identified:

- Presence of double fundamental frequency components due to negative sequence asymmetrical currents or voltages.
- Presence of double fundamental frequency torque components related to the electric system, these components are able to develop a pulsating torque in rotating machinery.
- When generators feed unbalanced loads, higher excitation currents are necessary to supply the demanded energy, otherwise the rated power reduces to a lower value.
- Asymmetrical currents in armature windings of synchronous machines induce currents in the damping windings, the energy consumed by those induced currents lowers the power capacity of the machine too.

As it was mentioned above, when the power factor becomes lower the portion of the power necessary to make the active power exchange optimal is related to non-active power components. **Non-active power can be defined as the power component remaining after subtracting the active power from the apparent power**. To identify the presence of non-active components, the active components need to be identified first. Regarding stationary periodic conditions, three non active power components can be listed:

1. Power due to phase displacement
2. Power components related to waveform distortion
3. Power components caused by asymmetry

A brief description of each non-active power components is presented in the following paragraphs.

2.4.1 Phase displacement related non-active power - Reactive Power

The following paragraphs intend to illustrate the concept of reactive power under sinusoidal and non-sinusoidal conditions.

2.4.1.1 Definition and physical meaning under sinusoidal conditions

Reactive power appears in alternative current systems under the following conditions:

- Presence of energy storage devices like coils and capacitors.
- Asymmetrical feeding lines.
- Nonlinear devices like ferromagnetic coils
- Commutating devices, such as solid state power converters, rectifiers, inverters, etc.

In the case of balanced and sinusoidal electric systems, phase displacement between voltage and current is caused mainly by the presence of capacitors and coils. Electric energy is stored in these devices during a portion of the cycle and then restored to the source, the mean electric energy absorbed by or delivered to the device is always zero. Thus, the electric energy is oscillating from the source to the storage devices and then back to the source, such energy oscillation is the reactive power. In [Lyo20] an analogy is given by Lyon to illustrate what reactive power under sinusoidal conditions means:

> *(...) there is one type of circuit, viz., a constant non-reactive resistance, which will absorb more power than any other type when a given current flows through it at a given loss in electric pressure. The commercial application of this is that a consumer who has any other type of load fails to utilize the power that is placed at his disposal. He demands the use of certain capacity of electrical equipment, and then regularly in every half cycle (of voltage) he returns a portion of the energy he receives. He is in the same category as the merchant who regularly orders merchandise, and just as regularly returns a portion of it.*

In order to understand the characteristics of the reactive power, a review of the instantaneous power provides some ideas. Given the voltage applied to a single phase load $u(t) = \sqrt{2}U \sin(wt)$ and the current absorbed by the load $i(t) = \sqrt{2}I \sin(wt + \phi)$, where ϕ is the phase displacement caused by the presence of energy storage devices, the instantaneous power is:

$$\begin{aligned}
p(t) &= 2UI \sin(wt)\sin(wt+\phi) \\
p(t) &= UI\left[\cos(\phi) - \cos(2wt)\cos\phi + \sin(2wt)\sin\phi\right] \\
p(t) &= P(1-\cos(2wt)) + Q\sin(2wt) \\
p(t) &= p_p + p_q \\
P &= UI\cos(\phi), \qquad Q = UI\sin(\phi)
\end{aligned} \tag{2.38}$$

P is the mean value of $p(t)$ over a period, i.e., the active power. The instantaneous power is divided in (2.38) into two double fundamental frequency power functions, p_p and p_q with the following characteristics:

- The instantaneous power has the form displayed in Fig. 2.2 part 1. It can be seen that the instantaneous power is a double frequency function, its mean value is P, representing the active power absorbed by the load.

- The mean value of p_p is exactly P, it has no instantaneous negative values, in [Ema90] this function is called **intrinsical instantaneous power**.

- The power p_p has been calculated using the active current component $i_a(t) = P/U^2 u(t)$. It can be observed in Fig. 2.2 part 2 that i_a is proportional to u, it does not present any phase displacement either and the power p_p is always positive.

- Finally, in Fig. 2.2 part 3 the complementary part of the instantaneous power $p(t)$, the function p_q is displayed. The function p_q is computed from the voltage u and the non-active current $i_x(t) = i(t) - i_a(t)$, it is a double frequency function as well, the mean value of this power is zero and its amplitude is Q_x. For single phase sinusoidal systems, the non-active power Q_x represents the reactive power Q.

- Given that the mean values of p and p_p are the same, the active power P, the complementary power p_q, does not contribute to the active power flow.

- The relevance of having a power function with positive values only is that the power exchange has **one single direction**. Although the power presents double frequency oscillations, it flows only towards the load and never backwards.

- The complementary power has positive and negative values, which means that electric energy flows towards the load and back to the source on each cycle, yielding a zero power exchange but increasing the rms value of the current.

The previous analysis illustrates the physical meaning of reactive power under sinusoidal conditions. The reactive power describes an electric energy oscillation between energy storage devices, caused by alternating currents and voltages. Reactive power is usually an undesirable phenomenon, but often unavoidable and acceptable at reasonable cost and effort. The capacitors and coils represent intrinsic components in the electric systems, the power associated to their presence and behavior is commonly necessary to use the electric energy.

The extension of the previous analysis to poly-phase systems with sinusoidal signals is straightforward. Again, reactive power results from energy oscillations, but in poly-phase circuits there are more possible causes than in the single-phase case. In Figure 2.3 is depicted an ideal load feeding a linear set of balanced coils. No resistive elements exist, all currents are purely inductive non-active and caused by the coils, the active power exchanged is zero all the time. Voltages and currents may be expressed as the space-vectors $\underrightarrow{u}(t)$ and $\underrightarrow{i}(t)$, for this case the current lags the voltage at any time.

In Figure 2.4 the same source in shown, but feeding a power electronics based device. The device's current is $\underrightarrow{i_x}(t)$. If needed or desired, such device is able to generate a set of three-phase reactive currents. This kind of devices are able to set currents $\underrightarrow{i_{ind}}(t)$ identical to those depicted in Figure 2.3, but it can generate a set of currents in the opposite direction $\underrightarrow{i_{cap}}(t)$. The former currents would behave as inductive loads, and the latter ones

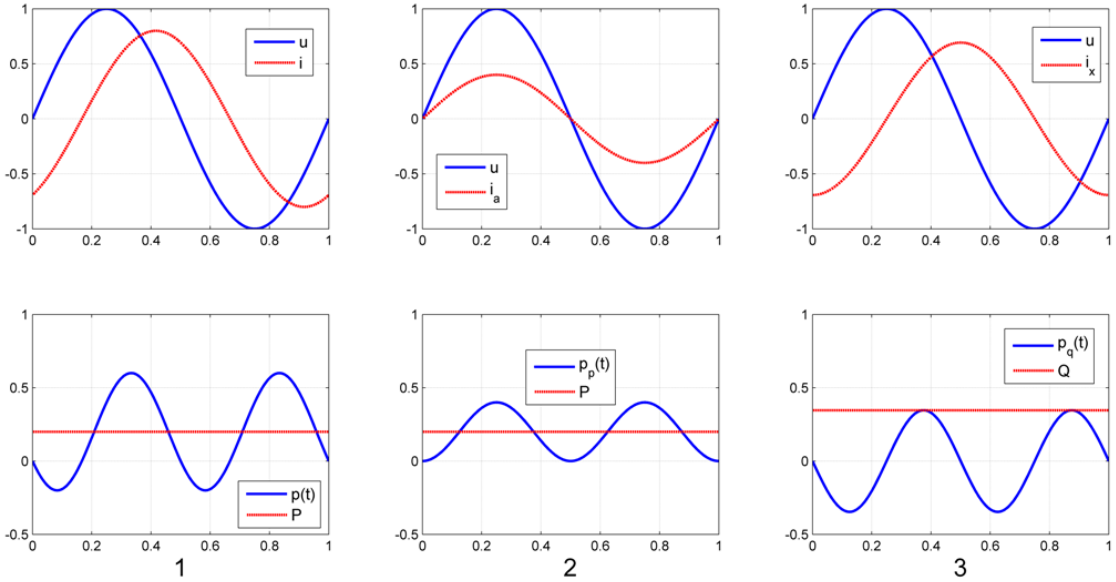


FIGURE 2.2: 1. Instantaneous power: voltage and current (up), instantaneous and active power (down). 2. Active part: voltage and active current (up), intrinsical instantaneous and active power (down). 3. Reactive part: Voltage and non-active current (up), complementary instantaneous and reactive power (down).

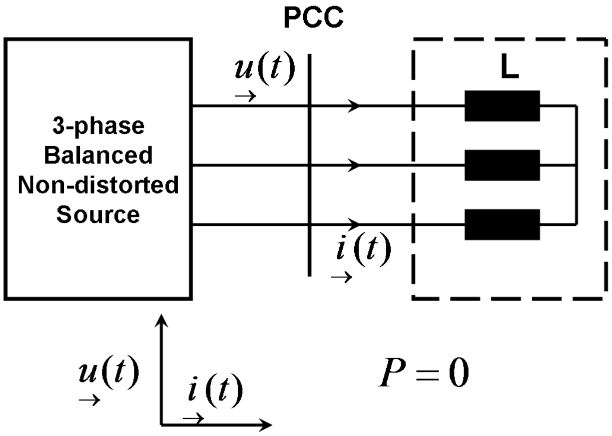


FIGURE 2.3: Reactive power caused by coils.

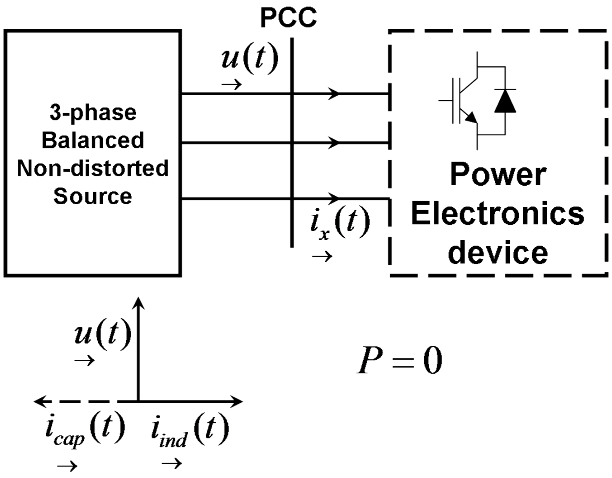


FIGURE 2.4: Reactive power caused by power electronic devices.

as capacitive loads. Thus, this device can be used to compensate any inductive load and no energy storage is required.

In single phase systems, the reactive power cannot be measured from the voltage and current signals directly, it cannot be calculated directly from the signals either. A mathematical treatment is necessary to compute the reactive power. For three-phase three-conductor systems, reactive power can be measured using active power meters in special connection, for four-conductor systems other methods must be employed. To determine the reactive power using the signals in time domain, the current or the voltage must be displaced and then operated through the inner product. In the following, the most common employed methods are listed:

1. Current or voltage displacement by means of time delay, either the voltage $u_d(t) = u(t - T/4)$ or the current $i_d(t) = i(t - T/4)$, the reactive power would result from the application of the inner product (2.6)

$$\begin{aligned} Q &= -\langle u_d, i \rangle = \langle u, i_d \rangle \\ Q &= -\frac{1}{nT} \int_{t=\tau}^{t=\tau+nT} u(t - T/4) i(t) dt = \frac{1}{nT} \int_{t=\tau}^{t=\tau+nT} u(t) i(t - T/4) dt \end{aligned} \tag{2.39}$$

   This method will be used in the next section to calculate the displaced power component Q_d, further details will be given later.

2. Current or voltage displacement by means of differentiation:

$$\begin{aligned} Q &= \frac{1}{w} \langle du/dt, i \rangle = -\frac{1}{w} \langle u, di/dt \rangle \\ Q &= \frac{1}{wnT} \int_{\tau}^{\tau+nT} \frac{du}{dt} i(t) dt = -\frac{1}{wnT} \int_{\tau}^{\tau+nT} u(t) \frac{di}{dt} dt \end{aligned} \tag{2.40}$$

3. Current or voltage displacement by means of integration, $\int udt = u_i(t)$, $\int idt = i_i(t)$

$$
\begin{aligned}
Q &= -w\langle u_i, i\rangle = w\langle u, i_i\rangle \\
Q &= -\frac{w}{nT}\int_{\tau}^{\tau+nT} u_i(t)i(t)dt = \frac{w}{nT}\int_{\tau}^{\tau+nT} u(t)i_i(t)dt
\end{aligned}
\tag{2.41}
$$

4. The aforementioned computation options are valid and equivalent exclusively under sinusoidal conditions, in such case the following applies too:

$$Q = UI\sin(\alpha - \beta) \tag{2.42}$$

where U and I are the effective values of voltage and current, $\alpha - \beta$ is the angular difference between voltage and current.

The Equation (2.42) results from the phasorial, analysis and displays the equivalence between frequency and time domain calculations of reactive power.

Regarding reactive power under sinusoidal unbalanced conditions, the symmetrical components can be used as well. Using the vectors, whose components are the voltage and current phasors, a similar expression to (2.28) can be made for the reactive power as follows:

$$
\begin{aligned}
Q_\Sigma &= imag\{\mathbf{I}_{abc}^T\mathbf{U}_{abc}\} \\
Q_\Sigma &= imag\{\left[S\mathbf{I}_{012}\right]^T\left[S\mathbf{U}_{012}\right]\} \\
Q_\Sigma &= imag\{\mathbf{I}_{012}^T S^* S\mathbf{U}_{012}\} \\
Q_\Sigma &= imag\{\hat{U}_{(0)}\hat{I}_{(0)}^* + \hat{U}_{(1)}\hat{I}_{(1)}^* + \hat{U}_{(2)}\hat{I}_{(2)}^*\} \\
Q_\Sigma &= Q_{(0)} + Q_{(1)} + Q_{(2)}
\end{aligned}
\tag{2.43}
$$

The Clarke transformation can be employed to determine the α, β and 0 components of the total reactive power, the transformation may be applied on the phasor vectors and the result will be similar. The usage of the Clarke transformation to define active and non-active power components is the base of the so called $p-q$ power theory, elaborated by Akagi et.al. [AKN83][AKN84], this power theory will not be considered along the thesis.

2.4.1.2 Reactive power under non-sinusoidal conditions

The presence of non-linear devices or distorted feeding signals has implications on the energy exchange when capacitors and coils are present. Power under non-sinusoidal conditions with regard to distorted voltages and currents has been studied deeply, one of the most renowned and discussed definition of reactive power is that proposed by Constantin Budeanu in his publication [Bud27] and recalled in the Roumanian Questionnaire, [rou28]. This definition results as an analogy to the active power under non-sinusoidal conditions defined in (2.25), yielding the following expression:

$$Q_B = \sum_{k=0}^{N} U_k I_k \sin(\phi_k) \tag{2.44}$$

This expression received several criticisms short after its publication [Lyo33]. In the seventies, other contributions were published and its usefulness was questioned again in [SZ72] and [Sha73]. More recently, new contributions were presented to reveal one more time the limitations and drawbacks of Budeanu's reactive power definition [Cza87]. The drawback of Budeanus's definition is that the series (2.44) may be zero even though a non-active current component do exists. This fact has implications in the calculation of the apparent power, power factor or in compensation when the compensating facilities or devices are programed in accordance with Budeanu's reactive power.

It is noteworthy to mention that Budeanu's definition had a wide acceptance, because it was the best method until more useful definitions were developed. It has not been recommended to employ Budeanu's reactive power nowadays. In case of the reader is interested in recent developments with regard to Budeanu's power, it is suggested to review [Wil11].

An interesting definition of reactive power was that proposed by Shepherd and Zakikhani [SZ72]. The rms value of current is decomposed into two sets of components by means of a trigonometric treatment:

$$\begin{aligned} I^2 &= \sum_{i=1}^{n} I_i^2 + \sum_{j=1}^{p} I_j^2 \\ U^2 &= \sum_{i=1}^{n} U_i^2 + \sum_{l=1}^{m} E_l^2 \\ I^2 &= \sum_{i=1}^{n} \left[I_i^2 \cos^2(\phi_i) + I_i^2 \sin^2(\phi_i) \right] + \sum_{j=1}^{p} I_j^2 \end{aligned} \tag{2.45}$$

where n is the number of harmonic components common to the voltage and the current, p is the number of harmonic components present in the current but not in the voltage, m the harmonic components present in the voltage but not in the current, ϕ_i represents the phase difference between the voltage and current harmonic components i. From (2.45), apparent power can be split into three components:

$$\begin{aligned} S^2 &= U^2 I^2 \\ S^2 &= S_R^2 + S_X^2 + S_D^2 \\ S_R^2 &= \sum_{i=1}^{n} U_i^2 \sum_{i=1}^{n} I_i^2 \cos^2(\phi_i) \neq P^2 \\ S_X^2 &= \sum_{i=1}^{n} U_i^2 \sum_{i=1}^{n} I_i^2 \sin^2(\phi_i) \\ S_D^2 &= \sum_{i=1}^{n} U_i^2 \sum_{j=1}^{p} I_j^2 + \sum_{l=1}^{m} E_l^2 \left[\sum_{i=1}^{n} I_i^2 + \sum_{j=1}^{p} I_j^2 \right] \end{aligned} \tag{2.46}$$

Upon this power definitions, a compensation procedure using only capacitors was developed. The power definitions are sound from the mathematical viewpoint, but their physical meaning is quite arguable.

Another alternative to calculate the reactive power proposed for sinusoidal systems is that presented in [DIfN94], where the voltage gets delayed a quarter of period and operated with the current or the non-active current using the inner product to yield the reactive power.

$$\begin{aligned} u_d &= u(t - T/4) \\ Q_d &= \langle u_d, i \rangle \end{aligned} \tag{2.47}$$

The operation (2.47) can be performed displacing the current in time, providing the same result with a negative value. As mentioned before, this operation is valid for non-distorted or slightly distorted systems. In the case of non-sinusoidal systems, i.e., when the whole signal's spectrum is employed, the power quantity extracted from (2.47) is called **displaced power**. The displaced power components are described as follows:

- If no even harmonics are present, the Q_d would give:

  $$Q_d = (-1) \sum_{i \in \{1,3,\cdots\}} (-1)^{(i-1)/2} Q_i$$

  where $Q_i = U_i I_i \sin(\phi_i)$

- if as even as odd harmonics are present, the Q_d would result in the following:

  $$Q_d = \sum_{j \in \{0,2,4,\cdots\}} (-1)^{i/2} P_i - \sum_{i \in \{1,3,\cdots\}} (-1)^{(i-1)/2} Q_i$$

  where $P_i = U_i I_i \cos(\phi_i)$.

The former results looks similar to the definition of Budeanu (2.44), with the terms alternated from positive to negative contributions, depending on the harmonic order. The latter contains harmonic active power components of even order. The power quantity (2.47) has been proposed for non-sinusoidal systems in [PST09] and [PST10], its usage and interpretation will be explained in subsequent chapters.

Two more contributions have been published on the analysis and computation of reactive power under non-sinusoidal conditions based on differentiation and integration of the voltages and currents. Both contributions show alternatives not only to determine the reactive power and its corresponding current, but also measurement methods. The first one is the proposal of N. L. Kusters and W. J. M. Moore [KM80], the second one is the power theory proposed by Paolo Tenti et.al. [TM04][TTTM09]. Both theories operate on voltages and currents as described in (2.40) and (2.41). Eventually these alternatives would have awaken the reader's interest to deal with reactive power, a deeper investigation of the references is suggested. The present document shall not go further concerning these alternatives.

Some final comments on reactive power. It is accepted that energy oscillations occur among capacitors, coils, and some electric machines under sinusoidal conditions. This phenomenon causes reactive power. Nevertheless, when non-sinusoidal conditions occur, the described concept of energy oscillations among energy storage devices looses its meaning completely. Non-linear conditions have effects and interact with capacitors and coils, but "reactive" components appear under non-sinusoidal conditions even when storage devices do not exist.

For this reason, the term "reactive" designates sinusoidal fundamental frequency conditions, as clearly stated in [IEC]. Under non-sinusoidal conditions, whatever is not related to active power is **non-active** power. This statement does not ignore the substantial role and significance of reactive power in the electric system. However, it assigns name and meaning to a power quantity, whose definition has to differ from "reactive", as the systems' distance from the desirable but less frequent ideal conditions grows. In this way, the term "reactive" keeps its long known and important meaning.

2.4.2 Waveform distortion related non-active power

Non linear elements are able to deform voltage and current waveforms. An electric system is said to be linear when the homogeneity and superposition principles are accomplished [KF61]. Differentiation, integration and multiplication by a real constant are linear operations. The systems considered in this chapter, when all currents and voltages are related through linear operations, can be called as linear systems. Any deviation from this behavior implies the presence of nonlinear devices.

With regard to Fourier analysis, a voltage signal has a set of frequency components. When its corresponding current has a set of frequency components with different elements, the linearity properties are not accomplished. Different frequency components in voltage and current make the waveforms to adopt different shapes, such situation is what in this section is named waveform distortion. The main cause for the presence of non-linearities in electric systems is the usage of non-linear devices like:

- Saturable ferromagnetic coils
- Electric arc based equipment, like lamps, furnaces, etc.
- Welding equipment
- Power electronics based converters and controlled sources
- Commutating devices like electronic switches, dimmers
- Solid state compensating facilities

among many others. Electric machines are constructed and designed to reduce as much as possible waveform distortion. Nevertheless, a minimal voltage and current distortion is expected and tolerated. Non-linear and distorted waveforms have been studied a long ago by several electricians like Charles P. Steinmetz [Ste94][Ste05]. Afterwards, Constantin Budeanu, among others, stated a reference point to analyze non-active components associated to waveform deviations [Bud27][rou28].

In order to facilitate the analysis of power quantities produced by a nonlinear load, an extension of the previously presented orthogonal current decomposition previously is presented. Additionally, an illustrative example will help to reveal some characteristics of power components when waveform distortion is present.

2.4.2.1 Orthogonal current decomposition revisited

Previously active i_a and non-active i_x currents were defined in (2.20) and (2.22). In (2.34) the rms current value is split into the orthogonal components, yielding a power decomposition (2.36). This decomposition includes the active power P and the so called non-active power Q_x. In (2.47) the displaced power Q_d was defined.

The orthogonal decomposition procedure will be revisited, in order to summarize and define the remaining necessary power components to be used.

1. Active and apparent power

$$S = UI \qquad P = \langle u, i \rangle$$

2. Active conductance, active current and non-active current

$$G = \frac{P}{U^2} \qquad i_a = Gu \qquad i_x = i - i_a$$

3. Non-active power

$$Q_x = UI_x$$

4. Displaced power. The revisited orthogonal decomposition will employ from now on the non-active current i_x to calculate the displaced power, the result holds exactly the same value.

$$u_d = u(t - T/4) \qquad Q_d = \langle u_d, i_x \rangle \tag{2.48}$$

5. From displaced power, the displaced susceptance B_d is extracted. This quantity and the displaced voltage u_d allow the definition of the displaced current.

$$\begin{aligned} B_d &= Q_d/U_d^2 = Q_d/U^2 \\ i_{Qd} &= B_d u_d \end{aligned} \tag{2.49}$$

   The displaced power and current were described previously. Its meaning was explained, it was clarified that it represents the reactive power under sinusoidal conditions, exclusively. This quantity is one orthogonal component, it is not the only possible power to be defined. This component has the same waveform of the voltage, but a quarter period delayed. The displaced current is a part of the non-active current, the remaining current component is the so called **distorted current**.

6. Distorted current. It is the last current orthogonal component to be extracted in single phase systems, it must be calculated as follows:

$$\begin{aligned} i_D &= i_x - i_{Qd} \\ i_D &= i_x - B_d u_d \\ i_x &= i_{Qd} + i_D \end{aligned} \tag{2.50}$$

The distorted current component does not have the same waveform of the voltage, does not contain any active power either. Constantin Budeanu proposed a quantity called distortion current and power [Bud27]. It was derived from the powers under non-sinusoidal, not from a current decomposition as it is proposed here. The distorted power is based on the current decomposition proposed by Manfred Depenbrock [Dep79][Dep93].

7. Complete current decomposition for single phase systems. Three current orthogonal components have been described, their rms values and corresponding powers are described in the next equations:

$$\begin{aligned} i &= i_a + i_x \\ i_x &= i_{Qd} + i_D \\ i &= i_a + i_Q d + i_D \\ I^2 &= I_a^2 + I_{Qd}^2 + I_D^2 \\ S^2 &= (UI_a)^2 + (UI_{Qd})^2 + (UI_D)^2 \\ S^2 &= P^2 + Q_d^2 + Q_D^2 \end{aligned} \tag{2.51}$$

This current decomposition will be extended to poly-phase systems in a later section.

2.4.2.2 Illustrative example of power under waveform distortion

Let us suppose that a purely resistive load is fed by a single phase sinusoidal voltage source, the load current is controlled by a triac in two operative conditions:

CASE A The load absorbs current from any voltage peak until the next voltage zero-crossing.

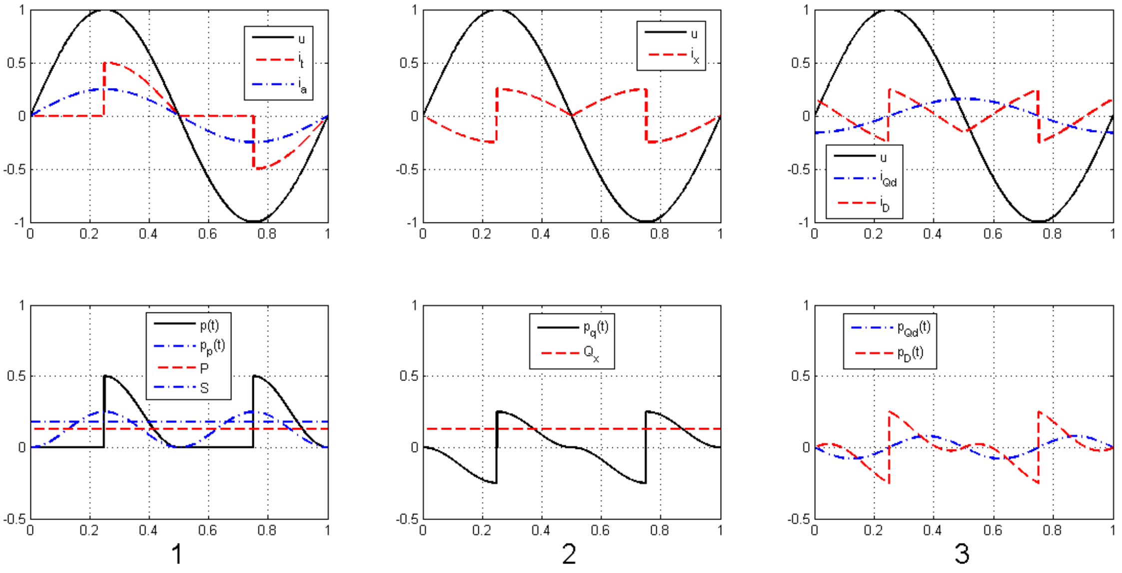
CASE B The load absorbs current from any voltage zero-crossing until the next voltage peak.

The triac is considered as an ideal switch and can operate at any possible condition of voltage and current. In the Figures 2.5 and 2.6 the waveforms are displayed on the left columns at the upper positions. The active current components are also displayed.

For **CASE A** and **B** the active currents are the same because the voltage waveform and the active power are the same. The lower positions of column 1 in Figures 2.5 and 2.6 show the instantaneous power functions for each case, the intrinsical instantaneous power, calculated from the active current and the voltage. Two more traces are displayed too, the active and the apparent power, which for both cases are the same as well.

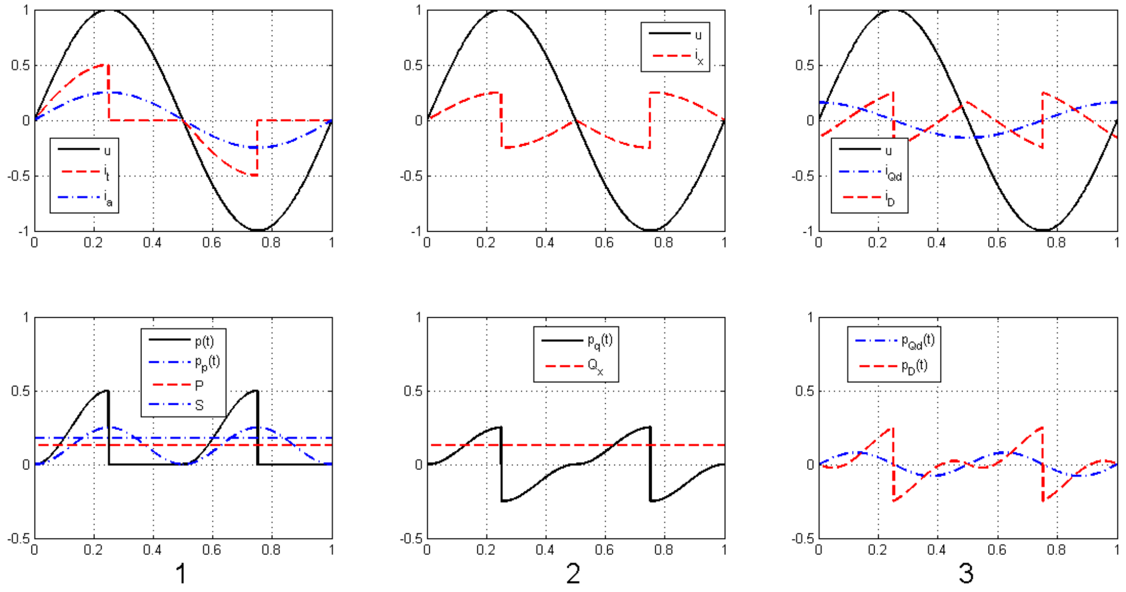
The Figures 2.5 and 2.6 on the columns marked with 2 show the non-active currents and their corresponding instantaneous powers. Both cases have the same waveform and magnitude, but the non-active current of **CASE B** is the negative of **CASE A** non-active current, so as the instantaneous power of each case differ in the sign. Non-active powers are the same for both cases.

Figures 2.5 and 2.6 on the columns marked as 3 show that displaced currents have the same waveform but multiplied times minus one. Then, the magnitudes of displaced power



1 2 3

FIGURE 2.5: 1. Voltage, current and instantaneous power, 2.Non-active current and power, 3. Displaced and distorted currents and powers



1 2 3

FIGURE 2.6: 1. Voltage, current and instantaneous power, 2.Non-active current and power, 3. Displaced and distorted currents and powers

in both cases are the same but with different sign. The procedure described in (2.39) was utilized to calculate the reactive power, therefore the displaced current and power might be associated to reactive currents and power inside the load's current. Nevertheless, in the cases presented in the example, no energy storage devices have been employed, such elements could be able to interchange energy between the source and the load. Hence some question arise:

Question 1

Why is there a *reactive alike* current and power component in a circuit, where neither capacitors nor inductors exist?

Question 2

If a linear circuit had been taken into account, and coils or capacitor would be present, the displaced power sign would reveal the nature of the demanded reactive power: positive for inductive reactive power and negative for capacitve one. In the examples, powers calculated from (2.49) do exist, have the same magnitude but different sign. Should it be said that capacitive or inductive reactive power is being delivered to the load?

Regarding the distorted current, the Figures 2.5 and 2.6 show that current components have a completely different waveform from the voltage, and their instantaneous power have zero mean value, just like the displaced currents. It is noteworthy that instantaneous power computed from distorted currents do dispose of energy oscillations with zero mean value, although no energy storage device is present. With the aim of providing lights to clarify the questions formulated above, some properties of the non-active currents are listed:

- Displaced currents have the same waveform as the voltage, but time delayed a quarter of period.
- Distorted currents have any waveform different to the voltage waveform.
- Displaced and distorted currents pertain to the non-active current, then they are orthogonal to the voltage and to the active current.
- Displaced and distorted currents are orthogonal to each other.
- As non-active currents, displaced and distorted currents do not contribute to active power.

Non-linear elements and signals are capable to disturb voltages and currents in a such a manner, that current components, which do not contribute to active power exchange, appear. Current components with similar characteristics to currents absorbed by coils and capacitors in sinusoidal systems (reactive currents) appear as well, but there are no energy storage devices in the circuit. Non-active current components contribute to enlarge the effective value of current, thus the apparent power increases correspondingly, therefore the non-linear devices able to produce distorted currents contribute to decrease the energy exchange efficiency.

From the analysis of the example's signals, the questions formulated above could be answered as follows:

Answer to Question 1

Non-linear devices are capable to generate energy oscillations between the device itself and its energy source. It does not mean that the non-linear device is able to store energy, as coils and capacitors do, it means that such oscillation belong to its natural behavior. Non-sinusoidal systems extend the situation a little further, increasing the possibilities of energy oscillations related to additional frequency components.

Answer to Question 2

The well known energy oscillations typical in coils and capacitors in sinusoidal systems, whose power is the reactive power, do not have the same meaning under non-linear and non-sinusoidal conditions. Energy oscillations can emerge in non-linear systems, regardless of the presence or absence of coils and capacitors. Therefore, the same meaning of sinusoidal systems' reactive power cannot be extended to non-linear non sinusoidal systems.

2.4.2.3 Other definitions of non-active power

Non-active power components can be synthesized from power quantities too. The Budeanu's reactive power (2.44) was used to determine a decomposition of power for non-sinusoidal voltages and currents, in the same manner as it has been developed the distorted current component and power (2.50), Budeanu defined the Distortion power [Bud27][rou28] as:

$$\begin{aligned} D_B &= \sqrt{S^2 - P^2 - Q_B^2} \\ S^2 &= P^2 + Q_B^2 + D_B^2 \end{aligned} \tag{2.52}$$

Several studies have been carried out to determine a physical meaning of Budeanu's distortion power and distorted components in non-sinusoidal cases [SvdW88][Ema90][Cza92]. In the standard IEEE 1459 [IC10] two power quantities related to waveform distortion are considered, the non-fundamental power and the non-active power. Non-active power is defined in the same manner as (2.36), but the effective apparent power is used instead of the apparent power. Non-fundamental power S_{eN} represents the portion of the apparent power not caused by fundamental frequency power components:

$$\begin{aligned} S_{eN}^2 &= S_e^2 - S_{e1}^2 \\ S_{eN}^2 &= D_{eI}^2 + D_{eU}^2 + S_{eH}^2 \end{aligned} \tag{2.53}$$

where S_{e1} is the fundamental effective power, D_{eI}, D_{eU} are the current and voltage distortion powers and S_{eH} is the harmonic distortion power.

Symmetrical components transformation may be applied to any frequency component. In [SvWC96] an elegant formulation of the transformation matrix (2.13) extended to any harmonic frequency component of order k is presented:

$$\begin{bmatrix} \hat{F}_0(k) \\ \hat{F}_1(k) \\ \hat{F}_2(k) \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \hat{h}(k) & \hat{h}(k)^2 \\ 1 & \hat{h}(k)^2 & \hat{h}(k) \end{bmatrix} \begin{bmatrix} \hat{F}_a(k) \\ \hat{F}_b(k) \\ \hat{F}_c(k) \end{bmatrix} \tag{2.54}$$

where F_k is a voltage or current phasor, $\hat{h}(k) = e^{\frac{j2\pi k}{3}}$.

2.4.3 Asymmetry and Unbalance related non-active power

Power can be absorbed or generated asymmetrically. There exist currently several alternatives to determine and quantify how much power is being spent on asymmetry. Two perspectives have gained acceptance in the last decades, the IEEE 1459 [IC10] and the DIN 40110 [DIfN96].

The Standard IEEE1459 relies on the application of the symmetrical coordinate transformation, presented previously. Its application revealed that the active power may be decomposed in zero, positive and negative sequence components, whose sum equals the total active power [For18]. Nevertheless, negative and zero sequence power components cannot be directly transformed in useful work, then they should be considered as undesired components. The symmetrical components are the most widely used tool to analyze unbalance in electric systems. Several standards use it, for instance: the IEEE 1459 [Ema04][WGE05][IC10], the IEC Standard 61000-4-30 [IEC08] on power quality evaluation methods and the European Standard EN50160 on reference values for voltage quality disturbances [CEN00].

In this section, two methodologies for assessing asymmetry are presented. The first one is the IEEE Standard 1459, the second is the German standard DIN 40110-2. The second methodology will provide a complement to the orthogonal decomposition proposed previously. Some alternative methods to deal with unbalance are presented too.

2.4.3.1 Asymmetry according to IEEE 1459

The standard IEEE 1459 proposes a method to calculate how much power is related to unbalance, this power component is extracted from a development in frequency components of the effective current and voltage (2.33) and from the application of the symmetrical components on the fundamental effective power.

$$\begin{aligned} U_e^2 &= U_{e1}^2 + U_{eH}^2 \\ I_e &= I_{e1}^2 + I_{eH}^2 \\ S_e^2 &= S_{e1}^2 + S_{eN}^2 \end{aligned} \tag{2.55}$$

where the subindex 1 means the fundamental frequency component, H and N mean non-fundamental frequency components. Although in [IC10] special emphasis is made on harmonic waveform distortion, interharmonic components may also be accounted. The fundamental equivalent power S_{e1}may be split into two components, the positive sequence apparent power S_1^+ and the unbalance power S_{U1}, which result from:

$$\begin{aligned} S_1^+ &= \sqrt{\left(P_1^+\right)^2 + \left(Q_1^+\right)^2} \\ P_1^+ &= 3U_1^+ I_1^+ \cos(\theta_1^+) \\ Q_1^+ &= 3U_1^+ I_1^+ \sin(\theta_1^+) \\ S_{U1} &= \sqrt{S_{e1}^2 - \left(S_1^+\right)^2} \end{aligned} \tag{2.56}$$

The unbalance power (2.56) can be developed in the negative and zero sequence components of voltage and currents, however it is clear that the whole information on the asymmetry of the fundamental frequency component, regarding Fortescue's symmetrical components, is included in S_{U1}.

The IEEE 1459 approach for quantifying the amount of power spent on asymmetry is based on the the philosophy that the only desirable power components are the fundamental frequency positive sequence active ones. Any other component, it might be reactive, unbalanced or distorted, is unwanted and should be reduced to a minimum or compensated by a suitable mean.

It is worth to note that the unbalance power has been computed from the voltage and current phasors at the fundamental frequency. Certainly, these components can be represented in time domain. However, such functions can have difficulties to be used in compensating devices, because the time domain representation of positive and negative sequence components has complex values in time domain [FSF91][Paa00]. In order to compensate any undesired power component, it is decisive to represent them by means of a time domain current component, which might be suppressed or compensated, improving the efficiency of energy exchange and complying the power quality requirements. The IEEE 1459 provides a measure of imbalance but it does not provide any current component linked to asymmetry.

2.4.3.2 Asymmetry according to DIN 40110-2

The german standard DIN 40110 [DIfN96], which is based on the FBD Power Theory proposed by Depenbrock [Dep79], another approach to analyze asymmetry is given. In contrast to the IEEE 1459, in the DIN 40110 standard a different philosophy is employed. An electric circuit is said to operate symmetrically if the following conditions are fulfilled:

- The total active power is distributed among all conductors proportionally to each conductor's squared rms value.
- All phase rms values are the same.

Any deviation from the previous conditions can be easily identified and measured. Such deviations are considered as unsymmetrical power components. The unbalanced current and power components resorts to the zero sum quantities, collective values and the total active power, described in (2.9) and (2.19), from these values the collective and phase conductances are extracted as follows:

$$\begin{aligned} G &= P_\Sigma / U_\Sigma^2 \\ G_\mu &= P_\mu / U_{\mu 0}^2 \end{aligned} \tag{2.57}$$

The active phase conductances allow the definition of the active $i_{\mu a}$, proportional $i_{\mu\|}$and active unbalanced $i_{\mu au}$ current components:

$$\begin{aligned} i_{\mu a} &= G u_{\mu 0} \\ i_{\mu\|} &= G_\mu u_{\mu 0} = i_{\mu a} + i_{\mu au} \\ i_{\mu x} &= i_\mu - G u_{\mu 0} \\ i_{\mu\perp} &= i_\mu - G_\mu u_{\mu 0} = i_{\mu x} - i_{\mu au} \\ i_{\mu x} &= i_{\mu au} + i_{\mu\perp} \\ i_{\mu au} &= i_{\mu\|} - i_{\mu a} = \big(G_\mu - G\big) u_{\mu 0} = \Delta G_\mu u_{\mu 0} \end{aligned} \tag{2.58}$$

The quantities $i_{\mu\|}$ and $i_{\mu\perp}$ are defined in [DIfN94] and are called proportional and orthogonal components, respectively. The non-active and the orthogonal components do not hold active power, both are orthogonal to the active current, consequently both components are orthogonal to the voltage as well. The difference between non-active and orthogonal components is that orthogonal component does not contain any information about active power related asymmetry, the non-active component does contain that information.

The vectorial formulation of the current components of (2.58) using (2.8) and (2.57) are:

$$\begin{aligned} \mathbf{i}_a &= G\mathbf{u}_0 \\ \mathbf{i}_x &= \mathbf{i} - \mathbf{i}_a \\ \mathbf{i}_\| &= [G_\mu]\mathbf{u}_0 \\ \mathbf{i}_{au} &= \mathbf{i}_\| - \mathbf{i}_a \\ \mathbf{i}_\perp &= \mathbf{i}_x - \mathbf{i}_{au} \end{aligned} \tag{2.59}$$

where $[G_\mu]$ is a diagonal matrix with the phase active conductances. From (2.57) and (2.58) it can be followed that the total power related to the active $\mathbf{i}_a$ and the proportional $\mathbf{i}_\|$ currents equals the total power (2.19).Then, the total power of the active unbalance currents $\mathbf{i}_{au}$ is zero. The subtraction of the active current from the proportional current yields the active unbalance current. This component is equivalent to the calculation of the difference between the phase conductance G_μ and the active conductance G. If the active power were equally distributed among all phase conductors, and the effective values of all phase voltage were the same, $G_\mu - G$ would be zero. If any asymmetrical behavior exists, such differences do not vanish.

The unsymmetrical conductances ΔG_μ may adopt as positive as negative values. If each conductor's current is observed in detail, negative active power related to the active unbalanced current can come out, specially for agents absorbing power. This apparent paradox is not unexpected. The unbalance criteria of the standard DIN 40110 says that the active power must be uniformly divided and the phase rms voltages must be equal as well, any deviation implies asymmetry. If the asymmetry is assessed regarding active power, the active and proportional currents contain the whole active power, the phase powers of the unbalanced active currents always sum up to null, it does not matter if one or more of them is negative. The active unbalanced current is orthogonal to the voltage and the active current.

So far only active unbalanced components have been considered. Asymmetry of displaced current components can be studied in the same way. As it was described before, orthogonal currents does not contain any active power and does not have any information about active power asymmetry either. This component will be used to analyse the asymmetry related to displaced components. Total $Q_{\Sigma d}$ and phase $Q_{\mu d}$ displaced powers must be calculated as follows, allowing the calculation of displaced B_d and phase $B_{\mu d}$ susceptances, respectively:

$$\begin{aligned} Q_{\Sigma d} &= \langle \mathbf{u}_{0d}, \mathbf{i}_\perp \rangle & \qquad Q_{\mu d} &= \langle u_{\mu d}, i_{\mu\perp} \rangle \\ B_d &= Q_{\Sigma d}/U_\Sigma^2 & \qquad B_{\mu d} &= Q_{\mu d}/U_\mu^2 \end{aligned} \tag{2.60}$$

Total and Phase displaced susceptances allow a decomposition of the orthogonal current, analog to the decomposition made on the active current using (2.58), yielding the displaced $i_{\mu Qd}$, asymmetrical displaced $i_{\mu Qu}$ and distorted $i_{\mu D}$ current components (2.61):

$$\begin{aligned} i_{\mu Qd} &= B_d u_{\mu d} \qquad i_{\mu Q||} = B_{\mu d} u_{\mu d} \\ i_{\mu\perp} &= i_{\mu Q||} + i_{\mu D} = i_{\mu Qd} + i_{\mu Qu} + i_{\mu D} \\ i_{\mu Qu} &= i_{\mu Qd||} - i_{\mu Qd} \\ i_{\mu D} &= i_{\mu\perp} - i_{\mu Qd} \end{aligned} \tag{2.61}$$

The vectorial representation of the previous decomposition is:

$$\begin{aligned} \mathbf{i}_{Qd} &= B_d \mathbf{u}_d \qquad \mathbf{i}_{Q||} = [B_{\mu d}]\mathbf{u}_d \\ \mathbf{i}_{\perp} &= \mathbf{i}_{Q||} + \mathbf{i}_D = \mathbf{i}_{Qd} + \mathbf{i}_{Qu} + \mathbf{i}_D \\ \mathbf{i}_{Qu} &= \mathbf{i}_{Qd||} - \mathbf{i}_{Qd} \\ \mathbf{i}_{\mu D} &= \mathbf{i}_{\perp} - \mathbf{i}_{Qd} \end{aligned} \tag{2.62}$$

The rms values of the currents defined in (2.58) and (2.61) can be used to compute a power components. In comparison with the IEEE 1459 unbalance assessment procedure presented above, the DIN 40110 method provides not only a representation of the asymmetry in terms of power quantities, but also a current in time domain, which might be compensated by a suitable mean.

2.4.3.3 Orthogonal current decomposition for poly-phase systems

Every current component defined for single phase systems can be extended to poly-phase straightforward. Those definitions were employed in (2.58) and (2.61) to define current components related to asymmetry. The orthogonal current decomposition for poly-phase systems is listed in the following.

1. Active and apparent power

$$S_\Sigma = U_\Sigma I_\Sigma \qquad P_\Sigma = \langle \mathbf{u}_0, \mathbf{i} \rangle$$

2. Active conductance, active and active unbalanced current components

$$G = \frac{P_\Sigma}{U_\Sigma^2} \qquad \mathbf{i}_a = G\mathbf{u}_0$$

$$G_\mu = \frac{P_\mu}{U_\mu^2} \qquad \mathbf{i}_{au} = \mathbf{i}_{||} - \mathbf{i}_a = [G_\mu]\mathbf{u}_0 - \mathbf{i}_a$$

$$P_\Sigma = \langle \mathbf{u}_0, \mathbf{i}_a \rangle \qquad Q_{\Sigma au} = U_\Sigma I_{\Sigma au}$$

3. Non-active and orthogonal current components

$$\mathbf{i}_x = \mathbf{i} - \mathbf{i}_a \qquad \mathbf{i}_\perp = \mathbf{i}_x - \mathbf{i}_{au}$$

$$Q_{\Sigma x} = U_\Sigma I_{\Sigma x} \qquad Q_{\Sigma\perp} = U_\Sigma I_{\Sigma\perp}$$

4. Displaced susceptance, displaced and displaced unbalanced current components.

$$\mathbf{u}_d = \mathbf{u}_0(t - T/4) \qquad Q_{\Sigma d} = \langle \mathbf{u}_d, \mathbf{i}_x \rangle = \langle \mathbf{u}_d, \mathbf{i}_\perp \rangle$$

$$B_d = \frac{Q_{\Sigma d}}{U_\Sigma^2} \qquad \mathbf{i}_{Qd} = B_d \mathbf{u}_d$$

$$B_{\mu d} = \frac{Q_d}{U_\mu^2} \qquad \mathbf{i}_{Qu} = \mathbf{i}_{Q||} - \mathbf{i}_{Qd} = [B_\mu]\mathbf{u}_0 - \mathbf{i}_{Qd}$$

$$Q_{\Sigma d} = U_\Sigma I_{\Sigma Qd} \qquad Q_{\Sigma Qu} = U_\Sigma I_{\Sigma Qu}$$

5. Distorted current.

$$\mathbf{i}_D = \mathbf{i}_\perp - \mathbf{i}_{Qd} - \mathbf{i}_{Qu} = \mathbf{i}_x - \mathbf{i}_{au} - \mathbf{i}_{Qd} - \mathbf{i}_{Qu}$$

$$Q_{\Sigma D} = U_\Sigma I_{\Sigma D}$$

6. Complete current decomposition for poly phase systems. Three current orthogonal components have been described, their rms values and corresponding powers are described in the next equations:

$$\begin{aligned}
\mathbf{i} &= \mathbf{i}_a + \mathbf{i}_x \\
\mathbf{i}_x &= \mathbf{i}_{au} + \mathbf{i}_{Qd} + \mathbf{i}_{Qu} + \mathbf{i}_D \\
\mathbf{i} &= \mathbf{i}_a + \mathbf{i}_{au} + \mathbf{i}_{Qd} + \mathbf{i}_{Qu} + \mathbf{i}_D \\
I^2 &= I_a^2 + I_{Qd}^2 + I_D^2 \\
S^2 &= (UI_a)^2 + (UI_{au})^2 + (UI_{Qd})^2 + (UI_{Qu})^2 + (UI_D)^2 \\
S^2 &= P_\Sigma^2 + Q_{\Sigma au} + Q_{\Sigma d}^2 + Q_{\Sigma Qu} + Q_{\Sigma D}^2
\end{aligned} \tag{2.63}$$

2.4.3.4 Other approaches to assess asymmetry

In addition to the two asymmetry analysis alternatives presented in the preceding paragraphs, two more methods will be briefly presented.

A voltage and current set can be expressed in terms of hyperspace vectors [Sta00], this representation has not been presented and will not be used along the thesis, it will be mentioned only in this section. The hyperspace vectors are a set of orthonormal functions aimed to represent any current or voltage system, like (2.1) and (2.2). The representation of voltages and currents by means of hyperspace vector allows the determination of generalized symmetrical components, proposed by Manfred Depenbrock and described in [Dep04].

The Depenbrock's approach to analyse the generalized symmetrical components uses the rms values only, that might be extracted from zero sum quantities. Positive, negative and zero sequence generalized components must be calculated as follows. First, the following effective values ought to be determined:

$$\begin{aligned} U_{\Yup} &= \sqrt{\frac{1}{3}\left[U_{1N}^2 + U_{2N}^2 + U_{3N}^2\right]} \\ U_{\Delta} &= \sqrt{\frac{1}{3}\left[U_{12}^2 + U_{23}^2 + U_{31}^2\right]} \\ A_{\Delta}^2 &= S\left[S - U_{12}\right]\left[S - U_{23}\right]\left[S - U_{31}\right] \\ 2S &= U_{12} + U_{23} + U_{31} \end{aligned} \tag{2.64}$$

where U_{1N} is the phase-to-neutral effective voltage value of conductor 1, U_{23} is the phase-to-phase effective value of the voltage difference between phase 2 and 3.

$$U_{\Delta}^{+} = \sqrt{U_{\Delta}^2 - (U_{\Delta}^{-})^2} \tag{2.65}$$

$$U_{\Delta}^{-} = \sqrt{\frac{1}{2}U_{\Delta}^2 - \frac{2}{\sqrt{3}}A_{\Delta}} \tag{2.66}$$

$$U_{\Yup}^{o} = \sqrt{U_{\Yup}^2 - \frac{1}{3}U_{\Delta}^2} \tag{2.67}$$

where U_{Δ}^{+}, U_{Δ}^{-} and $U_{\Yup}^{o}$ are the positive, negative and zero sequence generalized components. This generalized symmetrical components can be used in any kind of voltage or current systems, it does not matter if it is distorted or not, such property has an advantage in comparison to the Fortescue's symmetrical components approach.

finallly, the so called Current Physical Components - CPC Power Theory, proposed by Leszek Czarnecki [Cza88][Cza89], is a power theory aimed to analyze power components under asymmetrical and non-sinusoidal conditions in the frequency domain. The frequency domain current components of CPC theory are extended to time domain using the Steinmetz transformation. With regard to asymmetry, in the CPC power theory an unbalanced current component is calculated. For sinusoidal systems, CPC unbalanced current requires the following quantities:

$$\begin{aligned} G_e &= \frac{P}{\|\mathbf{u}\|^2}, \qquad B_e = -\frac{Q}{\|\mathbf{u}\|^2} \\ P &= real\{\hat{U}_a\hat{I}_a^* + \hat{U}_b\hat{I}_b^* + \hat{U}_c\hat{I}_c^*\} \\ Q &= imag\{\hat{U}_a\hat{I}_a^* + \hat{U}_b\hat{I}_b^* + \hat{U}_c\hat{I}_c^*\} \\ \|\mathbf{u}\|^2 &= U_a^2 + U_b^2 + U_c^2 \end{aligned} \tag{2.68}$$

these quantities allow the definition of active $\mathbf{i}_a$, reactive $\mathbf{i}_r$ and unbalanced $\mathbf{i}_u$ currents:

$$\begin{aligned} \mathbf{i}_a &= G_e\mathbf{u} = \sqrt{2}real\left\{\begin{bmatrix} G_eU_a \\ G_eU_b \\ G_eU_c \end{bmatrix} e^{jw_1t}\right\} \\ \mathbf{i}_r &= B_e\frac{d\mathbf{u}}{d(w_1t)} = \sqrt{2}real\left\{\begin{bmatrix} jB_eU_a \\ jB_eU_b \\ jB_eU_c \end{bmatrix} e^{jw_1t}\right\} \\ \mathbf{i}_u &= \mathbf{i} - \mathbf{i}_a - \mathbf{i}_r \end{aligned} \tag{2.69}$$

The unbalanced current according to CPC theory is defined similarly to the unbalanced current of the standard DIN 40110, but the collective effective voltage is defined differently and the unbalance is supposed to be the rest of the current after subtracting the active and reactive components. The procedure shown in (2.69) is an orthogonal decomposition, then the effective value of total current can be split into the sum of the squared effective values of the three current components. The Czarnecki's approach is extended to the non-sinusoidal case, calculating the quantities defined in (2.68) at each frequency component, which yields two new current components called the scattered current and the *generated* current, the former due to differences between the total active conductance G_e and each harmonic active conductance G_{ek}, being k the harmonic order, the latter complies the rest of the orthogonal decomposition.

2.5 Summary of the Chapter

The analysis of responsibilities requires analytic procedures to extract information regarding power quality disturbances from measured voltages and currents, as it has been explained in Chapter 1. The review of this chapter gives a frame of reference to analyze electric signals and power quantities, which in combination with suitable reference conditions conform a set of resources to evaluate the currently available methods to locate disturbances and assign responsibilities. Furthermore, novel methods can be developed.

This chapter has presented the definitions of electric power quantities. Several methods to calculate power were listed and described. Interpretation and physical meaning of the power were explained. The review of electric power quantities was made from available references regarding power quality phenomena.

Based on the German standards DIN 40110-1 and DIN 40110-2, an orthogonal decomposition procedure was presented. This procedure can be applied for single- and poly-phase systems. The displaced current component, and its corresponding displaced power, was proposed and included in the orthogonal decomposition procedure.

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CHAPTER 3

Measurements and Laboratory Setup

The currently available methods for assessing responsibilities in power quality require performing laboratory test to determine their advantages and drawbacks. Two sets of measurements were performed to illustrate and analyse the selected methods.

The first measurements were carried out in the campus of the Universidad Nacional de Colombia. The measured installation comprises three buildings having undetermined electric and electronic loads. These measurements will be employed to illustrate the application of the methods, demonstrating the situations to be expected in actual systems.

The second set of measurements were carried out at the Power Systems Technology and Power Mechatronics Institute of the Ruhr University of Bochum - Germany. The setup permitted to control the disturbances experienced by the feeder, providing controlled reference with a known disturbance behavior. The validity of all methods can be tested from this experimental setup.

The descriptions of each measurement setup will be presented in this chapter, including a summary of the corresponding electric power quality parameters.

3.1 Measurements in Colombia

These field measurements was carried out at the MV/LV substation of the Physic and Mathematics Faculty of the National University of Colombia. This substation feeds three buildings, where several unknown linear and non-linear loads were present and in operation. The Building 3 was not in operation when the measurements were executed, therefore simultaneuos measurements on Buildings 1 and 2 were taken, from now on these two measurement points will be named Circuit 1 and Circuit 2, respectively. The setup is illustrated in Figure 3.1.

The measurements were realized with two AEMC 3945 Power Quality Network Analyzers [AdAI03], phase currents and line-to-neutral voltages waveforms were captured on each circuit simultaneously, the waveforms were acquired with a resolution of 256 samples per cycle every four minutes, 429 sets of measured signals were captured, covering a time

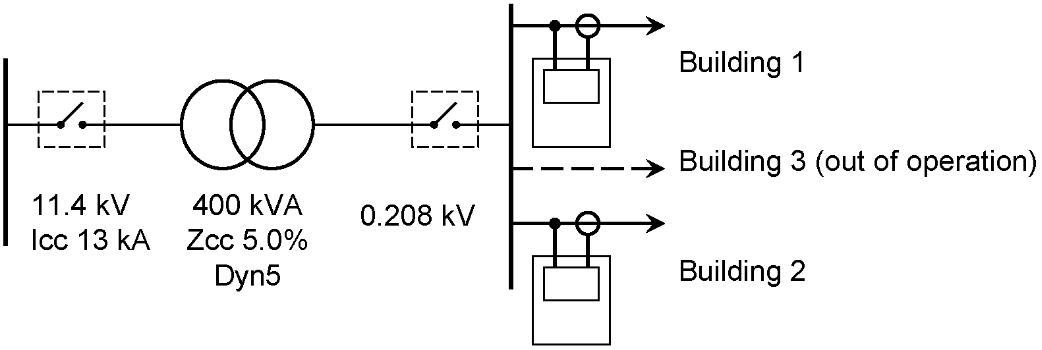


FIGURE 3.1: Measurement Setup

window of approximately 28 hours.

3.1.1 Waveforms description

The measured signals present a relative low distortion and high asymmetry, due to the predominance of unbalanced loads in the buildings. The Figure 3.2 shows time profiles for Apparent and Active power. The Circuit 1 demands active power from 80 kW at the beginning to approximately 40 kW at the end, with some variations in the meantime. In the case of the Circuit 2 it starts with 80 kW too and ends with 10 kW, the Circuit 2 has less significant power variations.

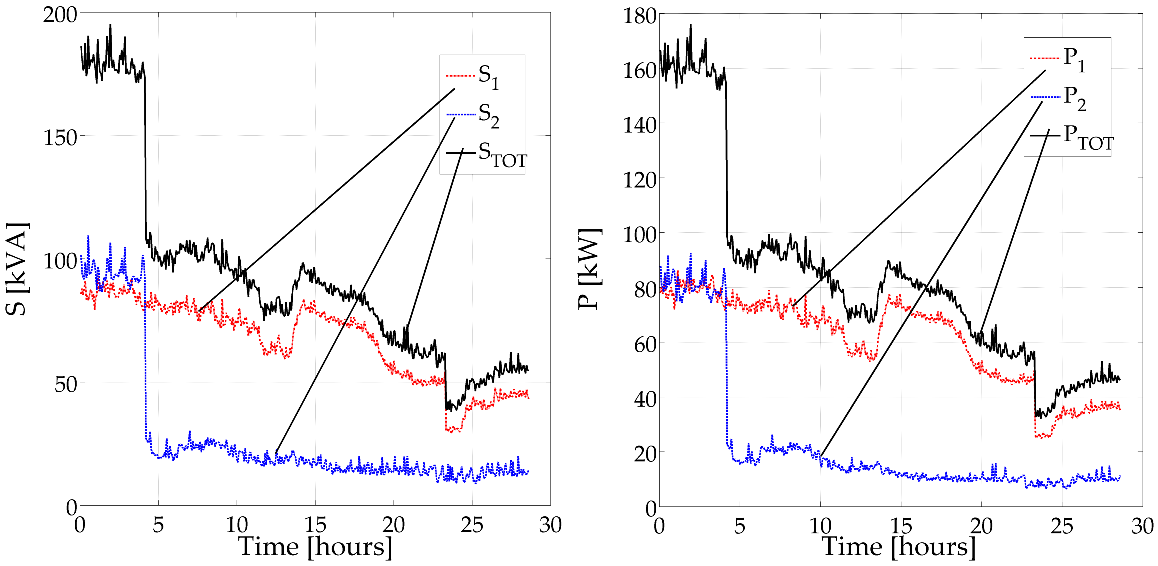


FIGURE 3.2: Apparent and Active Powers

The waveforms of voltages and currents changed constantly during the measurements, as usual. In order to illustrate the waveforms observed during the measurements, some operation states can be defined. For the Circuit 1, a first state comprising the measurements from the beginning to the twentieth hour, and a second one from the twentieth hour to the end. For the Circuit 2 can be defined two operation states, the first one from the beginning upto the fifth hour, and a second from that moment to the end of the measurements. Figures 3.3(a), 3.3(c) and 3.3(e) shows the waveforms at the fiftieth measurement, approximately hour 2.30, where the first operation states of both circuits coincide.

Figures 3.3(b), 3.3(d) and 3.3(f) shows the waveforms at the measurement number 400, approximately hour 20.00, the second operation states of both circuits coincide on this time. From Figure 3.3, it can be seen that the voltages are slightly distorted, the currents are more distorted and asymmetry is present.

3.1.2 Reactive power and phase displacement

In the last chapter, the displaced power was proposed to deal with phase displacement. In order to illustrate the similarities between reactive power and displaced power, Figures 3.4 and 3.5 are presented. Figure 3.4 displays the temporal evolution of the reactive power (left) and of hte displaced power (right). It can be seen that both Figures are quite similar, Figure 3.5 shows that both powers are related linearly. In this case, when the voltage is slightly distorted, both quantities are practically the same. It is worth to note that reactive power has been calculated as proposed in the Chapter 2, using fundamental frequency positive sequence components only.

Figure 3.6 shows the relationship between the reactive and apparent power. The relationship does not seem to be completely linear, it can only be said that the reactive or displaced increases as the apparent power does. The loads do not have a linear behavior, and they do not remain unchanged along the time either. The lack of a linear relationship between reactive-displaced power and apparent power responds to those reasons: presence of non-linear undetermined loads and their dynamic behavior.

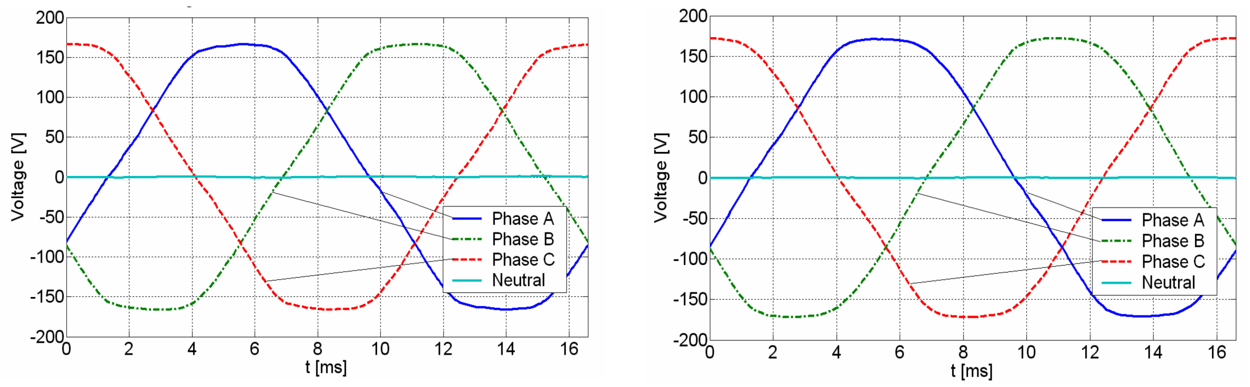
3.1.3 Unbalance or Asymmetry

Voltage and current asymmetries are illustrated. Asymmetry has been calculated according to the IEC 61000-4-30 [IEC08] and IEEE 1459 [IC10]. Additionally, the power quantities proposed in Chapter 2 to quantify asymmetry are employed as well. A brief description of the quantities is listed.

- **IEC 61000-4-30** In the standard [IEC08] unbalance is calculated using the method of symmetrical components, as the ratio of negative and/or zero component to the positive one:

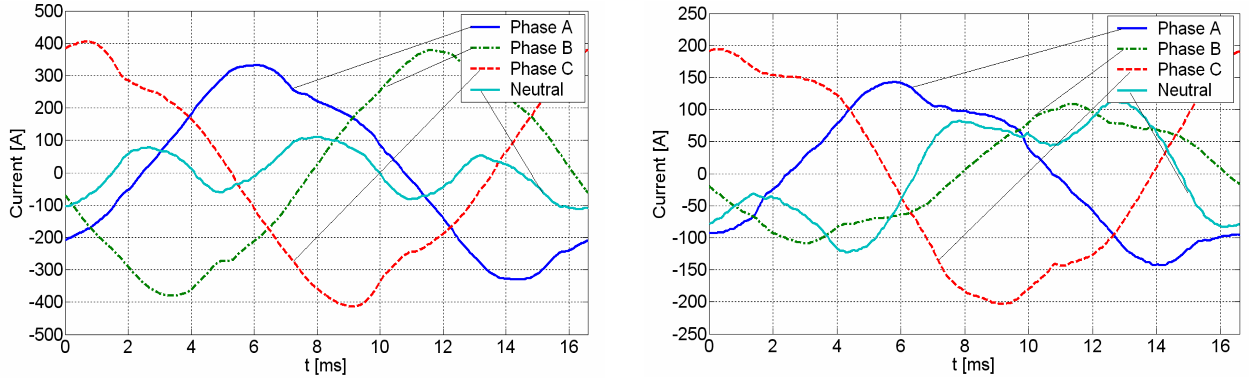
$$u_2 = \frac{Negative - sequence}{Positive - sequence} \times 100\% \qquad u_0 = \frac{Zero - sequence}{Positive - sequence} \times 100\% \quad (3.1)$$

  Although it is not recommended in the standards the assessment of current unbalance using (3.1), in the following paragraphs the current unbalance will be calculated with the same expression.



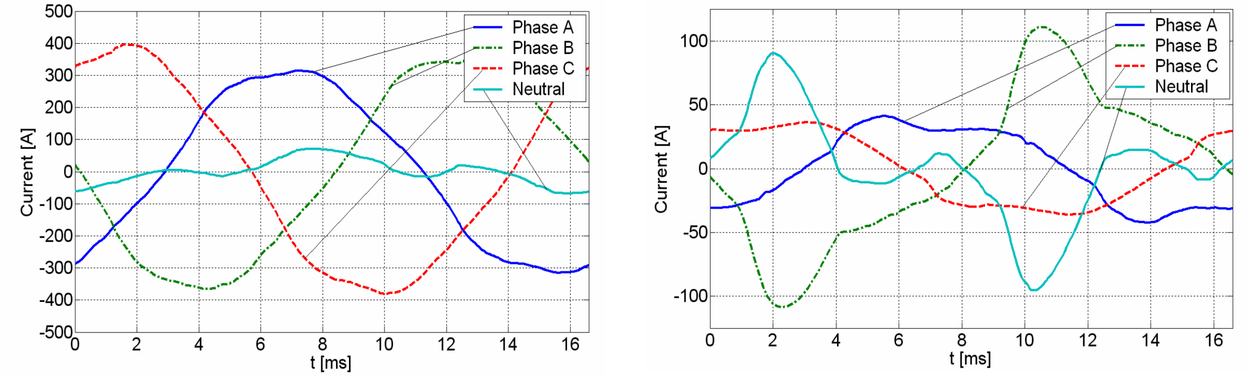
(a) Voltage Waveforms for both circuits

(b) Voltage Waveforms for both circuits



(c) Current Waveforms for Circuit 1

(d) Current Waveforms for Circuit 1



(e) Current Waveforms for Circuit 2

(f) Current Waveforms for Circuit 2

Figure 3.3: Waveforms' samples of Colombian measurements. Figures (a), (c) and (e) for Measurement number 50 (Hour 2.30). Figures (b), (d) and (f) for Measurement number 400 (Hour 20.00).

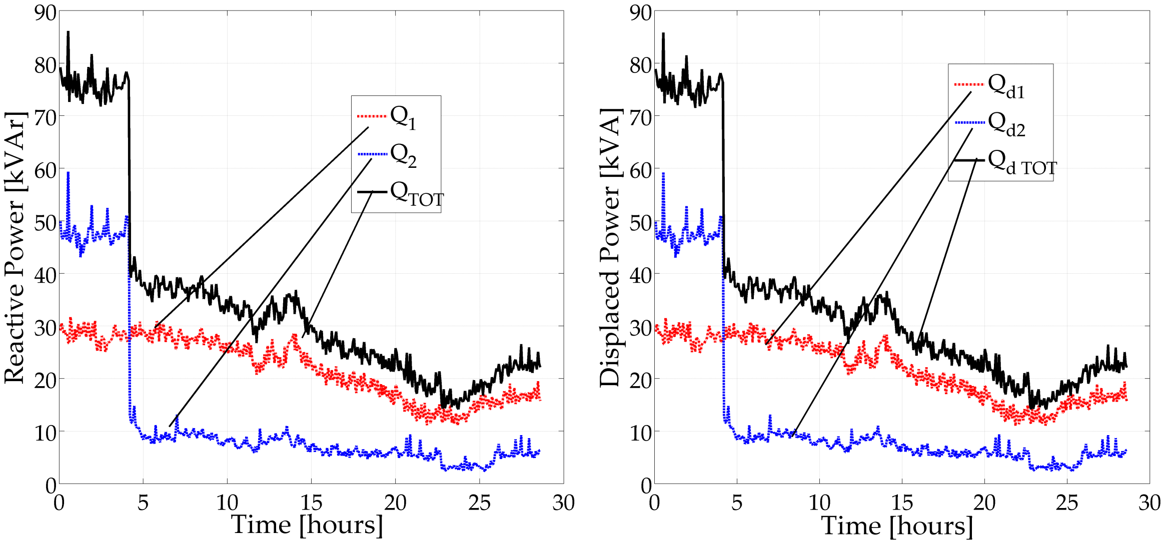


FIGURE 3.4: Reactive power (left) and Displaced power (right) along time

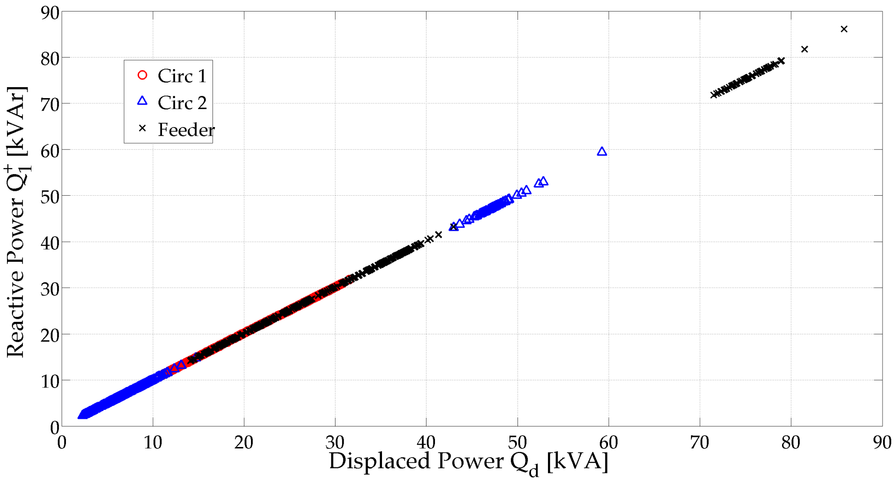


FIGURE 3.5: Reactive power versus Displaced power

- **IEEE 1459** The standard [IC10] proposes the utilization of a power based unbalance index called fundamental unbalanced power:

$$S_{U1} = \sqrt{S_{e1}^2 - (S_1^+)^2} \tag{3.2}$$

where: S_{e1} is the Equivalent fundamental apparent power and S_1^+ is the fundamental positive sequence apparent power.

- **Total unbalanced power from DIN 40110** The active and displaced unbalanced power components were defined in the last chapter. Both have corresponding current

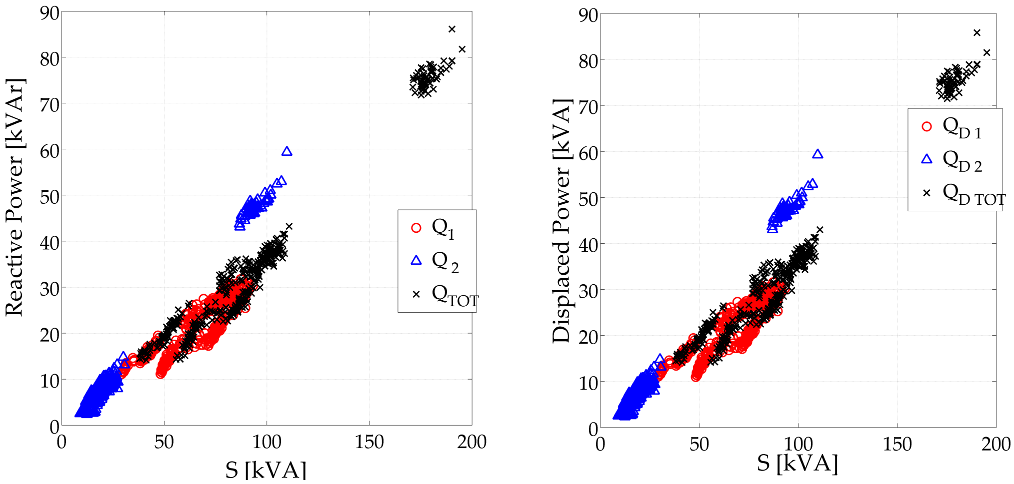


FIGURE 3.6: Reactive power (left) and Displaced power (right) plotted against apparent power

and power components orthogonal to each other, but they represent together the asymmetry phenomenon. In order to assess asymmetry as a single quantity, the total unbalanced power can be used:

$$Q_u = \sqrt{Q_{au}^2 + Q_{Qu}^2} \tag{3.3}$$

This quantity is similar to (3.2), but it employs the whole voltage signal, not only the fundamental frequency. Thus, different values of fundamental unbalanced power and total unbalanced power are expected.

Figure 3.7 displays the time behavior of fundamental and total unbalanced power. It can be seen that this power is not lesser than 10kVA and not greater than 20kVA in the feeder, meaning that from a 5% to a 10% of the apparent power is spent in asymmetry.

The Figure 3.8 shows reactive power versus total unbalanced power. Although both quantities increase simultaneously, no linear relationship can be observed. This behavior confirms what it was mentioned above, unbalance power definition based on [IC10] and [DIfN96] are different.

The Figure 3.9 shows the voltage negative and zero sequence components as a function of the apparent power. No direct relationship can be observed between voltage unbalance and the demanded apparent power. The negative sequence components are below the acceptable voltage negative sequence unbalance limit of 2% [CEN00]. The voltage zero sequence components is barely observable, always below 0.07%.

Current unbalance has a quite different behavior, depicted in Figure 3.10 against apparent power too. Unbalance in Circuit 2 does not seem to have a close relationship to apparent power. Two operation can be seen: for lower apparent power highly unbalanced currents were observed; for greater apparent powers, asymmetry below 10% is expected. On the contrary, Circuit 2 appears to hold a relationship with the power demanded by its load, the higher the load, the lower the current unbalance.

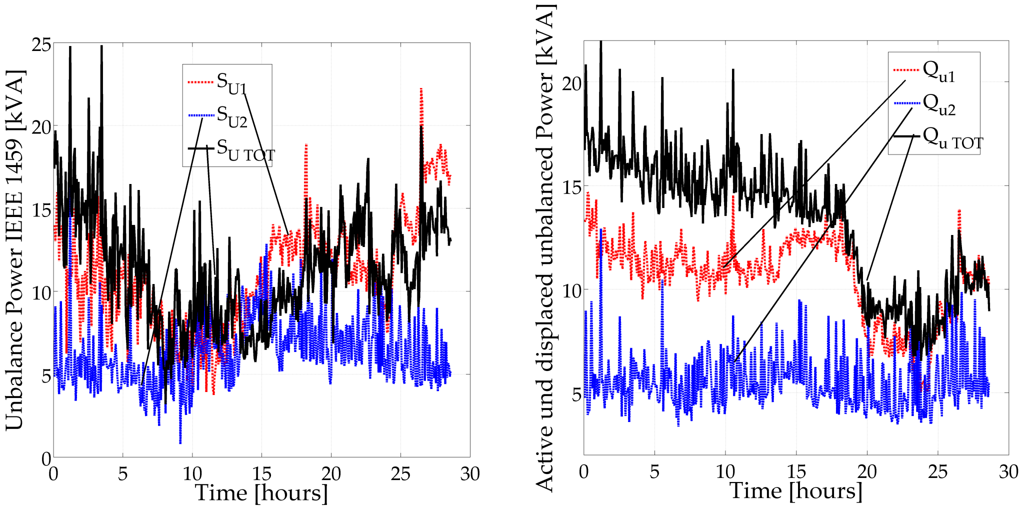


FIGURE 3.7: Unbalance power (left), Active and Displaced unbalanced power (right)

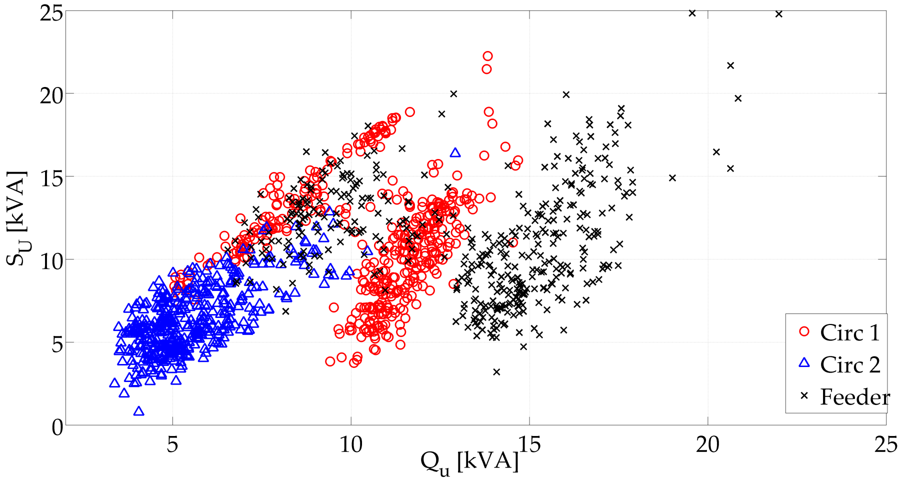


FIGURE 3.8: Unbalance power IEEE 1459 against total unbalanced components of DIN 40110

The Figure 3.11 shows the current unbalance indicators defined according to (3.1), displayed versus both unbalanced power quantities. It can be observed that unbalance indicator seem to have relationship with both power quantities, specially with IEEE 1459 fundamental unbalance power. As the indicators and the power were calculated from the same signals, this relationship is not surprising. Total unbalanced power from DIN 40110 shows a similar behavior: the higher the total unbalanced power, the higher the current asymmetry. This does not diminish the possibilities of the DIN 40110 based power definitions, it does point out that asymmetry can be assessed in the different way.

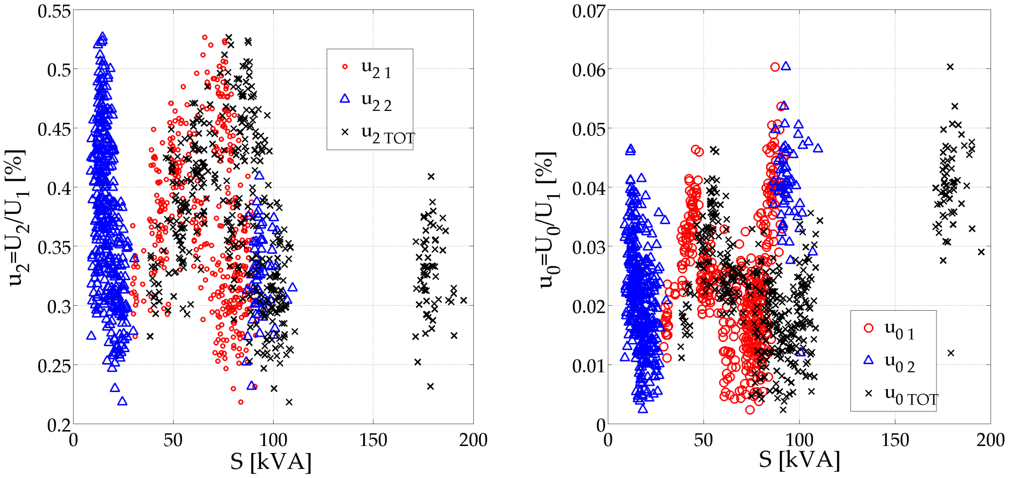


FIGURE 3.9: Voltage unbalance indicators versus apparent power. Negative to positive sequence ratio (left), Zero to positive sequence ratio (right)

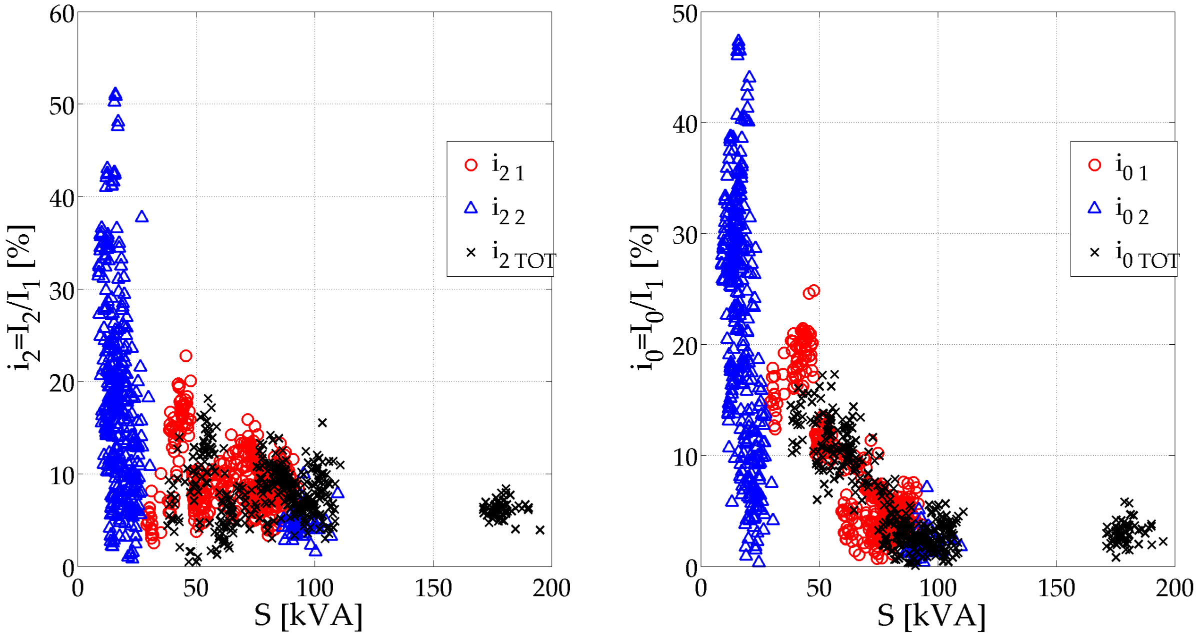


FIGURE 3.10: Current unbalance indicators versus apparent power. Negative to positive sequence ratio (left), Zero to positive sequence ratio (right)

3.1.4 Waveform distortion

The non-fundamental power S_{eN} (2.53) and the distorted power were proposed in Chapter 2 to quantify the power spent in waveform distortion. The difference between both power quantities is that non-fundamental power uses non-fundamental frequency components without considering whether they contain active power or not, distorted power does not

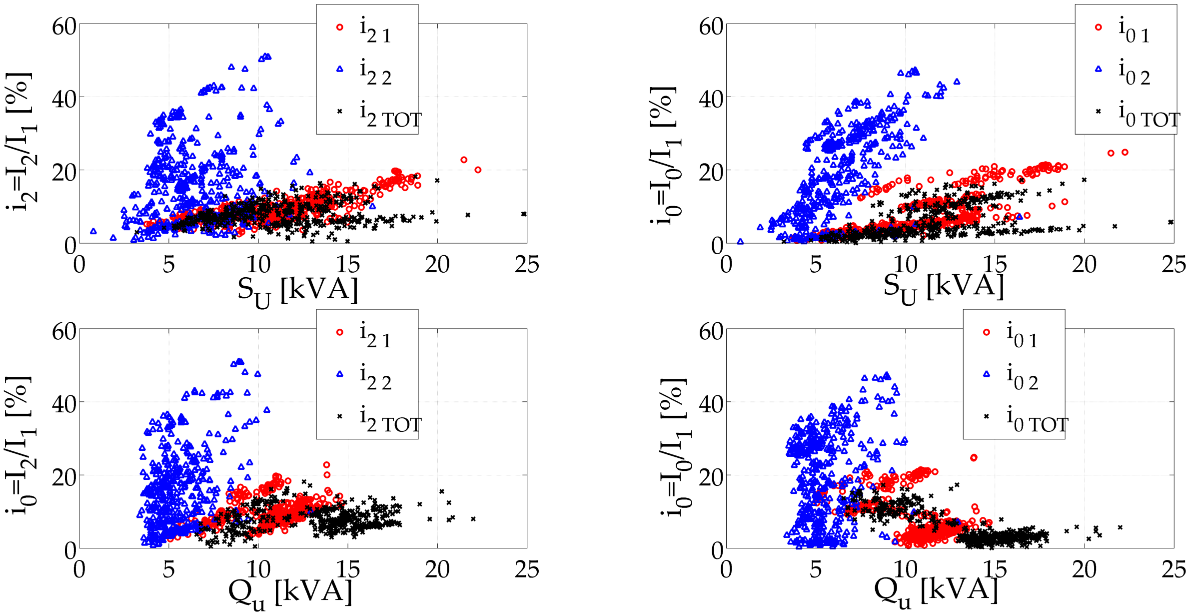


FIGURE 3.11: Current unbalance indicators versus unbalance power S_U (upper plots) and versus total unbalance power Q_u (lower plots). Negative to positive sequence ratio (left), Zero to positive sequence ratio (right)

contain any active power. Figure 3.12 shows the evolution of both power quantities. It reveals that power spent in waveform distortion comes from 5% to 10% in the this case.

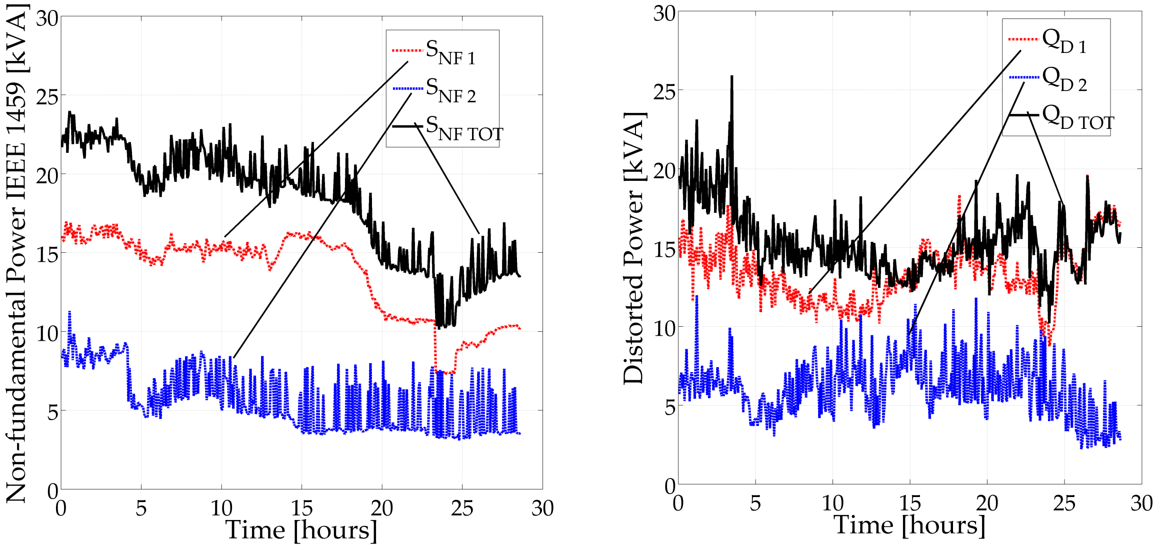


FIGURE 3.12: Non-fudamental power (left), Distorted power (right)

The Figure 3.13 that both quantities do not contain the same information. Nevertheless, it can be seen that both powers increase correspondingly, then both quantities reveal the presence of distortion, but from different viewpoints.

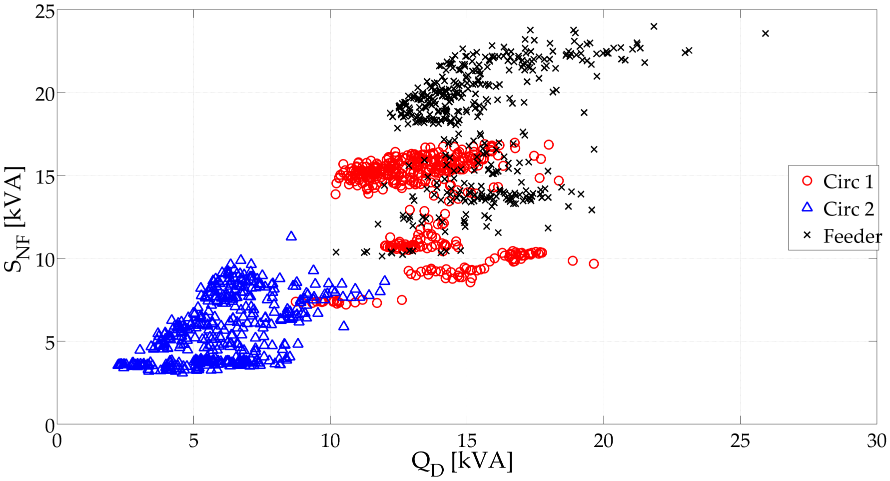


FIGURE 3.13: Non-fundamental power plotted against Distorted power

The voltage and current distortion indicators are depicted in Figure 3.14 against apparent power. Similar to voltage unbalance, voltage distortion does not seem to depend clearly on the load's demanded power. The Figure 3.15 shows the voltage distortion against the non-fundamental and the distorted power, the independence of voltage distortion from power remains unchanged.

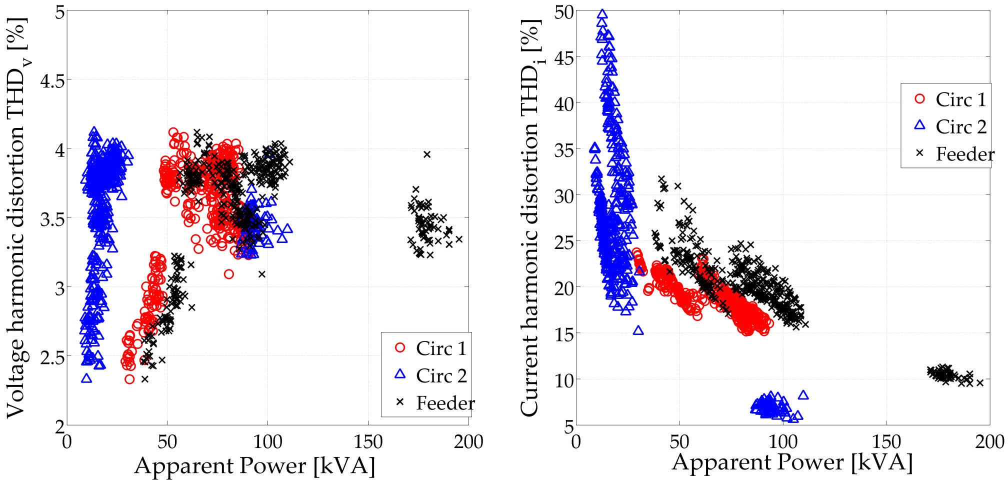


FIGURE 3.14: Voltage (left) and current (right) harmonic distortion against apparent power

Current distortion does present a different behavior as displayed in Figure 3.14, the greater the demanded power, the lower the current distortion.

The Figure 3.16 depicts the current harmonic distortion versus non-fundamental and distorted power. A clear relationship between those quantities cannot be observed. It

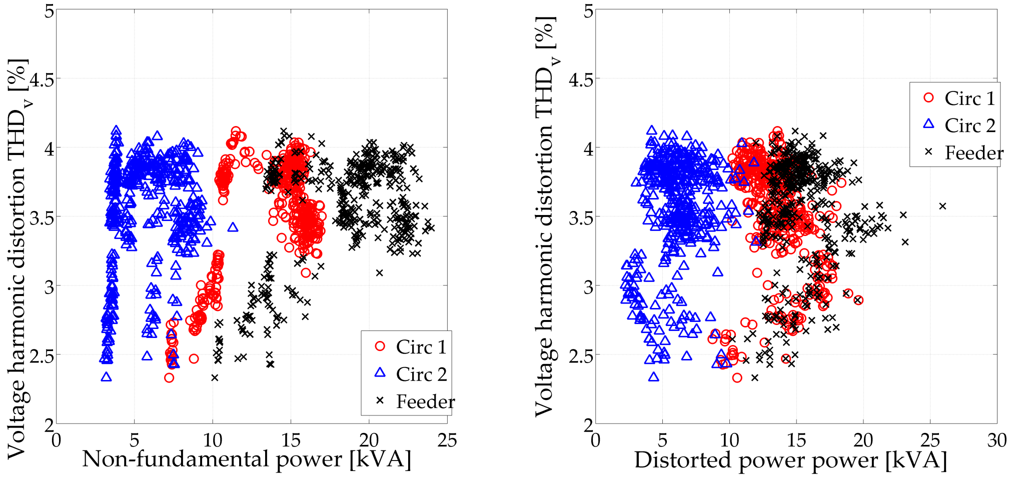


FIGURE 3.15: Voltage harmonic distortion against non-fundamental power (left) and against distorted power

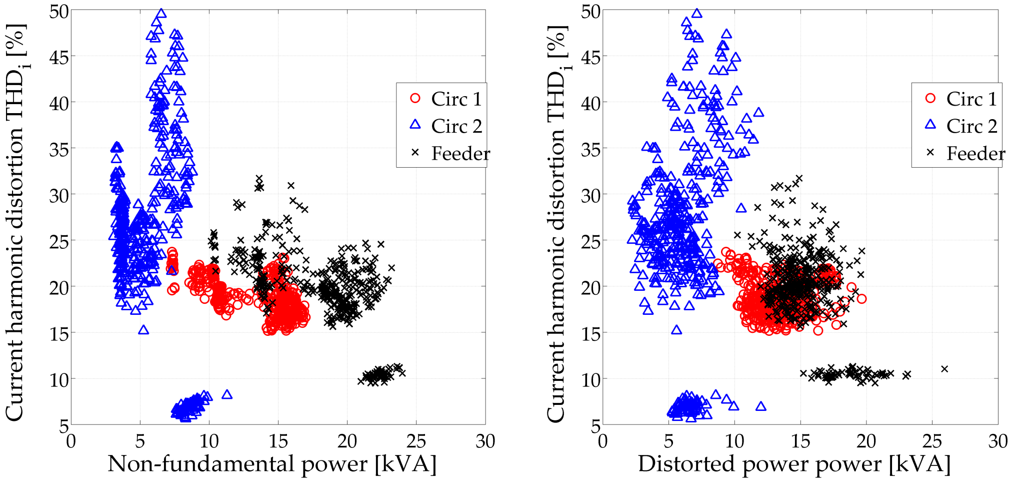


FIGURE 3.16: Current harmonic distortion against non-fundamental power (left) and against distorted power

seems to exist a trend of increasing current distortion as the power enlarge. The absence of a relationship between power quality indicators does not affect the application of the power quantities, it reveals only particular characteristics of the setup.

3.2 Measurements in Germany

The experimental setup comprises two non-linear electrically and mechanically coupled loads. These loads can be driven at 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 corresponding Transformers 1 and 2, as shown in Fig. 3.17. (Switches S1 to S4 closed and S5 open, receptively).
- **Trafo 2**: Both loads are fed by Transformer 2. (Switch S2 open, switches S3 to S5 closed).

The feeding configurations make possible two disturbance flow conditions. In the **Separated Transformers** configuration, the influence of current distortion of one load has no appreciable influence on the voltage of the other load. The loads seem to be isolated at the measuring point. This is because the 10kV short circuit capacity is high enough to avoid load's currents affecting the voltage or the other load. In the **Transformer 2** configuration, the disturbances can flow from one load to the other through the 0.4kV bus bar. Additionally, the short circuit capacity at the 0.4kV is smaller than the capacity for the **Separated Trafos** configuration, allowing the presence of voltage disturbances generated by both loads. In the following paragraphs, special attention will be paid to the configuration fed by Transformer 2, because it provides the most easy way to allow disturbance to flow between the loads.

A schematic diagram of the load setup can be seen in Fig. 3.17. 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 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 3.2 and 3.2 show a summary of the performed tests. 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 driven.

3.2.1 Waveforms Description

The Figure 3.2.1 displays some samples of the recorded waveforms. It can be seen that current can be displaced with respect to the voltage back and forth. As result from the current displacement, power flow changes correspondingly. Some example values of power are put in the Figure 3.2.1.

The apparent and active powers for each test is shown in Figure 3.19. It can be seen that the DC machine has identifiable apparent power values. Regarding its active power, the tests started with positive active power values and ended with negative ones. From

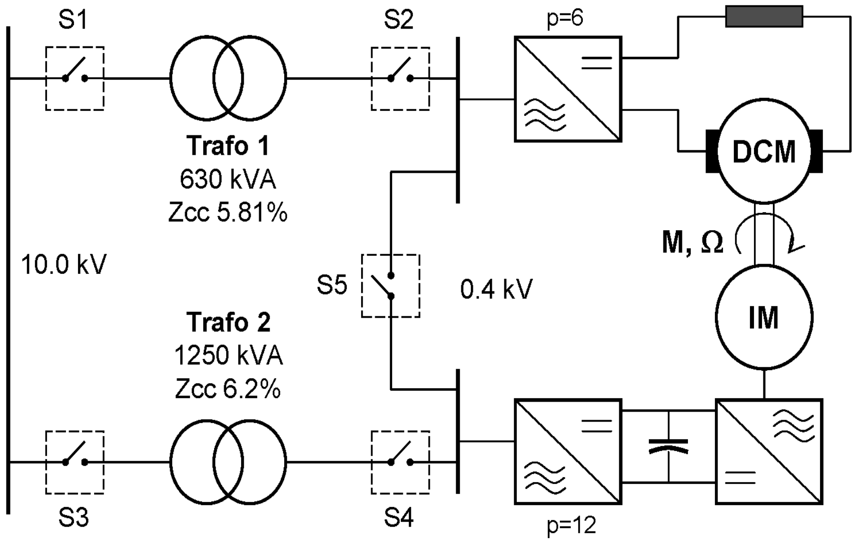


FIGURE 3.17: Laboratory Setup

	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 3.1: States for the feeding configuration Separated Trafos

Figure 3.19 it cannot be easily observed how apparent power changed along the tests in the induction machine. However, its active power behavior can be identified from the Figure 3.19.

3.2.2 Reactive power and phase displacement

It was explained already, that setup of Figure 3.17 allow the control of powers, causing the currents to be displaced backwards or forwards. The Figure 3.20 helps to clarify how the setup affects the power. At the left side, each device's behavior is clearly understandable:

Induction Machine group

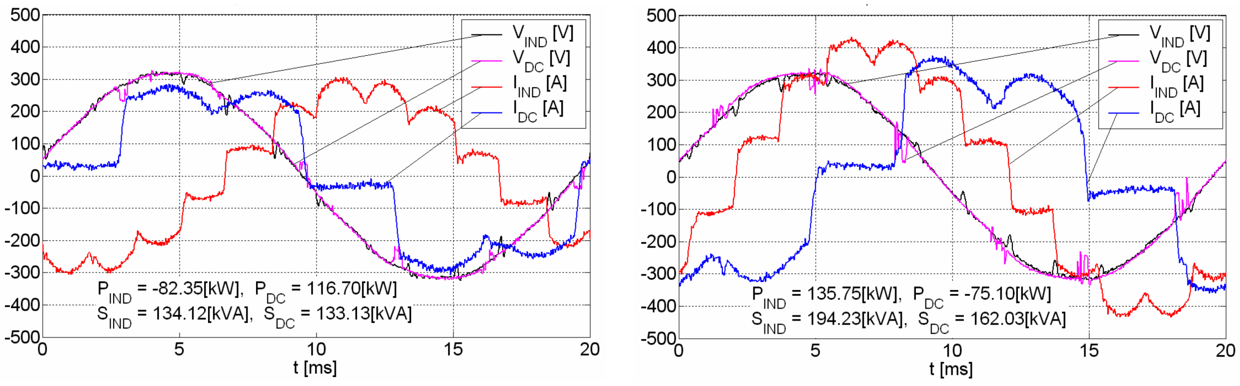
The active power increases as the apparent power increases. The power converter delivers reactive power to sustain the machine operation as the apparent power gets greater.

DC Machine group

The active power has positive and negative active power values for specific apparent

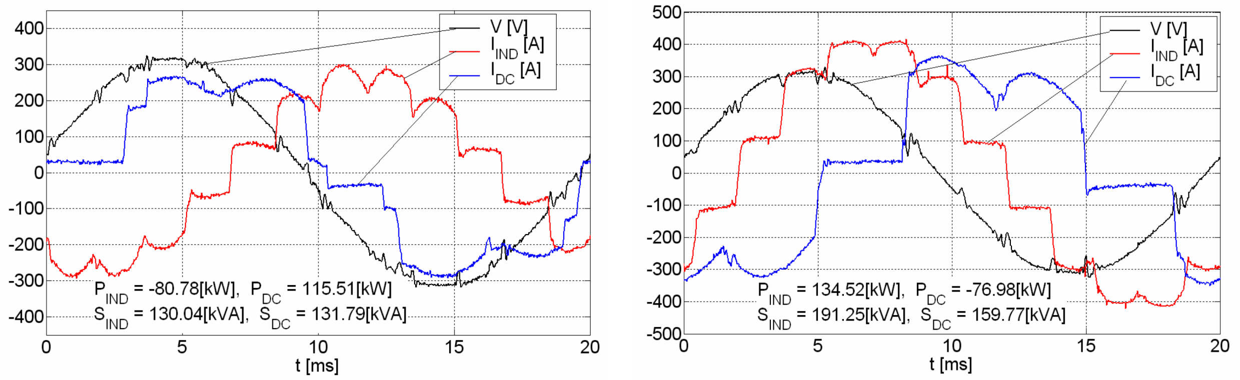
	Speed [rpm]				
Torque [pu]	0	500	1000	1500	2000
0.0	p	-	-	-	-
0.1	p	n/p	n/p	n/p	n/p
0.2	p	n/p	n/p	n/p	n/p
0.3	p	n/p	n/p	n/p	-

TABLE 3.2: States for the feeding configuration Trafo 2



(a) (-2000 rpm / T = 0.2 pu)

(b) (+1500 rpm / T = 0.3 pu)



(c) (-2000 rpm / T = 0.2 pu)

(d) (+1500 rpm / T = 0.3 pu)

FIGURE 3.18: Waveforms' sample of German measurements. Figures (a) and (b) for separated trafos, (c) and (d) for trafo 2.

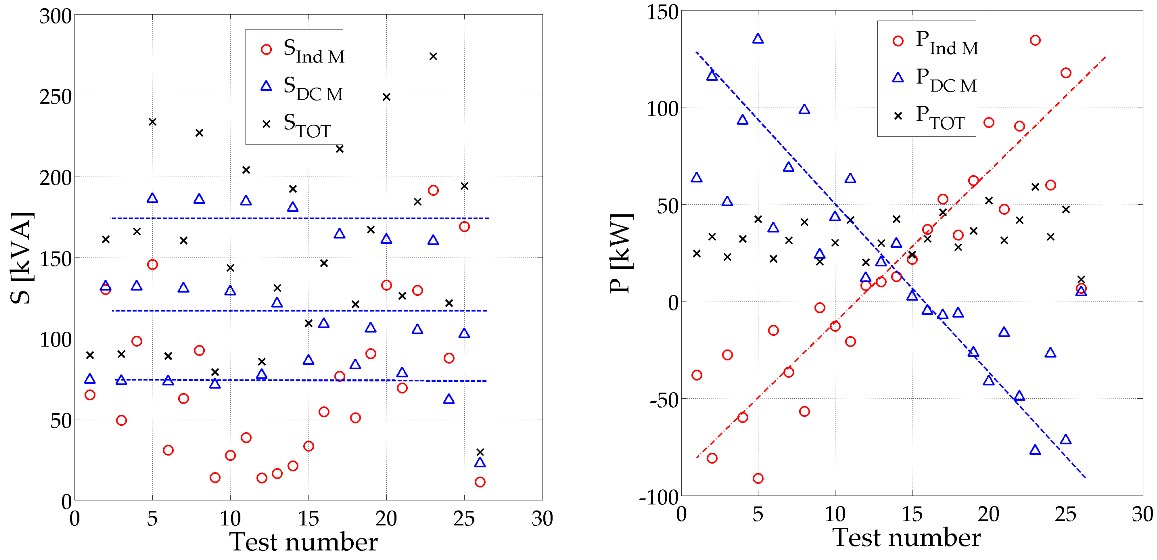


FIGURE 3.19: Apparent and active powers for different tests

power values, i.e., the active power flows in different directions whereas the apparent power remains almost constant. Its power converter delivers reactive power as the other converter as well.

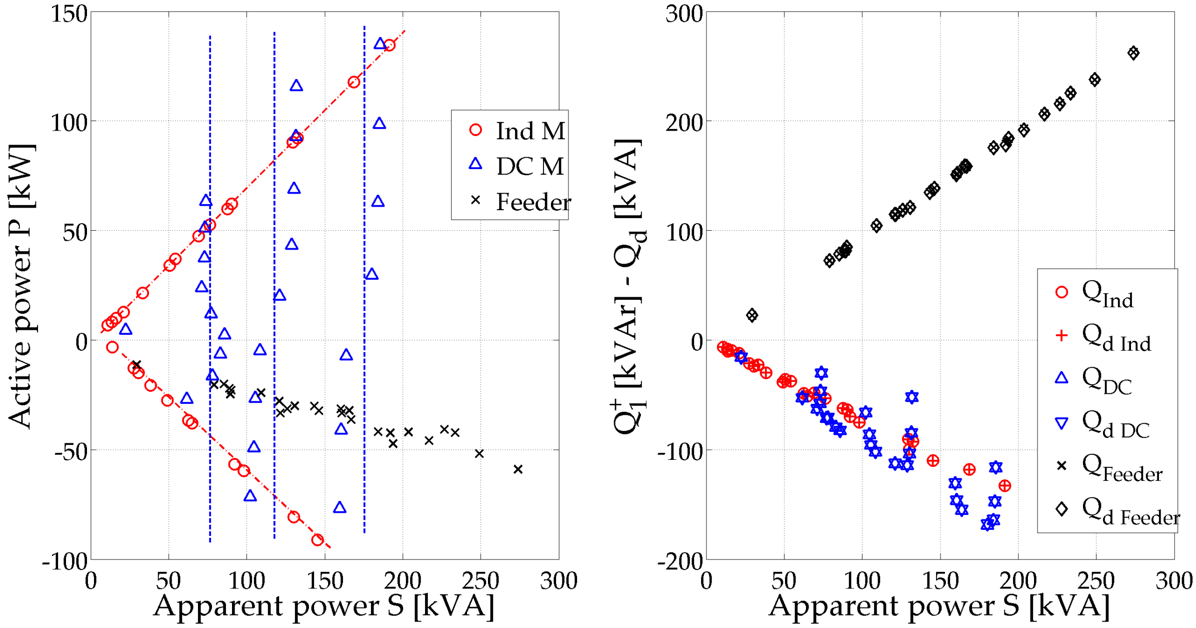


FIGURE 3.20: Apparent and active powers for different tests

The Figure 3.20 shows the numerical similarities between reactive and displaced power. In this case, the voltage distortion is lower than that of the Colombian measurement setup. Differences between reactive and displaced power are negligible in this case.

3.2.3 Unbalance or asymmetry

The power converters employed to feed the electric machines were built and controlled under laboratory conditions. From their construction characteristics, they operate symmetrically, therefore no asymmetry is expected. Unbalanced (3.3) and total unbalanced (3.2) powers are shown in Figure 3.21.

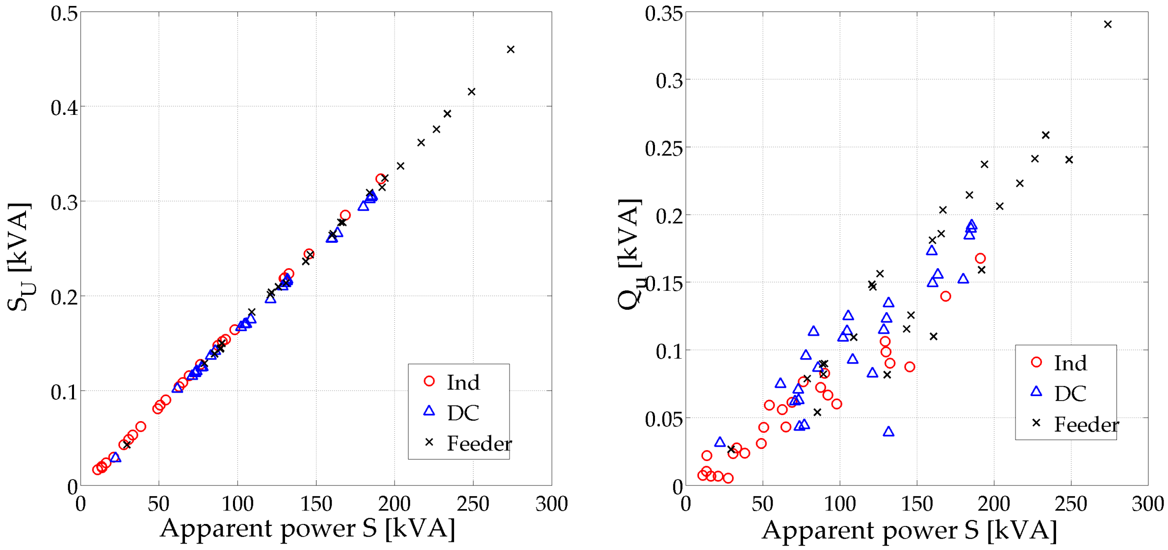


FIGURE 3.21: Unbalance powers. IEEE 1459 (left) and DIN 40110 (right)

In any case, asymmetry power does not reach 0.5kVA. Thus, unbalance cannot be studied from the German measurements setup.

3.2.4 Waveform distortion

As it was shown in Figures 3.2.1, current waveforms are highly distorted. Figure 3.22 shows the THD values for voltages and currents. It can be observed that both loads are capable to disturb the voltage waveform, the THD_v increases with corresponding increases in the apparent power. A quite different situation is seen by the current distortion. Current distortion in the DC machine group seems to hold approximately the same THD_i for any apparent power. The Induction machine group decreases the current distortion as the apparent power increases.

Considering the Non-fundamental S_{eN} and distorted Q_D powers, capable of accounting for waveform distortion, the Figure 3.23 shows values for the German setup. It can be seen that both power quantities increase as the apparent power increases. This means that both loads develop more power related to waveform distortion as it increases its demand.

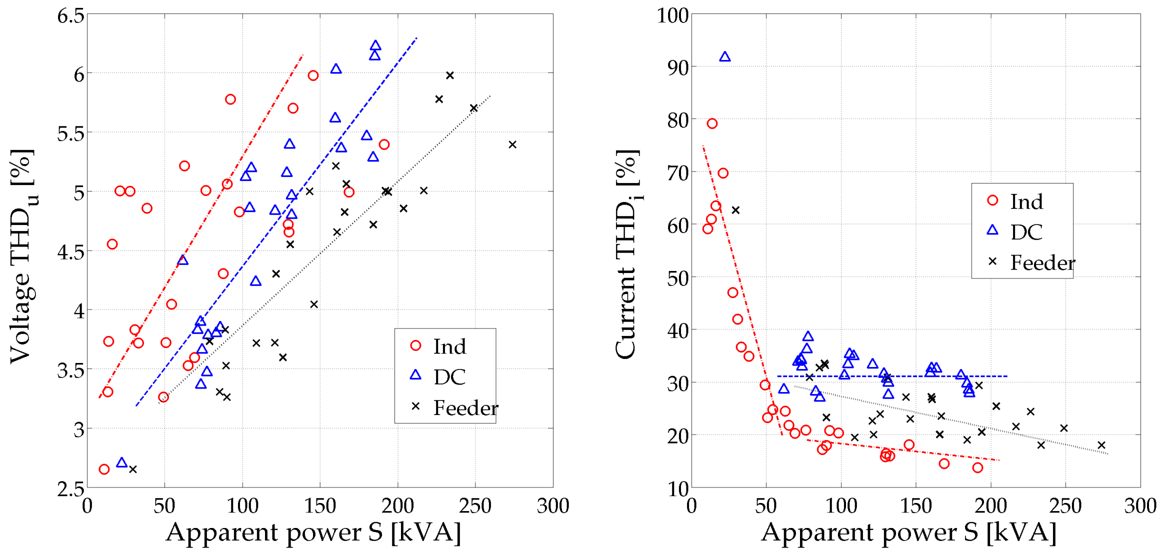


FIGURE 3.22: Voltage and current total harmonic distortion. Voltage (left) and current (right) THD

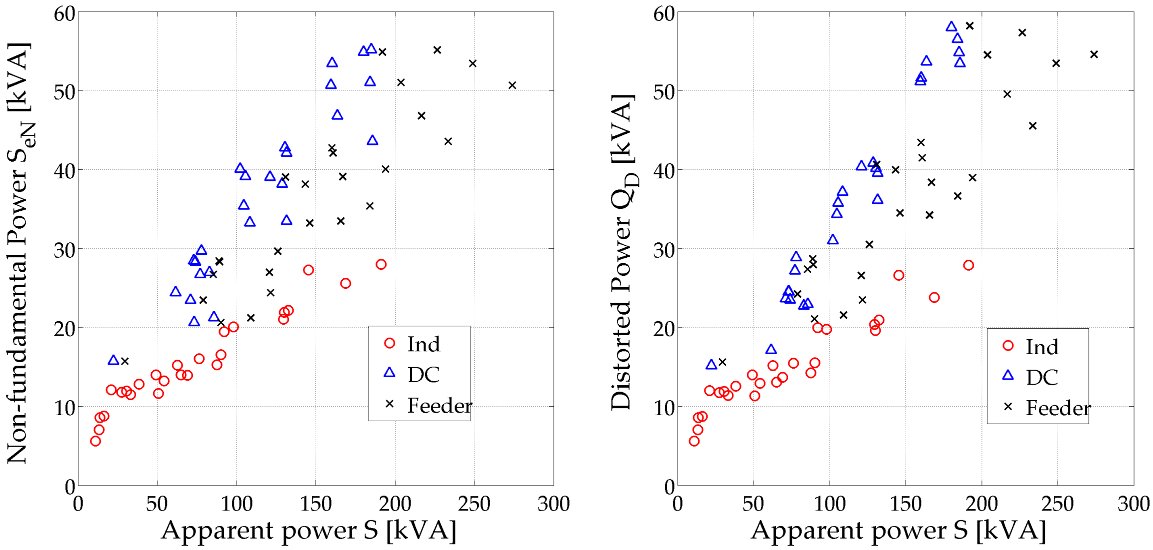


FIGURE 3.23: Non-fundamental S_{eN} and distorted Q_D powers.

The relationship between waveform distortion and the powers shown in Figure 3.23 can be better seen in Figures 3.24 and 3.25.

Figure 3.24 reveals that non-fundamental or distorted power makes the voltage distortion to increase for both loads. Current distortion seems to hold approximately the same distortion regardless of the distorted power in the DC machine group, as depicted in Figure 3.25. The Induction machine group decreases the waveform distortion as its distorted power gets greater.

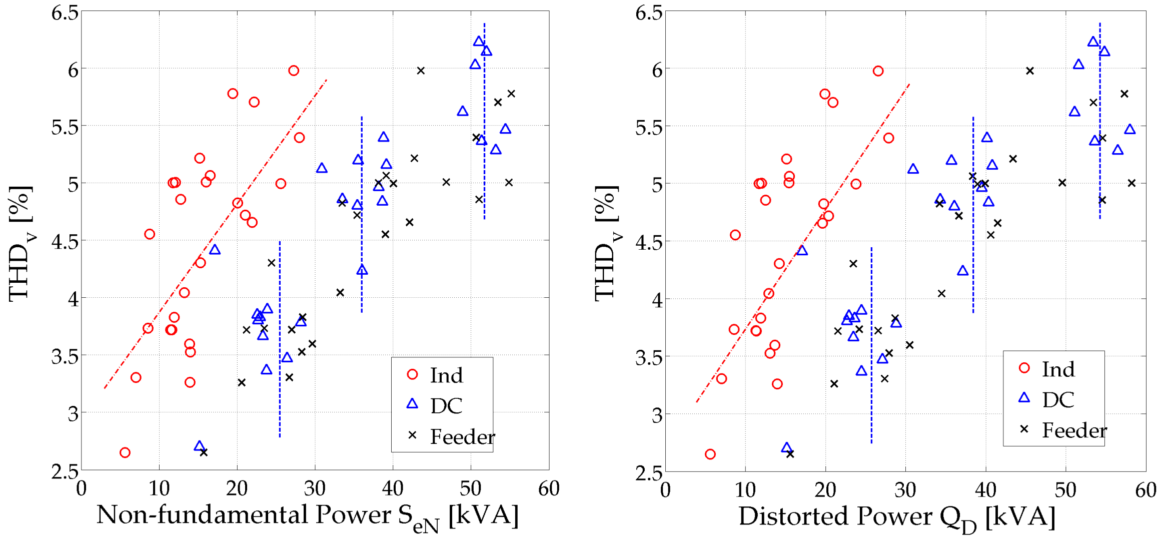


FIGURE 3.24: Voltage THD_v versus Non-fundamental S_{eN} (left) and distorted Q_D (right) powers.

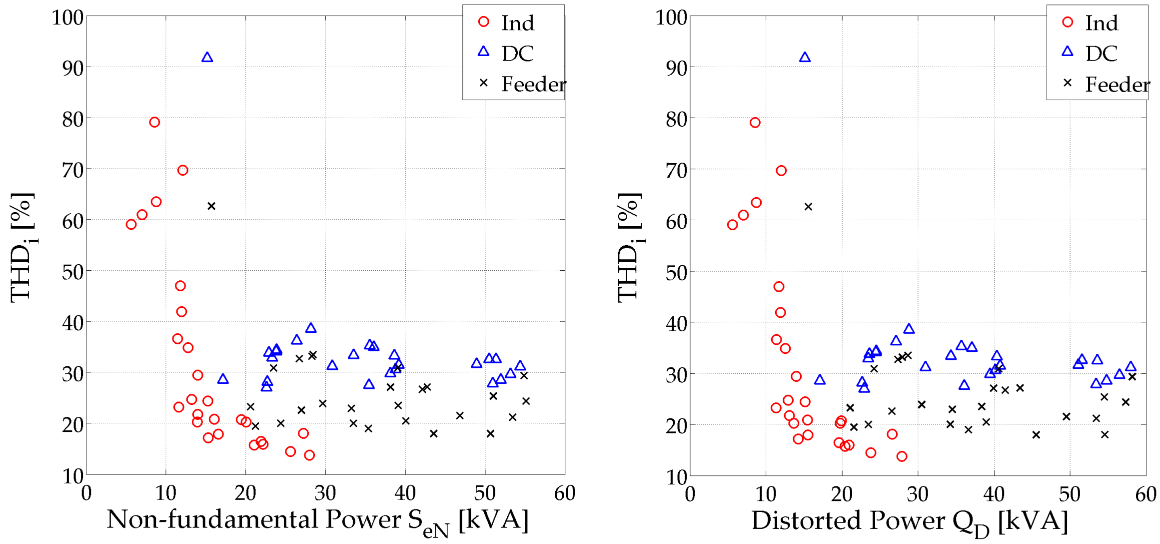


FIGURE 3.25: Current THD_v versus Non-fundamental S_{eN} (left) and distorted Q_D (right) powers.

3.3 Summary of the Chapter

The setups for the two measurement experiments were described. The first setup is a typical public installation, were the usual stationary disturbances were observed. For this case, there was no control of the disturbing loads. The second setup has two controllable loads, allowing the determination of certain disturbance and power flow between the loads.

The general characteristics of both setups were presented. Special attention was paid to the power components and the stationary power quality conditions.

The Colombian measurements setup has a typical power quality condition, no specific behavior can be assigned to each load. It has a time variable behavior, so these measurements can be specially useful to assess the evolution of indicators in time.

The German measurements setup does have a clearly determined power quality behavior. The DC Machine group causes distortion in the same amount and waveform regardless of its operation condition. The Induction Machine group generates more distorted power as it demands more current from the systems. It increases the voltage distortion but decreases the current distortion as its demanded current increases.

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CHAPTER 4

Review of Available Methods

> *Scientific theories need reconstruction every now and then. If they didn't need reconstruction they would be facts, not theories.*
>
> *Charles Proteus Steinmetz*

In the following pages the revision of currently available Methods to evaluate responsibilities in the frequency domain are listed and summarized.

In this chapter, three available method to assess responsibilities are investigated and illustrated. The measurements of Chapter 3 are employed, specially the German measurements setup. A discussion about the usefulness aqnd application of each method is presented too. Finally, a method to assess responsibilities is presented.

4.1 Critical Impedance Method - $\mathcal{CIM}$

The Critical Impedance Method - $\mathcal{CIM}$ was proposed first proposed by Wilsun Xu in [XL00]. Afterwards the $\mathcal{CIM}$ was revisited and improved in [XLL03] [CLK$^+$04] and [LXT04]. Some characteristics of this method are:

- The method is capable to determine the major contribution between two entities connected to a Point of Common Coupling
- The method presents difficulties when it is necessary to evaluate the major contributions of more than two entities connected to a PCC.

4.1.1 Deduction of central relation for Critical Impedance Method

The circuit of Figure 4.1 is used to develop and describe the $\mathcal{CIM}$. First, the X_2 impedance value must be determined, for which the Voltage V_m reaches its minimum value. The impedance X_2 is the impedance value from the Utility point U to some specific point in the network connection, between the utility and the customer, where the minimum voltage

V_m is located. For the sake of simplicity, the impedances are considered purely inductive by now.

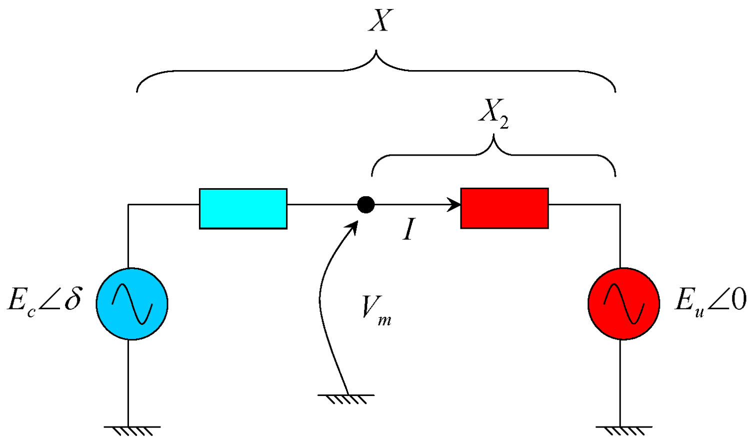

FIGURE 4.1: Circuit model for Critical Impedance Method

The analysis of the circuit of Figure 4.1 will help to understand the method's principles, especially the power flow. From the circuit of Figure 4.1, the following equations can be extracted:

$$|I|^2 = \left|\frac{E_C - E_U}{X}\right|^2 = \frac{E_C^2 + E_U^2 - 2E_C E_U \cos(\delta)}{X^2} \tag{4.1}$$

$$P = E_U I \cos(\theta) = \frac{E_U E_C}{X}\sin(\delta) \tag{4.2}$$

$$Q = E_U I \sin(\theta) = \frac{E_U}{X}(E_C \cos(\delta) - E_U) \tag{4.3}$$

The voltage V_m can be expressed as (4.4):

$$V_m = \frac{X_2}{X} E_C \angle\delta + \frac{X - X_2}{X} E_U \tag{4.4}$$

The customer voltage can be expressed as:

$$E_C \angle\delta = E_C \cos(\delta) + jE_C \sin(\delta)$$

therefore,

$$V_m = \frac{X_2}{X} E_C \cos(\delta) + \frac{X - X_2}{X} E_U + j\frac{X_2}{X} E_C \sin(\delta)$$

calculating the magnitude of this expression, yields:

$$|V_m|^2 X^2 = X_2^2 E_C^2 \cos^2(\delta) + 2X_2(X - X_2)E_C E_U \cos(\delta) + X^2 E_U^2 - 2XX_2E_U^2 + X_2^2 E_U^2 + X_2^2 E_C^2 \sin^2(\delta)$$

$$|V_m|^2 X^2 = X_2^2 E_C^2 + X^2 E_U^2 + X_2^2 E_U^2 - 2XX_2 E_U^2 + 2XX_2 E_C E_U \cos(\delta) - 2X_2^2 E_C^2 \cos(\delta)$$

The last expressions can be used to determine the X_2 impedance value for the minimum voltage V_m. The equation (**??**) shows the expression to be minimised:

$$\frac{\partial |V_m|^2}{\partial X_2} X^2 = 2X_2(E_C^2 + E_U^2 - 2E_C E_U \cos(\delta)) + 2(XE_C E_U \cos(\delta) - XE_U^2) = 0 \tag{4.5}$$

which yields:

$$X_2 = \frac{E_U^2 - E_C E_U \cos(\delta)}{E_C^2 + E_U^2 - 2E_C E_U \cos(\delta)} X \tag{4.6}$$

The equation (4.6) can be analyzed to determine which source is the major contributor. Let us suppose that $E_U = \alpha E_C$, where $\alpha > 0$. Considering 4.6, it yields:

$$\frac{X_2}{X} = \frac{\alpha^2 - \alpha \cos(\delta)}{(1 + \alpha^2) - 2\alpha \cos(\delta)} \tag{4.7}$$

The expression (4.7) illustrates the dependence of X_2 on the ratio of source magnitudes $\alpha = E_U/E_C$ and the angle δ of the customer's side source. In order to avoid the presence of cosine terms, the following cases can be considered:

- If $\delta = 0$, the equation 4.7 turns into:

$$\frac{X_2}{X} = \frac{\alpha^2 - \alpha}{(1 + \alpha^2) - 2\alpha} = \frac{\alpha(\alpha - 1)}{(\alpha - 1)^2} = \frac{\alpha}{\alpha - 1} > 1 \tag{4.8}$$

  The interpretation of (4.8) is: if the angular difference between the Customer source and the Utility source is approximately zero, the impedance related to the minimum voltage between the Utility and the Customer is greater that the aggregated equivalent impedances of both. Therefore, this point could be "placed" inside the customer's side, which does not have any practical or physical sense. Instead of that, it can be interpreted that the point where the minimum voltage between the Customer and the Utility is the Customer's source, thus **the Utility is the major contributor to the disturbance condition**.

- If $\delta = \pi$, the equation 4.7 yields:

$$\frac{X_2}{X} = \frac{\alpha^2 + \alpha}{(1 + \alpha^2) + 2\alpha} = \frac{\alpha(\alpha + 1)}{(\alpha + 1)^2} = \frac{\alpha}{\alpha + 1} < 1 \tag{4.9}$$

  If $\delta = \pm\pi/2$, the equation 4.7 is:

$$\frac{X_2}{X} = \frac{\alpha^2}{(1+\alpha^2)} < 1 \tag{4.10}$$

> The conditions obtained in (4.9) and (4.10) illustrate the most common cases, where the angular difference between the Customer and the Utility voltage can take any value. The minimum voltage lays on an intermediate point along the aggregated impedance, for any angular difference. Additionally, the minimum value of the ratio X_2/X is $1/2$ and occurs when $\alpha \approx 1$, any other ratio produces a greater value.

Excepting the case of $\delta = 0$, the general cases lead us to the following conclusion. If the ratio X_2/X is greater than $1/2$, the magnitude of Utility's voltage source is greater than the Customer's source. This conclusion can be summarized as follows:

$$\begin{aligned} X_2 > \frac{X}{2} &\iff E_U > E_C \\ 2X_2 > X &\iff E_U > E_C \end{aligned} \tag{4.11}$$

Taking into account the previous observations, a procedure to determine the major contributor to the harmonic disturbance conditions can be established as follows. The procedure must performed at each harmonic frequency component observed from measurements.

1. Calculate the Utility voltage source from Point od Common Coupling measurments as $E_U = U_{PCC} - Z_U I_{PCC}$
2. Calculate $Q = E_U I \sin(\theta)$, where θ is the phase by which E_U leads I
3. Calculate the Critical Impedance as:

   $$CI = 2\frac{Q}{|I|^2}$$

4. If $CI > 0$,
   - Yes, then **the Customer has the major contribution to the disturbance condition**, the Customer is able to inject disturbances into the Utility.
   - No, the next options must be considered:
     (a) If $|CI| > X_{max}$, where X_{max} is the maximal aggregated impedance due to, normally, the Customers load variation, then **the Utility is the main contributor to the disturbance condition**.
     (b) If $|CI| < X_{min}$, where X_{min} is the minimal aggregated impedance due to, normally, the Customers load variation, then **the Customer is the main contributor to the disturbance condition**.
     (c) If $X_{min} < |CI| < X_{max}$, where X_{min} is the minimal aggregated impedance due to, normally, then no definite conclusion can be drawn from this analysis. The contribution of the Customer and the Utility are similar, **it cannot be established the major contribution**.

4.1.2 Generalization of Critical Impedance Method

The previous paragraphs illustrated the principle of Critical Impedance Method, using a simplified network model. For the most common situations, a more complete and general model must be considered. The presence of resistive impedance components represents the normality in the electric distribution networks, as depicted in Figure 4.2.

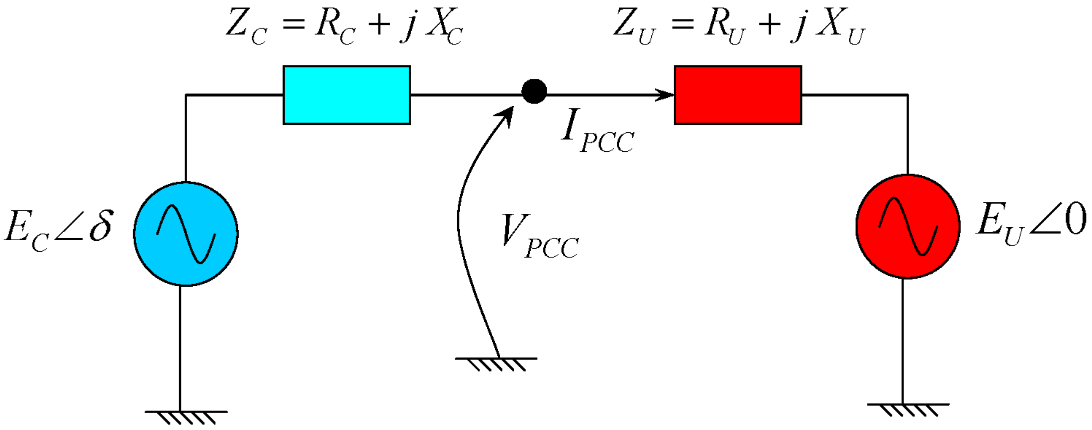

FIGURE 4.2: Critical Impedance Method for the general case

For applying the method in the general case, the same procedure described above must be carried out. The usage of a coordinate rotation transformation is required to adjust the power attained in the general case. The powers absorbed by the Utility can be calculated as follows:

$$\begin{aligned} P_U &= \frac{E_U E_C}{|Z|}\sin(\delta+\beta) - \frac{E_U^2}{|Z|}\sin(\beta) \\ Q_U &= \frac{E_U E_C}{|Z|}\cos(\delta+\beta) - \frac{E_U^2}{|Z|}\cos(\beta) \end{aligned} \tag{4.12}$$

where $\beta = \tan^{-1}(R/X)$, $R = R_U + R_C$ und $X = X_U + X_C$. The β angle is not calculated to represent directly the network's impedance angle. This angle is calculated to adjust the power expressions to the model previously developed. Applying a coordinates rotation to the powers absorbed by the Utility, which will be rotated β degrees, the following rotated power expression appears:

$$T = \begin{bmatrix} \cos\beta & -\sin\beta \\ \cos\beta & \sin\beta \end{bmatrix}$$

$$S_U = \begin{bmatrix} P_U \\ Q_U \end{bmatrix}$$

$$S_U^t = T S_U$$

$$S_U^t = \begin{bmatrix} P_U^t \\ Q_U^t \end{bmatrix} = \begin{bmatrix} \frac{E_U E_C}{|Z|}\sin(\delta) \\ \frac{E_U E_C}{|Z|}\cos(\delta) - \frac{E_U^2}{|Z|} \end{bmatrix} \tag{4.13}$$

The rotated reactive power of Equation 4.13 has the same form of the simplified case, as stated in Equation 4.3. The Critical Impedance Method for the general case uses this new expression to determine the major contributor to the disturbance condition, but some modifications must be made to the evaluation procedure as follows:

1. Calculate the Utility voltage source from Point od Common Coupling measurments as $E_U = U_{PCC} - Z_U I_{PCC}$
2. Calculate the Critical Impedance as:

$$CI = \begin{cases} 2\dfrac{E_U}{|I|}\sin(\theta+\beta) \\ \dfrac{2}{|I|^2}\left[\dfrac{E_U E_C}{|Z|}\cos(\delta) - \dfrac{E_U^2}{|Z|}\right] \end{cases} \tag{4.14}$$

3. If $CI > 0$,
    - Yes, then **the Customer has the major contribution to the disturbance condition**, the Customer is able to inject disturbances into the Utility.
    - No, the next options must be considered:
        (a) If $|CI| > |Z|_{max}$, where $|Z|_{max}$ is the maximal aggregated impedance due to, normally, the Customers load variation, then **the Utility is the main contributor to the disturbance condition**.
        (b) If $|CI| < |Z|_{min}$, where $|Z|_{min}$ is the minimal aggregated impedance due to, normally, the Customers load variation, then **the Customer is the main contributor to the disturbance condition**.
        (c) If $|Z|_{min} < |CI| < |Z|_{max}$, where $|Z|_{min}$ is the minimal aggregated impedance due to, normally, then no definite conclusion can be drawn from this analysis. The contribution of Customer and Utility are similar, **it cannot be established the major contribution**.

The flow diagram of Figure 4.3 illustrates the steps to use Critical Impedance Method described before.

4.1.3 Application of $\mathcal{CIM}$

The more relevant frequency components of the German test setup, described in the last chapter, are the 5th, 7th, 11th and 13th harmonic components. The Critical Impedance method was applied on these frequency components. The Figure 4.4 shows the rms values of the harmonic components. It can be observed that the highest harmonic component in the Induction machine group is the 11th, followed by the 5th, the 7th and 13th harmonic components are the below for most cases. In the DC Machine group, the highest harmonic component is the 5th, then the 11th, 7th and 13th are the lowest ones. At least for the two highest harmonic frequency components, the $\mathcal{CIM}$ should judge the loads as major contributors.

The Figure 4.5 shows the results provided by the Critical Impedance Method. The following observations can be made:

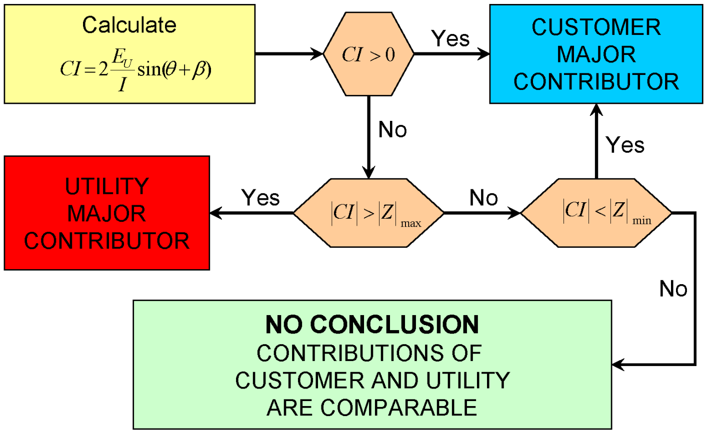

FIGURE 4.3: Critical Impedance Method for the general case

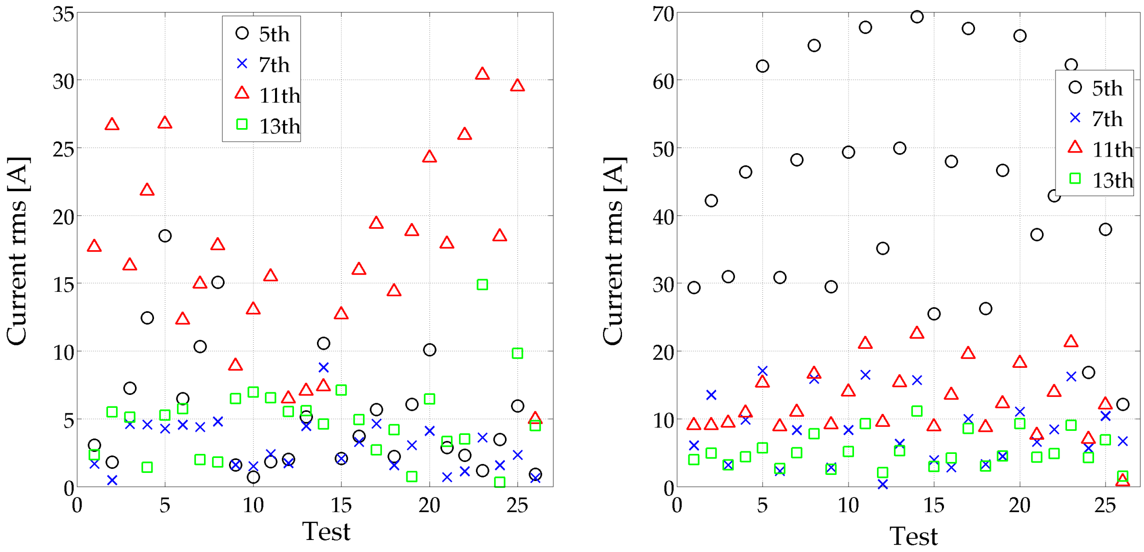

FIGURE 4.4: Harmonic current rms values for 5th, 7th, 11th and 13th components. Induction Machine group (left) and DC Machine group (right).

5th harmonic

The DC Group is judged as major contributor of the 5th harmonic component for all cases, excepting only one. This corresponds to the expected judgment. Although the Induction machine group has the 5th harmonic as the second highest $\mathcal{CIM}$ does not point out it as major contributor, this cannot necessarily means a failure in the method as the current components are lower in comparison of the currents in the DC group.

No other load was connected to the transformer during the test, then the DC group must have caused any 5th harmonic voltage component. It is noteworthy that the 5th harmonic assessment at the Induction machine group does not provide any judgment, perhaps the DC group should make this judgment to turn towards the utility.

7th harmonic

At the 7th harmonic component, the Induction group has no judgment for almost all cases, for 8 cases this load is judged as major contributor. The results for the DC group are somehow mixed, 14 times it gets judged as major contributor and 9 times the utility is judged as responsible.

11th harmonic

The Induction machine group is judged most of the cases as the major contributor. It is noteworthy that the cases without judgment correspond to intense demanded power operative conditions. The DC group is judged as major contributor at this frequency in 14 of 26 test cases, 5 cases resulted undetermined and 6 cases had the utility as major contributor. The harmonic current rms values of both loads are quite similar, revealing that the rms values does not have implication in the judgment.

13th harmonic

For the Induction machine as for the DC machine group, there is no case where the utility is judged as major contributor at the 13th harmonic. Either the loads are judged as major contributors or no judgment is provided.

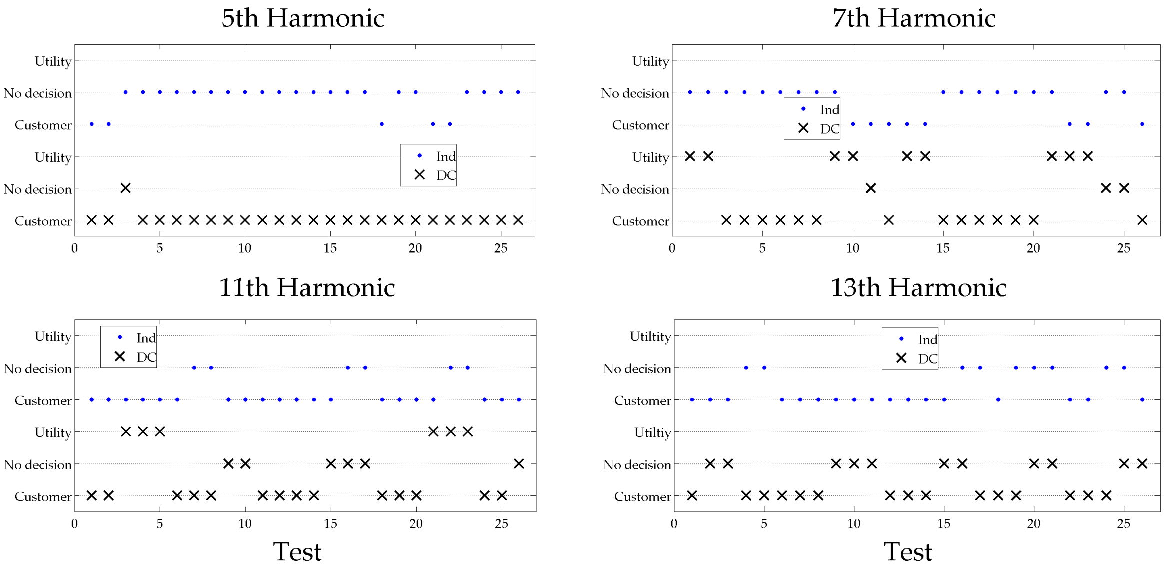

FIGURE 4.5: Application of $\mathcal{CIM}$ to German tests

4.1.4 Discussion

Some characteristics about the usage of the Critical Impedance Method must be highlighted.

- This method has the aim of determining the major contributor to the distortion condition at the Point of Common Coupling. It can be applied to to evaluate two agents

only. Thus, its application to conditions with more than two agents connected to the same PCC is restricted.

- The method foresees cases, when it is not possible to decide which is the major contributor. This situation represents a limitation of the method, furthermore those cases cannot be identified identified in advance.
- Although a qualitative determination of the major contributor helps to concentrate efforts to improve the Power Quality conditions, the method does not provide a precise quantitative estimation of the disturbing contribution.
- The $\mathcal{CIM}$ remarks an important fact related to the Responsibilities Assignment Problem - $\mathcal{R_AP}$. Both sides involved in a power quality argument, i.e. the Customer and the Utility, interact to produce a specific condition at the Point of Common Coupling. From this point of view, a question arises about the $\mathcal{R_AP}$ itself: is it more important to establish which agent is responsible or is it more relevant to determine the size of its contribution? Both criteria are very important, but a measure of the contribution is needed to determine the size of compensating devices and its corresponding power. This consideration was taken into account in the definition of the $\mathcal{R_AP}$, as it can be found in Chapter 1.
- The $\mathcal{CIM}$ proposes indirectly a very interesting discussion about the waveform distortion. Two perspectives can be taken: A collective point of view represented by the Total Harmonic Distortion in contrast to an individual point of view, represented by Individual Harmonic Distortion. Under distorted waveform conditions, the $\mathcal{CIM}$ permits to extract a conclusion like: the customer is the major responsible **for the fifth harmonic component**, the utility is responsible **for the seventh**. From the viewpoint of the Critical Impedance Method, it has all sense to assign responsibilities for each harmonic frequency component. But from the practical point of view, it proposes that the solution must be split into pieces, one part at the Customer's side and the other at the Utility's. It has sense, as it does have sense too that a whole evaluation of harmonic distortion is required in many cases.
- The Critical Impedance Method evaluates the contributions of two agents, a single Customer and its electricity Utility. Let us suppose that a first evaluation was performed, resulting that the Utility is responsible for the fifth harmonic. A new evaluation is carried out between the utility and a second customer, the result is that the utility is not responsible for the fifth harmonic. The problem with the fifth harmonic component will remain if no measures are taken, regrettably the method does not provide clear instruction about the decisions to be made. Responsibilities require the evaluation of all involved agents simultaneously, otherwise misleading results can be obtained.
- A final note about the Critical Impedance Method is related to load modeling. The $\mathcal{CIM}$ requires to model the customer and the utility. Utility's models are usually very reliable for any operation condition, inclusive when non-sinusoidal conditions are present. Modern loads are non-linear in most cases, demanding a suitable modeling technique for simulation and analysis, the application of $\mathcal{CIM}$ for instance.

Most techniques for non-linear load modeling resort to linearisation around observed operation states. Non-linear load's models extracted for specific conditions are not necessarily suitable for different conditions, then any analysis performed over them could yield misleading results. It is advisable that any responsibilities assignment method does not rely on modeling but on measurements, thus the risk of model related errors is minimum or inexistent.

- The application revealed that the method behaves as it was expected, at least for the highest harmonic frequency components. Some mixed results were found for components having lower rms values.

- Some harmonic components revealed results, where both the load and the utility are judged as major contributor. In this case, what decision should me made if both agents seem to be responsible.

4.2 Multi-point method - $\mathcal{M}_{\mathcal{P}}\mathcal{M}$

The Multi-point Method - $\mathcal{M}_{\mathcal{P}}\mathcal{M}$ was proposed by Alessandro Ferrero et al [CF94][CFS02] and [DC03]. The method consists of the calculation of three indexes, extracted from measurements. The method is capable to analyse the disturbance flow at a Point of Common Coupling with multiple customers and feeders. Therefore, the $\mathcal{M}_{\mathcal{P}}\mathcal{M}$ is capable of assessing the contribution of several users connected to the same feeder.

The Multi-point Method was designed to assess stationary disturbances propagation in a typical electric distribution system shown in Figure 4.6.

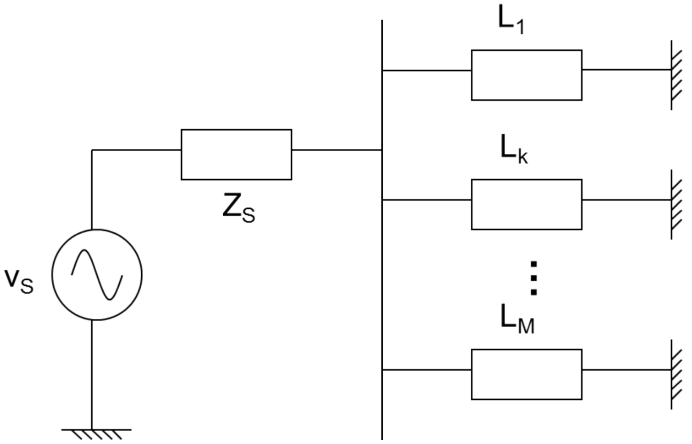

FIGURE 4.6: Multi-point Method circuit configuration

The method requires the calculation of three different indicators for each branch belonging to the system. Afterwards a weighting must be made, finally an evaluation is performed to judge the origin of disturbances. In the following paragraphs the development of the composing indicators is described.

4.2.1 Description of the method

The Multi-point Method was developed along several years and had contributions from many researchers. A short review of the $\mathcal{M}_{\mathcal{P}}\mathcal{M}$ development is presented in the following paragraphs.

4.2.1.1 First proposal of indicators

In the paper [CF94] by Loredana Cristaldi and Alessandro Ferrero, the necessity of identifying the harmonic disturbance sources was presented, in order to apply any method to reduce the harmonic contamination. In fact, the possible solutions are quite different if the harmonics come from the load than from the utility. By 1994 it was thought that the presence of a nonlinear load or source caused harmonic power flowing backward from load to the source, it was dissipated in the resistive part of the systems impedance. Thus, any harmonic active power flowing towards the source was expected to be generated at the customer's side.

The proposed method used the Clarke Transformation, introduced in Chapter 2 in (2.10) and (2.11), to calculate two complex signals, a voltage and a current. The three-phase voltages and currents must be expressed in Clarke's $\{\alpha, \beta, 0\}$ coordinate systems as follows:

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

From this new set of signals, complex voltage and currents signals must be calculated as (4.15):

$$\begin{aligned} \underset{\rightarrow}{u}(t) &= v_\alpha(t) + jv_\beta(t) \\ \underset{\rightarrow}{i}(t) &= i_\alpha(t) + ji_\beta(t) \end{aligned} \tag{4.15}$$

The signals of (4.15) can be described through their Fourier series, as follows:

$$\underset{\rightarrow}{w}(t) = \sum_{k=-\infty}^{\infty} \mathbf{W}_k e^{jkwt} \tag{4.16}$$

where $\mathbf{W}_k$ and $\mathbf{W}_{-k}$, for $k = 1, 2, \ldots$ are not complex conjugated. The frequency components of (4.16) are related to the positive and negative sequence phasors at each harmonic frequency kw. The harmonic frequency components of (4.16) are used to calculate harmonic active power components as follows:

$$P_k = \begin{cases} Re\{\mathbf{U}_k \mathbf{I}_k^*\} \text{ , for } k \geq 0 \\ Re\{\mathbf{U}_k^* \mathbf{I}_k\} \text{ , for } k < 0 \end{cases} \tag{4.17}$$

The harmonic power components are employed along with the following criteria to classify the power components:

- If the load is linear and balanced, at each harmonic frequency $|k|w$ it holds that P_k and P_{-k} are positive.
- If the load is linear but unbalanced, for some harmonic frequencies it can occur that that $P_k > 0$ and $P_{-k} < 0$, or vice versa.
- If the load is nonlinear (or time variant), it may exist some harmonic frequencies $|k|w$ at which P_k and P_{-k} are both negative.

These criteria may lead us to a sorting of the mentioned frequency components in the sets listed below:

$$\begin{aligned} K_1 &= \{k|(P_k > 0)\text{and}(P_{-k} > 0)\} \\ K_{unb} &= \{k|(P_k < 0)\text{and}(P_{-k} > 0)\} \\ K_{unb} &= \{k|(P_k > 0)\text{and}(P_{-k} < 0)\} \\ K_{nl} &= \{k|(P_k < 0)\text{and}(P_{-k} < 0)\} \end{aligned} \tag{4.18}$$

These sets permit define indicators related to load unbalance and nonlinearity. When one of these indicators are different than cero, specially the nonlinearity indicator, a source of harmonic distortion can be located. The following coefficients must be calculated:

$$\begin{aligned} C_u &= \frac{\sum_{k\in K_u, P_k<0} P_k}{P} \\ C_{nl} &= \frac{\sum_{k\in K_{nl}, P_k<0} P_k}{P} \end{aligned} \tag{4.19}$$

P is the total active power. From the sets' definition (4.18), $C_u \leq 0$ and $C_{nl} \leq 0$. If any of them are zero, its corresponding phenomenon is not predominant at any harmonic frequency.

The paper [CF94] points out an important issue in the application of any method for the $\mathcal{R}_\mathcal{A}\mathcal{P}$. If the measurement accuracy is not high enough, the location of distorting sources can be imprecise, causing the indicators to be very unreliable.

4.2.1.2 Harmonic Spectrum analysis for harmonic power calculation

Previously the harmonic active power components were employed for calculating indicators. The following procedure illustrates how to determine the frequency components required to calculate the power components. First, the harmonic spectra for each phase must be acquired from measurements, that is:

$$\begin{aligned} \big|\mathbf{F}\{u_a(t)\}\big| &= \big\{U_{a1}, U_{a3}, \ldots, U_{aN}\big\} \\ ang\big\{\mathbf{F}\{u_a(t)\}\big\} &= \big\{\alpha_{a1}, \alpha_{a3}, \ldots, \alpha_{aN}\big\} \end{aligned} \tag{4.20}$$

The signals can be represented in time domain by means of the Steinmetz transformation, using the following expressions:

$$\begin{aligned}
u_a(t) &= \sum_{k=-N}^{-1} \mathbf{U}_{ak}^{*} e^{jk\omega_0 t} + \sum_{k=1}^{N} \mathbf{U}_{ak} e^{jk\omega_0 t} \\
u_b(t) &= \sum_{k=-N}^{-1} \mathbf{U}_{bk}^{*} e^{jk\omega_0 t} + \sum_{k=1}^{N} \mathbf{U}_{bk} e^{jk\omega_0 t} \\
u_c(t) &= \sum_{k=-N}^{-1} \mathbf{U}_{ck}^{*} e^{jk\omega_0 t} + \sum_{k=1}^{N} \mathbf{U}_{ck} e^{jk\omega_0 t}
\end{aligned} \tag{4.21}$$

where:

- $\omega_0 = 2\pi f_0$
- f_0 is fundemantal frequency (50 or 60 Hz)
- $\mathbf{U}_{ak} = \frac{U_{ak}}{2} e^{j\alpha_{ak}}$
- $\mathbf{U}_{ak}^{*}$ is the conjugate of $\mathbf{U}_{ak}$
- In this expressions, all DC and zero sequence components are assumed to be zero.

The index k gives the negative sign for the left part of the series, corresponding to negative frequency components. From the last expression, the Clarke's coordinates components can be extracted using:

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{4.22}$$

which yields:

$$\begin{aligned}
u_\alpha &= \frac{2}{3} u_a - \frac{1}{3} u_b - \frac{1}{3} u_c \\
u_\beta &= \frac{1}{\sqrt{3}} u_b - \frac{1}{\sqrt{3}} u_c \\
u_0 &= \frac{1}{3}(u_a + u_b + u_c)
\end{aligned} \tag{4.23}$$

The components of (4.23) can be represented in Fourier series as:

$$\begin{aligned}
u_\alpha(t) &= \sum_{k=-N}^{-1} \mathbf{U}_{\alpha k}^{*} e^{jk\omega_0 t} + \sum_{k=1}^{N} \mathbf{U}_{\alpha k} e^{jk\omega_0 t} \\
u_\beta(t) &= \sum_{k=-N}^{-1} \mathbf{U}_{\beta k}^{*} e^{jk\omega_0 t} + \sum_{k=1}^{N} \mathbf{U}_{\beta k} e^{jk\omega_0 t}
\end{aligned} \tag{4.24}$$

where:

$$\left.\begin{aligned}\mathbf{U}_{\alpha k} &= \frac{2}{3}\mathbf{U}_{ak} - \frac{1}{3}\mathbf{U}_{bk} - \frac{1}{3}\mathbf{U}_{ck} \\ \mathbf{U}_{\beta k} &= \frac{1}{\sqrt{3}}\mathbf{U}_{bk} - \frac{1}{\sqrt{3}}\mathbf{U}_{ck}\end{aligned}\right\} \text{ for } k \geq 0 \tag{4.25}$$

$$\left.\begin{aligned}\mathbf{U}^*_{\alpha k} &= \frac{2}{3}\mathbf{U}^*_{ak} - \frac{1}{3}\mathbf{U}^*_{bk} - \frac{1}{3}\mathbf{U}^*_{ck} \\ \mathbf{U}^*_{\beta k} &= \frac{1}{\sqrt{3}}\mathbf{U}^*_{bk} - \frac{1}{\sqrt{3}}\mathbf{U}^*_{ck}\end{aligned}\right\} \text{ for } k < 0 \tag{4.26}$$

The frequency components of the complex voltage and current signals spectra, defined from the application of the Clarke's transformation to the three-phase system signals, can be summarized as follows:

$$\begin{aligned} u(t) = u_\alpha + ju_\beta &= \sum_{k=-N}^{-1} \mathbf{U}^*_k e^{jk\omega_0 t} + \sum_{k=1}^{N} \mathbf{U}_k e^{jk\omega_0 t} \\ i(t) = i_\alpha + ji_\beta &= \sum_{k=-N}^{-1} \mathbf{I}^*_k e^{jk\omega_0 t} + \sum_{k=1}^{N} \mathbf{I}_k e^{jk\omega_0 t}\end{aligned} \tag{4.27}$$

where:

$$\begin{aligned}\mathbf{U}_k &= \mathbf{U}_{\alpha k} + j\mathbf{U}_{\beta k} \text{ , for } k \geq 0 \\ \mathbf{U}^*_k &= \mathbf{U}^*_{\alpha k} + j\mathbf{U}^*_{\beta k} \text{ , for } k < 0\end{aligned} \tag{4.28}$$

Taking into account the previous results, the frequency spectra for the signals in the time domain can be calculated. The frequency components can be organized in such a manner, that the powers calculation is easily achieved.

$$\begin{aligned}\mathbf{F}\{u(t)\} &= \{\mathbf{U}^*_{-N}, \ldots, \mathbf{U}^*_{-3}, \mathbf{U}^*_{-1}, \mathbf{U}_1, \mathbf{U}_3, \ldots, \mathbf{U}_N\} \\ \mathbf{F}\{i(t)\} &= \{\mathbf{I}^*_{-N}, \ldots, \mathbf{I}^*_{-3}, \mathbf{I}^*_{-1}, \mathbf{I}_1, \mathbf{I}_3, \ldots, \mathbf{I}_N\}\end{aligned} \tag{4.29}$$

The harmonic powers are calculated from the frequency components, multiplying voltages for their respective conjugated current at each frequency. This simple procedure is summarized in the following equation:

$$P_k = \begin{cases} Re\{\mathbf{U}_k \mathbf{I}^*_k\} \text{ , for } k \geq 0 \\ Re\{\mathbf{U}^*_k \mathbf{I}_k\} \text{ , for } k < 0 \end{cases} \tag{4.30}$$

4.2.1.3 Harmonic Phase ξ_{HPI} and Global Index ξ_{HGI}

The paper [Mus98], written by Carlo Muscas, proposes two indicators for assessing the location of a disturbing load. Both indicators are based on the harmonic active power direction to decide if a harmonic component is generated by the user or comes from the system.

Harmonic Phase Index ξ_{HPI}

Current harmonic components are split into two sets: $\mathbf{I}_S$ with the current components whose harmonic active power is $P_k \geq 0$; $\mathbf{I}_L$ with the current components whose harmonic active power is $P_k < 0$. This classification does not perform any transformation on the signals, the frequency components are the phase $\{a, b, c\}$ components. If the fundamental frequency component has a negative sequence component and its corresponding power is $P_{-1} < 0$, then this current component is added to the set $\mathbf{I}_L$. The harmonic phase index ξ_{HPI} is calculated as follows:

$$\xi_{HPI} = \frac{k_{-1}||\mathbf{I}_{-1}||^2 + ||\mathbf{I}_L||^2}{||\mathbf{I}_S||^2} \tag{4.31}$$

Harmonic Global Index ξ_{HGI}

Currents are transformed using Clarke's transformation, defining the complex current $\underset{\rightarrow}{i}(t)$, using exactly the same procedure for (4.15). The harmonic active powers of (4.30) are used to split the current's harmonic components into the sets $\mathbf{I}_S$ and $\mathbf{I}_L$. Current components with harmonic active powers $P_k < 0$ are assigned to $\mathbf{I}_L$, the remaining components are assigned to $\mathbf{I}_S$.

The harmonic phase index ξ_{HGI} is calculated as follows:

$$\xi_{HGI} = \frac{||\mathbf{I}_L||^2}{||\mathbf{I}_S||^2} \tag{4.32}$$

If any of those indicators in greater than zero, the customer is supposed to be generating the disturbances.

4.2.1.4 Multi-point Method

A method based on multi-point measurements to evaluate the location of a disturbing source was proposed in [CFS02] and an indicator based on that method was first proposed in [DC03]. The innovation presented in [DC03] is the usage of three indicators, whose individual application could fail to assess the disturbance location. The three indicators are weighted with the hope that a combination of all of them provides better results. The mentioned indicators are listed below:

Global Total Harmonic Distortion Factor Ratio

The following indexes, explained in detail in [FMS96], provide information about the distortion of a three-phase system and ought to be calculated as:

$$\begin{aligned} \mathsf{GTHD}_U &= \sqrt{\frac{U_\Sigma^2}{U_{\Sigma_1}^2} - 1} & \mathsf{GTHD}_{U+} &= \sqrt{\frac{U_\Sigma^2}{U_{\Sigma_{+1}}^2} - 1} \\ \mathsf{GTHD}_I &= \sqrt{\frac{I_\Sigma^2}{I_{\Sigma_1}^2} - 1} & \mathsf{GTHD}_{I+} &= \sqrt{\frac{I_\Sigma^2}{I_{\Sigma_{+1}}^2} - 1} \end{aligned} \tag{4.33}$$

where U_Σ, U_{Σ_1} and $U_{\Sigma_{+1}}$ are the collective, fundamental collective and positive sequence collective rms values, respectively, the symbols for the currents are similar. These quantities were defined in Chapter 2, see Equation (2.9).

The ratios between the global harmonic factors, as stated in [CFS02], 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. These ratios are calculated as follows:

$$\eta = \frac{\mathsf{GTHD}_I}{\mathsf{GTHD}_U} \qquad \eta^+ = \frac{\mathsf{GTHD}_{I+}}{\mathsf{GTHD}_{U+}} \tag{4.34}$$

Supply and Load Quality Index

This index was proposed by Alessandro Ferrero et al in [FMS96]. It establishes a relationship between the total active power and the total active power associated to the fundamental positive sequence component, that is:

$$\xi_{slq} = \frac{P_\Sigma}{P_{\Sigma_{+1}}} \tag{4.35}$$

Harmonic Global Index

This index was proposed by Carlo Muscas in [Mus98] and explained in the previous paragraphs. This indicator relates the three-phase collective rms current value of the components associated to the harmonic power flowing from the load backward to the source, $|\mathbf{I}_{\Sigma_L}|$, and that of the power flowing from the source toward the load, $|\mathbf{I}_{\Sigma_S}|$.

$$\xi_{HGI} = \frac{||\mathbf{I}_{\Sigma_L}||^2}{||\mathbf{I}_{\Sigma_S}||^2} \tag{4.36}$$

By measuring the indexes related to each circuit connected to the PCC, as depicted in Figure 4.6, including the feeder line. These indexes can be improved. Comparing the indexes by means of ratios, it is possible to extract some conclusions additional conclusions:

- The indexes ξ_{HGI_k} and η_k^+ corresponding to one customer k line can be divided by the feeder indexes, ξ_{HGI_s} and η_s^+ respectively. This ratios increase if the disturbance is injected by the customer to the supply line and decrease if the disturbance comes from the supply side.
- The ratio between the index ξ_{slq_k} and ξ_{slq_s} has an inverse relationship, that is this ratio gets higher when the disturbance comes from the supply side and gets lower for disturbances produced at the customer k.

As stated in the paper [CFS02]:

> *This can be explained by the fact that, due to the different equivalent sources seen by the metering section connected to the supplying PCC and the lines supplying the single loads, the index variations caused by the disturbances injected*

> *by the loads are greater than those affecting the same index measured on the line supplying the PCC. Vice versa, if the disturbances are injected by the supply, the variations of the indexes measured on the supply line are greater than those measured on the other lines.*

Considering the interpretation of each index and their corresponding ratios, the following index was proposed for each customer k:

$$\upsilon_k = \frac{1}{3}\left(\frac{\xi_{slq_k}{}^{-1}}{\xi_{slq_s}{}^{-1}} + \frac{\xi_{HGI_k}}{\xi_{HGI_s}} + \frac{\eta_k^+}{\eta_s^+}\right) \tag{4.37}$$

where s subscript means "supply" and k means k-customer. Under sinusoidal conditions, $\upsilon_k = 1$, it 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. Some examples to illustrate the application of this methodology can be found in [CFS02] and [DC03].

4.2.2 Multi-point Method revisited

An adjustment to the Multi Point Method presented in [CFS02] was presented in [CFST04]. The change proposed for the $\mathcal{M}_{\mathcal{P}}\mathcal{M}$ is a different weighting to each index, in order to contemplate some particular variations of each subindex corresponding to load changes.

$$\upsilon_k = \frac{1}{\gamma + \alpha + \beta}\left(\gamma\frac{\xi^{-1}_{slg_k}}{\xi^{-1}_{slg_s}} + \alpha\frac{\xi_{HGI_k}}{\xi_{HGI_k}} + \beta\frac{\eta_k^+}{\eta_s^+}\right) \tag{4.38}$$

The factors γ , α and β weight the indexes. This weighting factors are calculated as follows:

$$\gamma = 1$$

$$\alpha = \frac{N}{\sum_{k=1}^{N}\frac{\xi_{HGI_k}}{\xi_{HGI_s}}}\left(\frac{I_{\Sigma_k}}{I_{\Sigma_{n_k}}}\right)/\left(\frac{I_{\Sigma_s}}{I_{\Sigma_{n_k}}}\right) \tag{4.39}$$

$$\beta = \left(\frac{I_{\Sigma_k}}{I_{\Sigma_{n_k}}}\right)/\left(\frac{I_{\Sigma_s}}{I_{\Sigma_{n_k}}}\right) \tag{4.40}$$

4.2.3 Application of $\mathcal{MPM}$

The Multi-point Method is going to be illustrated resorting to the German setup. As it was explained in Chapter 3, two machine groups were employed. The DC machine group caused a coherent distortion for any operative condition, the Induction machine group caused increasing disturbances as its demanded power increased.

In order to illustrate easily the results, the $\mathcal{MPM}$ index will be plotted against each test's active power. Results achieved form both feeding configurations (separated transformers and transformer 2) will be shown. The Figure 4.7 shows the results of applying the method, each load's trend was shaded.

It can be seen that the method does not work as it would be expected. For positive active power, no load is responsible for disturbing the network, such results do not correspond to the loads behavior. There could be many reasons for this, the fact is that the method itself does not identify the disturbing behavior of the test.

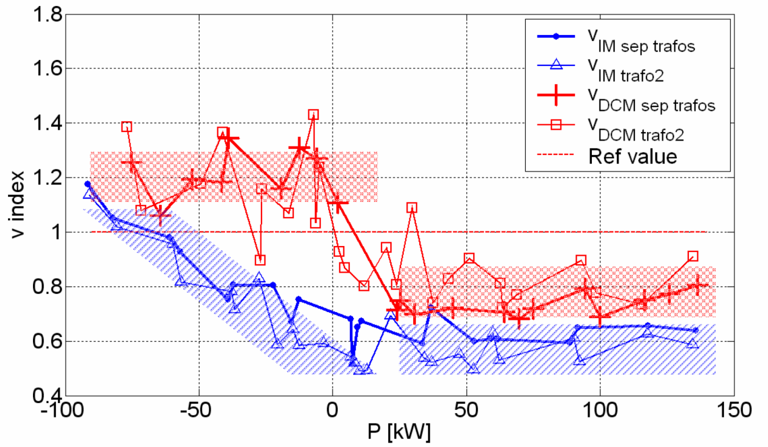

FIGURE 4.7: $\mathcal{MPM}$ indices

Resorting to the current decomposition presented in Chapter 2, some modifications to the $\mathcal{MPM}$ were performed. First, the active currents (2.20) were subtracted, the remaining currents are the non-active ones (2.22). The results of the application of the $\mathcal{MPM}$ are displayed in Figure 4.8. A new trend starts to appear in the modified indicators, specially for strong power conditions. Nevertheless, for low power operative cases, the index does not judges properly, a new modification seems to be necessary.

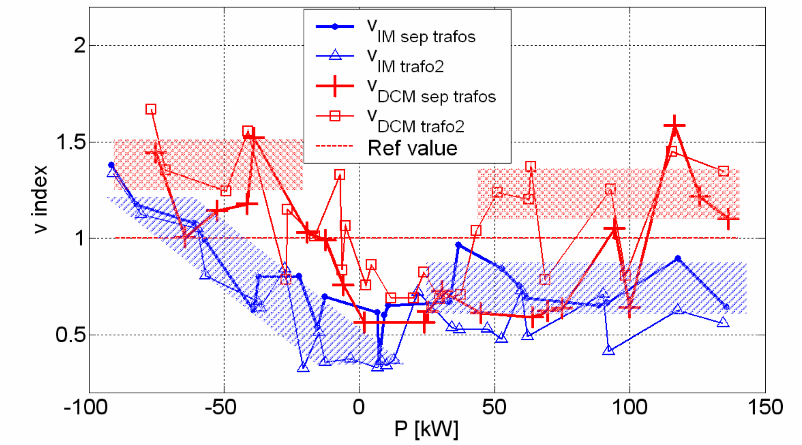

FIGURE 4.8: $\mathcal{MPM}$ indices. Active current subtracted, Non-active current evaluated

The second modification consists of removing the currents related to the fundamental frequency reactive power. This current component was determined using a procedure analog to (2.49) for the displaced current, but the voltage frequency components were filtered, only the fundamental frequency was held. The results are shown in Figure 4.9.

This modification does not present any improvement compared to the previous cases.

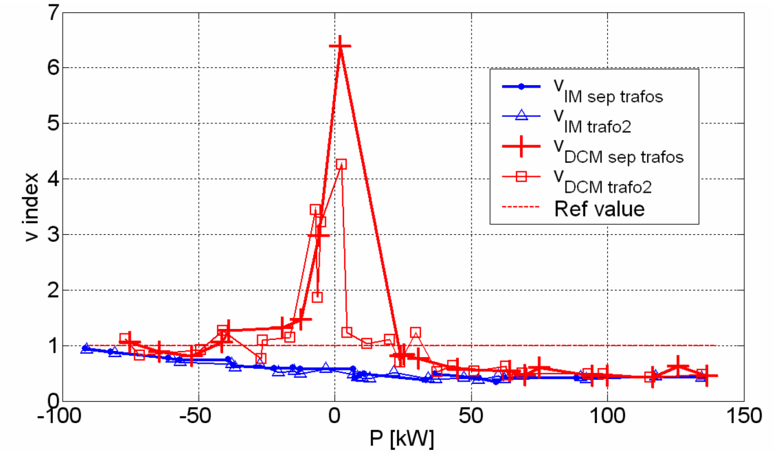

FIGURE 4.9: $\mathcal{MPM}$ indices. Fundamental reactive current subtracted

A last modification was tried. Now the active current and the reactive current were removed. The results are shown in Figure 4.10. The indicator's trend adjusts to the expected behavior: the DC machine group is always judged as responsible; the Induction machine group increases its index as its demanded power increases. However, the values are not adjusted to the reference level of $\upsilon_k = 1$. This can be solved adjusting the weights or changing the reference level. These adjustments will not be presented in the thesis and are left for future work.

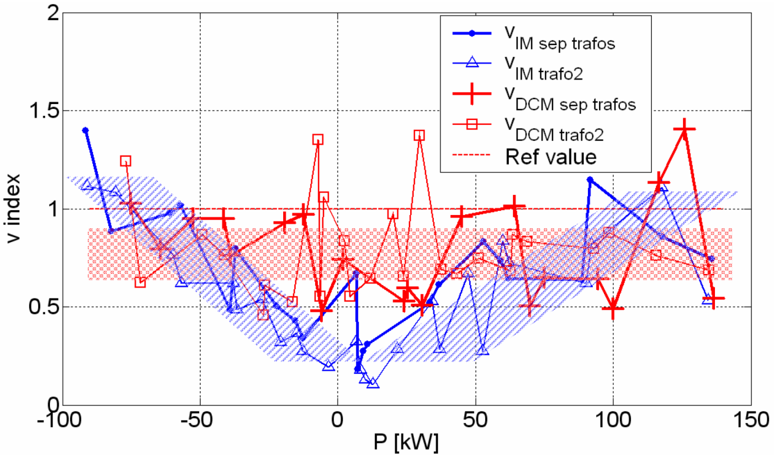

FIGURE 4.10: $\mathcal{MPM}$ indices. Active and Reactive currents subtracted, Distorted Current remaining

4.2.4 Discussion

The review and application of the Multi-point Method, so as its composing indicators, permit the following observations.

- The usage of the harmonic real power has been discussed by many researchers. Special attention should be paid to the fact that this power is a very small quantity. Measuring the harmonic active power is a difficult task to carry out. The interaction among customers and utilities can influence the magnitude and the direction of these powers, even if the distorting or unbalance producing condition remains changed. The usage of distributed energy resources can affect the flow of harmonic active components, such situation needs to be carefully assessed.

- The $\mathcal{M}_{\mathcal{P}}\mathcal{M}$ proposes the evaluation of harmonic sources location and also pretends to assess unbalance. However, no separation of these phenomena is made, so the proposed index could assess both conditions indistinctly. If an index does not discriminate between asymmetry and distortion, a conclusion cannot be easily extracted about each phenomenon.

- The indicators extracted from effective values can provide information about asymmetry or distortion conditions. Additionally, they can be handled in a very simple manner because they are real positive values. Nevertheless, this effective values must be calculated taking into account which phenomenon is being analysed, because these indexes can involve both conditions simultaneously.

- This method gave a step forward in the direction of assessing power quality by means of multiple site measurements. Although some questions about its validity remain unsolved, the $\mathcal{M}_{\mathcal{P}}\mathcal{M}$ represents a valuable advance.

- The Multi-point Method does not seem to be able of providing the expected results when it is applied to a reference disturbance test. However, the $\mathcal{M}_{\mathcal{P}}\mathcal{M}$ can be improved by using the current decomposition proposed in Chapter 2.

4.3 Harmonic pollution method - $\mathcal{HPM}$

The Harmonic Pollution Method, proposed by Alexander Eigeles Emanuel et al in [DEP00], suggests an approach for quantifying the contribution of the customers to an specific branch belonging to an electric network. This method was not proposed to evaluate the origin of the disturbances. The $\mathcal{HPM}$ evaluates the customer's contribution at a specific point of interest of an electric system, as depicted n Figure 4.11. The currents of all branches belonging to the network are projected on the current of the interest branch. Some currents contribute to increase the current, others cause that current to decrease.

4.3.1 Description of the method

The method proposed by Alexander Emanuel et al [DEP00], 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 (4.41) depending on the contribution of each element connected to the system:

$$\xi = f\left[\sum_{h,h\neq 1} (w_h I_h)^2\right] \tag{4.41}$$

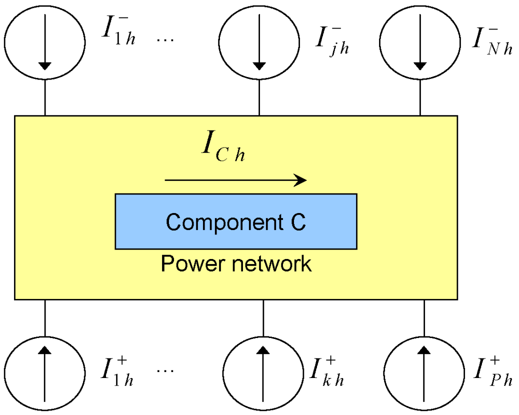

FIGURE 4.11: Description of the Harmonic Pollution Method

where w_h is a weighting, whose value depends on the harmonic order h and the behavior of the element itself. The $\mathcal{HPM}$ 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. This classification is shown in Figure 4.12.

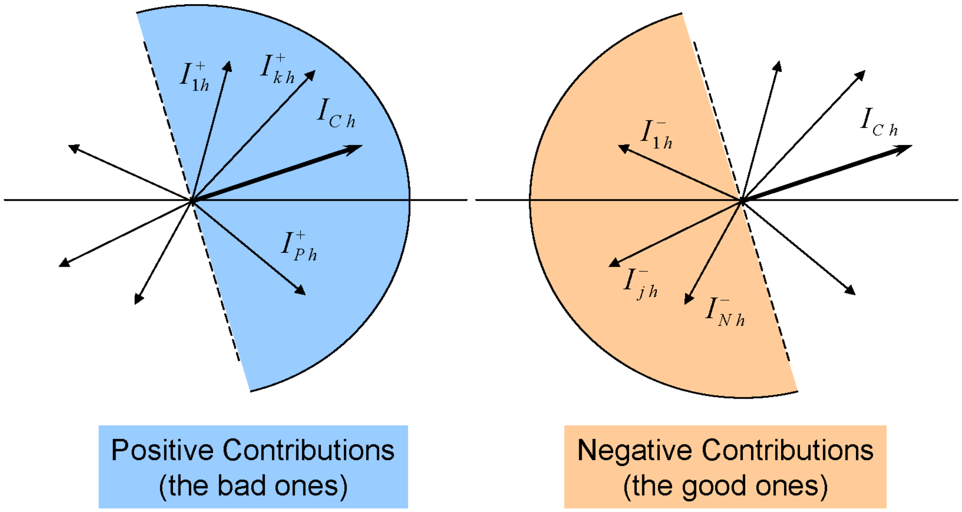

FIGURE 4.12: Separation of currents into N and P sets

It is possible to determine the negative and positive contribution of each customer to the point under study in order to calculate the cost function, as shown in (4.42).

$$\sum_{h,h\neq1} w_h^2 I_{Ch}^2 = \sum_{h,h\neq1} w_h^2 \left[A_h \sum_{k=1}^{P} \tilde{I}_{pkh}^2 + B_h \sum_{j=1}^{N} \tilde{I}_{njh}^2\right] \tag{4.42}$$

In (4.42) $\tilde{I}_{pkh}$ 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.

$$\begin{aligned}\hat{I}^{+}_{Ckh} &= \hat{\alpha}^{+}_{Ckh}\hat{I}^{+}_{kh}\\ \hat{I}^{-}_{Cjh} &= \hat{\alpha}^{-}_{Cjh}\hat{I}^{-}_{jh}\end{aligned} \tag{4.43}$$

where:

- h is the harmonic index
- $k \in P$
- $j \in N$
- $\hat{I}$ and $\hat{\alpha}$ are complex numbers. The number $\hat{\alpha}$ is the projection factor of $\hat{I}^{+}_{kh}$ over the interest current $\hat{I}^{+}_{Ckh}$.

All projections are compared with the current $\hat{I}^{+}_{Ch}$ and classified into the P or N groups. The projection can be carried out using the phasor angles of all currents at each frequency component, as described in Figure 4.13.

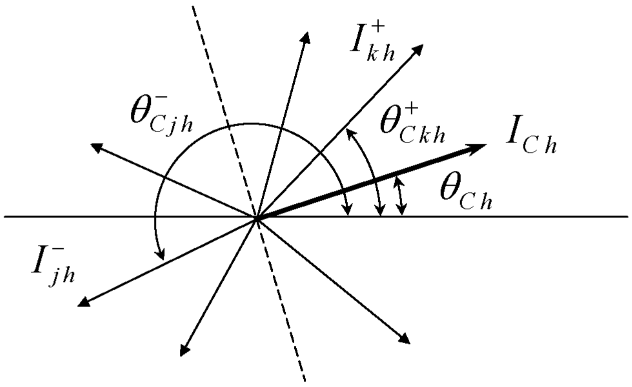

FIGURE 4.13: Angles for the harmonic k

All contributions belonging to each P or N group are calculated as (4.44):

$$\begin{aligned}I_{Ph} &= \sum_{k=1}^{P} I_{pkh}, \quad I_{pkh} = I^{+}_{Ckh}\cos(\theta^{+}_{Ckh} - \theta_{Ch})\\ I_{Nh} &= \sum_{j=1}^{N} I_{njh}, \quad I_{njh} = I^{-}_{Cjh}\cos(\theta^{-}_{Cjh} - \theta_{Ch})\end{aligned} \tag{4.44}$$

The current projections accomplish the current balance of (4.45):

$$I_{Ch} = I_{Ph} - I_{Nh} \tag{4.45}$$

The magnitude of I_{Ch} will allow the calculation of the projection factors. From (4.45), the magnitude of I_{Ch} is:

$$\begin{aligned} I_{Ch}^2 = \left(I_{Ph} - I_{Nh}\right)^2 &= I_{Ph}^2 + I_{Nh}^2 - 2I_{Ph}I_{Nh} \\ 2I_{Ph}I_{Nh} &= \left(A' + B'\right)2I_{Ph}I_{Nh} \\ A' &= 2I_{Ph}I_{Nh}\frac{I_{Ph}^2}{I_{Ph}^2 + I_{Nh}^2} \\ B' &= 2I_{Ph}I_{Nh}\frac{I_{Nh}^2}{I_{Ph}^2 + I_{Nh}^2} \end{aligned} \tag{4.46}$$

From (4.46), the magnitude of I_{Ch} can be reformulated as:

$$\begin{aligned} & I_{Ch}^2 = I_{Ph}^2 + I_{Nh}^2 - 2I_{Ph}I_{Nh} \\ & I_{Ch}^2 = A_h I_{Ph}^2 + B_h I_{Nh}^2 \\ & I_{Ch}^2 = I_{Ph}^2 - 2I_{Ph}I_{Nh}\frac{I_{Ph}^2}{I_{Ph}^2 + I_{Nh}^2} + I_{Nh}^2 - 2I_{Ph}I_{Nh}\frac{I_{Nh}^2}{I_{Ph}^2 + I_{Nh}^2} \end{aligned} \tag{4.47}$$

Both factors A_h and B_h are equal are calculated using (4.48):

$$A_h = B_h = 1 - 2I_{Ph}I_{Nh}\frac{I_{Nh}^2}{I_{Ph}^2 + I_{Nh}^2} \tag{4.48}$$

The previous results allow the calculation of the positive and negative contributions with (4.49) and (4.50), as follows:

$$\begin{aligned} I_{Ph}^2 &= \left(\sum_{k=1}^{P} I_{pkh}\right)^2 \\ &= \sum_{k=1}^{P}\left[I_{pkh}^2 + 2I_{pkh}\sum_{i=k+1}^{P} I_{pih}\right] \\ &= \sum_{k=1}^{P} \tilde{I}_{pkh}^2 \\ \tilde{I}_{pkh}^2 &= I_{pkh}^2 + 2I_{pkh}\sum_{\substack{k=1 \\ i\neq k}}^{P} a_{pkih}I_{pih} \\ a_{pkih} &= \frac{I_{pkh}^2}{I_{pkh}^2 + I_{pih}^2} \end{aligned} \tag{4.49}$$

$$\begin{aligned} I_{Nh}^2 &= \left(\sum_{j=1}^{N} I_{njh}\right)^2 \\ &= \sum_{j=1}^{N}\left[I_{njh}^2 + 2I_{njh}\sum_{i=k+1}^{N} I_{nih}\right] \\ &= \sum_{j=1}^{P} \tilde{I}_{pjh}^2 \qquad (4.50) \\ \tilde{I}_{njh}^2 &= I_{njh}^2 + 2I_{njh}\sum_{\substack{j=1\\ i\neq j}}^{P} b_{njih} I_{nih} \\ b_{njih} &= \frac{I_{njh}^2}{I_{njh}^2 + I_{nih}^2} \end{aligned}$$

The cost function (4.42) can be calculated now using the measured current components:

$$\begin{aligned} \sum_{h,h\neq 1} w_h^2 I_{Ch}^2 &= \sum_{h,h\neq 1} w_h^2 \left[A_h \sum_{k=1}^{P} \tilde{I}_{pkh}^2 + B_h \sum_{j=1}^{N} \tilde{I}_{njh}^2\right] \\ &= \sum_{k=1}^{P}\sum_{h,h\neq 1} w_h^2 A_h \tilde{I}_{pkh}^2 + \sum_{j=1}^{N}\sum_{h,h\neq 1} w_h^2 B_h \tilde{I}_{njh}^2 \end{aligned} \qquad (4.51)$$

4.3.2 Application of $\mathcal{HPM}$

The German test setup fed by transformer 2 was employed to illustrate the Harmonic Pollution Method. Positive and negative contributions to the feeder's current are shown in Figure 4.14. Contributions are normalised with respect to each squared rms corresponding current.

The application of the method reveals which load has a major contribution the the harmonic current of the feeder. Doubtless the DC machine group has greater positive contributions than the Induction machine group, just for two cases this result is not applicable, but it is quite clear the predominance of the DC group as major contributor.

It seems that the Induction machine group has the opposed behavior regarding the negative contributions. It looks like almost all cases have a major contribution of the Induction machine group in comparison to the negative contributions of the DC machine load.

These results show that the distortion of the feeder's current gets increased by the operation of the DC machine group and decreased by the operation of the Induction machine load. The contributions have different magnitudes for each case. In an uncontrolled experiment these magnitude would probably change randomly. Thus, the usage of statistics can help to characterise the quantities easier. Figure 4.15 shows the cumulative probability distributions of both negative and positive contributions.

From Figure 4.15, the expected positive contributions can be extracted: Induction group has a contribution below 0.5%, the DC group has approximately 4.0%. The 90%

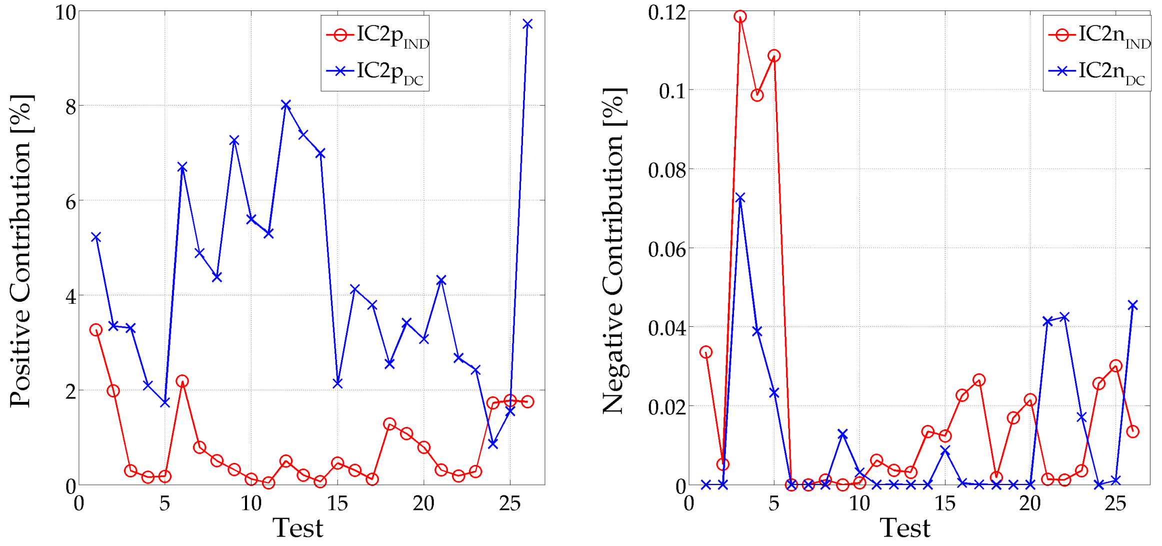

FIGURE 4.14: Positive and negative contributions of both loads to feeder's current

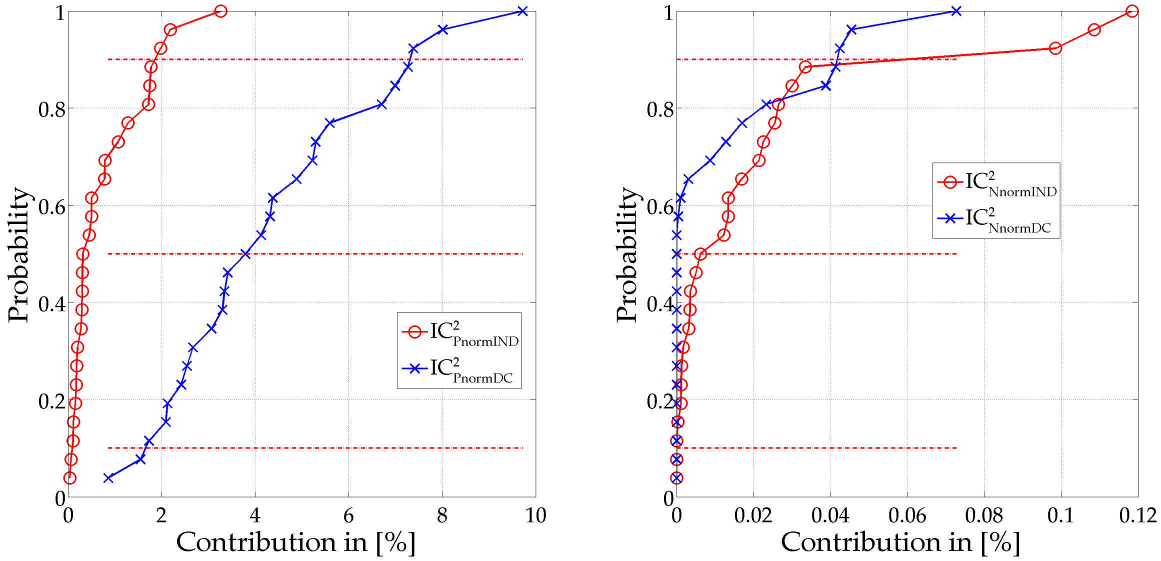

FIGURE 4.15: Cumulative probability functions for positive and negative contributions

percentiles for the Induction and DC groups are 1.9% 7.3%, respectively. The negative contributions' expected values are 0.0% and 0.05% for the DC and Induction machine groups, respectively. The DC group has a 60% probability of having a negative contribution of 0.0%.

4.3.3 Discussion

It was stated from the beginning of this section, the Harmonic Pollution Method was not proposed to evaluate the origin of disturbances. The most attractive attribute of this method is its capability of quantifying the contribution of several agents connected to a point of common coupling. Its application on more complex systems requires the modeling of the network to calculate the current's projections at each point of interest. The networks models are not expected to affect the accuracy in the calculation of projections, then the method promises good results for those cases.

The method requires multi point measurements for the contributions' calculation. Furthermore, the authors consider that there is not other way to assess the contributions but using measurements in all agents.

The $\mathcal{HPM}$ current classification has been used with the orthogonal decomposition proposed previously to develop another method to assess responsibilities, it will be described in the following section.

4.4 Method of Disturbances Interaction - $\mathcal{M}_{\mathcal{D}}\mathcal{I}$

The Method of Disturbances Interaction - $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ consists in performing an orthogonal decomposition of currents and comparing them using the reference conditions described in [PST10]. The proposed decomposition is based on the FBD Power Theory proposed by Manfred Depenbrock [Dep93][Sta08] for stationary cases and on the current decomposition presented in the German Standards 40110-1 and 40110-2 [DIfN94],[DIfN96], which are based partially on Depenbrock's power theory as well.

The $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ was designed to fulfill the necessities identified in the review of the available method for the assessment of responsibilities in power quality. It does not solve completely the Responsibilities Assignment Problem, described in Chapter 1, but is gives s step forward to provide a more suitable alternative to evaluate and distribute the contribution of agents to the power quality conditions.

4.4.1 Description of the method

The $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ comprises five stages described in the following paragraphs. The currents orthogonal decomposition proposed in [PST10] allows to analyse how the components of one circuit interact with the components of other circuits connected to the same Point of Common Coupling. Such analysis provides information about the flow of current components and how the components interact.

The current components must be compared by means of inner products (2.6). The five current components proposed in Chapter 2 for poly-phase systems must be used: active i_a, displaced i_{Qd}, unbalanced active i_{au}, unbalanced displaced i_{Qu} and distorted i_D. The comparison of current components provides information on the active power flow and on the flow of the three considered stationary disturbances, as it is summarized in Table 4.1.

In order to properly assess the interaction of disturbances among customers and utilities, measurements must be carried out along a suitable period of time. The IEC Standard 61000-4-30 [IEC08] proposes a power quality measurement procedure, described briefly as follows:

Phenomenon	Current Component				
	i_a	i_{Qd}	i_D	i_{au}	i_{Qu}
Active Power	✓	-	-	✓	-
Phase Displacement	-	✓	-	-	✓
Waveform Distortion	-	-	✓	-	-
Unbalance	-	-	-	✓	✓

TABLE 4.1: Relationship among phenomena and current components for single- and poly-phase circuits

- All stationary signals must be measured using time windows each 200ms, suitable sampling frequencies are suggested according to the maximum expected frequency components and the rated frequency. Sampling rates of 256 and 512 samples per cycle are commonly used by commercial devices and accomplish the requirements of IEC Standard 61000-4-7 [IEC02].

- From each 200 ms time window, all rms values, powers, unbalance indicators, harmonic components, etc., must be calculated. These values are aggregated along registering times. The IEC standard suggests 3 seconds, 1 minute and 10 minutes registering intervals. The measurements aggregation means to calculate the rms value of all 200 ms rms related values acquired along the registering interval. The aggregated values will be compared with power quality standards in order to assess limits compliance.

- Several registering intervals must be recorded. A one week minimum monitoring time is suggested. Longer monitoring periods are desirable, lesser than one week can be used in particular cases only.

A proper Power Quality analysis depends strongly on the accuracy of current and voltage measurement equipment, either the measurement devices as the signals transducers. As long as these devices have a proper bandwidth and do not saturate for the measured currents, the $\mathcal{M_DI}$ can be applied without any inconvenience. However, if the saturation limits of current transducers are exceeded, for instance under short circuit or high resonant currents, the measurements will not represent the actual condition of the system and the method will yield wrong results. If the currents are measured properly even for those extreme conditions, the $\mathcal{M_DI}$ will provide useful information. The $\mathcal{M_DI}$ comprises five stages, described below.

4.4.1.1 Ordering Currents

First, a sign must be assigned to each current in such a manner that the sum of all currents is always zero at any time point. For accomplishing this purpose, a direction convention around a point of common coupling is defined from here on: currents *coming from* the system or utilities into the PCC are *negative*; currents *flowing out* the PCC into the loads are *positive*. This convention does not influence the results, simply provides a reference for analysis. The Figure 4.16 shows how the currents need to be reasigned, currents i^*_A

and i_B^* belopng to the feeders, they are expected to deliver energy to the loads L_1, L_2 and L_3 connected to the PCC, whose currents are i_1, i_2 and i_3.

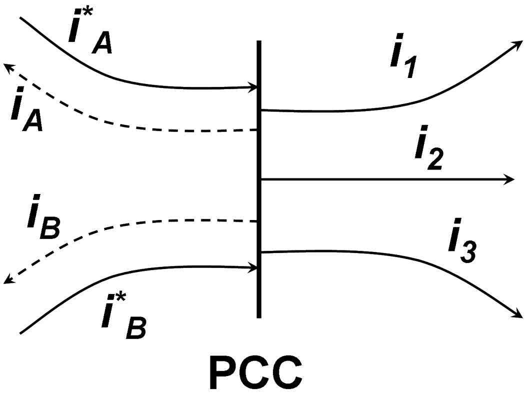

FIGURE 4.16: Currents diagram

4.4.1.2 Orthogonal current decomposition

Once a sign has been assigned to each current, three components i_a, i_{Qd} and i_D for single-phase circuits and five components i_a, $i_a u$, i_{Qu}, i_{Qd} and i_D for poly-phase must be calculated. The decomposition procedure and its properties were presented in Chapter 2.

4.4.1.3 Calculation of Interaction Matrices

The inner product comparison has two factors: the first factor is the signal under comparison i_X^k, where X represents the circuit the current belongs to, $X \in \{A, B, 1, 2, 3\}$, and k the current component under analysis, $k \in \{a, au, Qu, Qd, D\}$. The second factor is the signal, which the signal i_X^k is compared to, i_Y^k. Two sets of indicators are calculated: the normalized interaction matrix and the interaction matrix. Each term of the normalized interaction matrix is calculated as shown in (4.52), the terms of the interaction matrix are calculated according to (4.53).

$$\xi(i_X^k, i_Y^k) = \frac{\langle i_X^k, i_Y^k \rangle}{I_X^k} \tag{4.52}$$

$$\eta(i_X^k, i_Y^k) = \langle i_X^k, i_Y^k \rangle \tag{4.53}$$

Current components of the same kind and the same conductor must be compared. The decomposition is orthogonal, therefore the inner product of currents of different kinds yields always zero $\langle i_X^k, i_X^j \rangle = 0$. Each term of the normalized interaction matrix $[\xi]$ is useful to establish how all circuits interact with each other for every current component (disturbance type). The terms of the interaction matrix $[\eta]$ are used to determine the contributions of each circuit, for this purpose the contributions need to be calculated as will be explained below.

4.4.1.4 Organising the Interaction Matrices

Diagonal components of $[\xi]$ are always positive and represent the rms value of the corresponding current. If no normalization were employed (4.53), diagonal values would be the squared rms values. The sum of all values of the column corresponding to the circuit X, is always zero due to the currents ordering described in the first $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ step. This means that the current rms value I_X^k is the sum of the inner products of i_X^k times the currents of the resting circuits. For example, at the circuit B:

$$\begin{aligned} I_B^k &= \frac{\langle i_B^k, i_B^k\rangle}{I_B^k} \\ 0 &= \frac{\langle i_B^k, i_A^k\rangle}{I_B^k} + \frac{\langle i_B^k, i_B^k\rangle}{I_B^k} + \frac{\langle i_B^k, i_1^k\rangle}{I_B^k} + \frac{\langle i_B^k, i_2^k\rangle}{I_B^k} + \frac{\langle i_B^k, i_3^k\rangle}{I_B^k} \end{aligned} \tag{4.54}$$

In order to accomplish the sum of (4.54), where $I_B^k \neq 0$, some terms must be negative and some positive. The inner product comparison reveals how similar two signals are. For instance, let us assume that the distorting currents of two circuits are compared. If the inner product is zero, no interaction between the signals exists, this means that no distorted current flows from one circuit to the other. If the inner product is grater than zero, both circuits interact with a third one in such a manner that: either they receive distorted currents from the third, or they inject them into it. For inner products less than zero, both circuits interact in such a manner they interchange distorted currents.

All positive terms represent disturbance acting on the same direction and negative ones on the opposite, i.e., the *positive terms* contribute to make the rms current value of the component k *higher* and *negative terms* contribute to make it *lower*. Regarding the previous considerations, the matrix $[\xi]$ can be reordered according to the signs. Let us suppose that i_A^k and i_2^k interact together against the group composed by i_B, i_1 and i_3, thus the reordered interaction matrix has the form of (4.55).

$$\begin{array}{cc}
 & \begin{array}{ccccccc} i_A & & i_2 & i_B & & i_1 & i_3 \end{array} \\
\begin{array}{c} i_A \\ \\ i_2 \\ i_B \\ \\ i_1 \\ i_3 \end{array} & \left[\begin{array}{ccccccc} + & & + & - & & - & - \\ & G_\alpha & & & & & \\ + & & + & - & & - & - \\ - & & - & + & & + & + \\ & & & & G_\beta & & \\ - & & - & + & & + & + \\ - & & - & + & & + & + \end{array}\right]
\end{array} \tag{4.55}$$

Two groups can be defined, G_α and G_β for each current component $k \in \{a, au, Qu, Qd, D\}$. The interpretation of this result is: For the current component $k \in \{a, au, Qu, Qd, D\}$, circuits A and 2 interact as a group with the group composed by the circuits B, 1 and 3. The specific flow direction of the disturbance cannot be established, but the circuits where the disturbance is concentrated can be precisely determined. In the case where a single circuit is assigned to any of the groups, it would mean that: either the disturbance is generated in that circuit or the disturbance is being absorbed completely by the circuit. This decomposition and ordering provides information about how stationary disturbances are distributed among all circuits connected to a point of common coupling.

In order to take into account the contributions of all conductors belonging to each circuit in poly-phase circuits with n conductors, the interaction matrix must be constructed in a different manner. The procedure is described as follows.

- An interaction matrix $\left[\eta(i_k^j)\right]$ must be calculated, where k is the current component and j one of the n conductors. The matrix $[\eta]$ is calculated as:

$$\eta(i^k_{(X,j)}, i^k_{(Y,j)}) = \langle i^k_{(X,j)}, i^k_{(Y,j)} \rangle \tag{4.56}$$

  where X and Y represent the circuits to be compared.

- The components of each $[\eta]$ matrix belonging to each circuit must be added for all conductors, yielding:

$$\eta(\mathbf{i}^k_X, \mathbf{i}^k_Y) = \sum_{j=1}^{n} \eta(i^k_{(X,j)}, i^k_{(Y,j)}) \tag{4.57}$$

- The poly-phase case normalized interaction matrix is calculated as:

$$\xi(\mathbf{i}^k_X, \mathbf{i}^k_Y) = \frac{\eta(\mathbf{i}^k_X, \mathbf{i}^k_Y)}{I^k_{\Sigma X}} \tag{4.58}$$

  where $I^k_{\Sigma X}$ is the collective value of current, as described in (2.9), for the circuit X and component k.

The interaction matrix $[\eta]$ is reordered too, using the interaction groups G_α and G_β. The ordering into groups depend on the interaction's signs. The group G_α will contain the highest squared rms current value, this is a convention and does not affect the analysis, it only provides a manner to define which group the indicators are assigned to.

4.4.1.5 Calculation of Contributions

Once the circuits connected to a PCC have been organized into the Groups G_α and G_β, the contributions of each circuit to the disturbance condition can be calculated. First, two group currents must be calculated as:

$$i^k_\alpha = \sum_{j\in G_\alpha} i^k_j \qquad i^k_\beta = \sum_{j\in G_\beta} i^k_j \tag{4.59}$$

being k the current type. As supposed in the example, $i_\alpha = i_A + i_2$ and $i_\beta = i_B + i_1 + i_3$. Afterwards, group rms values are calculated as:

$$\begin{aligned} I^2_\alpha &= \langle i_\alpha, i_\alpha \rangle = I^2_A + I^2_2 + 2\langle i_A, i_2 \rangle \\ I^2_\beta &= \langle i_\beta, i_\beta \rangle \\ I^2_\beta &= I^2_B + I^2_1 + I^2_3 + 2\langle i_B, i_1 \rangle + 2\langle i_B, i_3 \rangle + 2\langle i_1, i_3 \rangle \end{aligned} \tag{4.60}$$

allowing the definition of the normalized group currents:

$$\hat{i}_\alpha = \frac{i_\alpha}{I_\alpha} \qquad \hat{i}_\beta = \frac{i_\beta}{I_\beta} \tag{4.61}$$

The contribution of each circuit belonging to the group α are:

$$\begin{aligned} \rho_{(A,\alpha)} &= \langle \hat{i}_\alpha, i_A \rangle = \frac{I_A^2 + \langle i_A, i_2 \rangle}{I_A^2 + I_2^2 + 2\langle i_A, i_2 \rangle} \\ \rho_{(2,\alpha)} &= \langle \hat{i}_\alpha, i_2 \rangle = \frac{I_2^2 + \langle i_2, i_A \rangle}{I_A^2 + I_2^2 + 2\langle i_A, i_2 \rangle} \end{aligned} \tag{4.62}$$

Likewise, the contributions of all circuits belonging to group β, $\rho_{(B,\beta)}$, $\rho_{(1,\beta)}$ and $\rho_{(3,\beta)}$, are extracted.

$$\begin{aligned} \rho_{(B,\beta)} &= \frac{I_B^2 + \langle i_B, i_1 \rangle + \langle i_B, i_3 \rangle}{I_B^2 + I_1^2 + I_3^2 + 2\langle i_B, i_1 \rangle + 2\langle i_B, i_3 \rangle + 2\langle i_1, i_3 \rangle} \\ \rho_{(1,\beta)} &= \frac{I_1^2 + \langle i_1, i_B \rangle + \langle i_1, i_3 \rangle}{I_B^2 + I_1^2 + I_3^2 + 2\langle i_B, i_1 \rangle + 2\langle i_B, i_3 \rangle + 2\langle i_1, i_3 \rangle} \\ \rho_{(3,\beta)} &= \frac{I_3^2 + \langle i_3, i_1 \rangle + \langle i_3, i_B \rangle}{I_B^2 + I_1^2 + I_3^2 + 2\langle i_B, i_1 \rangle + 2\langle i_B, i_3 \rangle + 2\langle i_1, i_3 \rangle} \end{aligned} \tag{4.63}$$

The above mentioned interaction matrix $[\eta]$ has all the information to calculate the contributions $\rho(X, \alpha)$ and $\rho(Y, \beta)$. The inner product allows the calculation of all interaction indices and the contribution numbers as well. The interaction matrix and the contribution indices provide information about the qualitative and quantitative contribution of each agent, what a single inner product between two signals cannot provide by itself.

The contribution terms of (4.62) and (4.63) add up to 1.0, and they represent the contribution of each user to the total group rms value. In other terms, the contribution of A to α, $\rho(A, \alpha)$, is the portion of G_α the circuit A is responsible for.

Previously, it has been described how measurements must be carried out to register suitable information to assess disturbances interaction. The contributions $\rho(X, \alpha)$ or $\rho(Y, \beta)$ shall be extracted from those measurements and analyed in statistical terms. The disturbance magnitudes and propagation form change dynamically in time as many other power quantities in the distribution systems. Hence, their change must be taken into account considering its dynamic nature.

4.4.2 Application of $\mathcal{M}_{\mathcal{D}}\mathcal{I}$

The Method of Disturbances Interaction will applied to the German test measurements. Only active, displaced and distorted currents are displaced because the German tests do not have asymmetry. The first two stages, ordering currents and orthogonal decomposition do not require illustration. The interaction matrices for one test case are shown in the Table 4.2.

The ordered interaction matrices, fourth stage, are shown in Table 4.3. The terms in bold letters correspond to the group G_α, italic letters to the group G_β. Displaced and distorted components interaction have already the representation of (4.55).

Circuit	German test case 17								
	i_a			i_{Qd}			i_D		
	Feeder	*Ind*	*DC*	*Feeder*	*Ind*	*DC*	*Feeder*	*Ind*	*DC*
Feeder	14.4	-16.6	2.1	291.4	-75.2	-216.2	16.8	0.3	-17.1
Ind	-16.6	19.0	-2.4	-75.2	19.4	55.8	0.3	1.6	-1.9
DC	2.1	-2.4	0.3	-216.2	55.8	160.4	-17.1	-1.9	19.0

TABLE 4.2: Interaction matrices for the German test case 17: Arbitrary units A^2

For the sake of simplicity the active current interaction matrix has not been reordered in the format. However, from the interaction of active components can be observed a useful attribute of the $\mathcal{M}_{\mathcal{D}}\mathcal{I}$. In the test case 17, the induction machine group has the highest active current, corresponding to the highest active power, not the feeder. The desirable attribute of the method is that all agents are assessed in the same manner, regardless tehy are customers of utilities.

Circuit	German test case 17								
	i_a			i_{Qd}			i_D		
	Feeder	*Ind*	*DC*	*Feeder*	*Ind*	*DC*	*Feeder*	*Ind*	*DC*
Feeder	*14.4*	-16.6	*2.1*	**291.4**	-75.2	-216.2	*16.8*	*0.3*	-17.1
Ind	-16.6	**19.0**	-2.4	-75.2	*19.4*	*55.8*	*0.3*	*1.6*	-1.9
DC	*2.1*	-2.4	*0.3*	-216.2	*55.8*	*160.4*	-17.1	-1.9	**19.0**

TABLE 4.3: Interaction matrices for the German test case 17: Arbitrary units A^2

The interaction matrices provide the following information:

Active currents

The feeder and the DC machine group concentrate the effect of the Induction machine group. The active power of the feeder, Induction and DC machine groups are 45.95kW, -52.54kW and 6.59kW. The Induction machine circuit was classified in the group G_α, for this component it means that the power is generated in the circuit.

Displaced currents

A similar interpretation can be extracted from the displaced currents. Here, the feeder concentrates the effect of Induction and DC groups. Nevertheless, the powers of feeder, Induction and DC group are 206.6277kVA, -53.0750kVA and -153.55kVA. The feeder circuit has the most intense interaction, therefore is classified into the group G_α, but it does not mean that it generates the corresponding power.

Distorted currents

The DC machine circuit is classified into the group G_α, meaning that it interacts with the group G_β conformed by the feeder and the induction machine group. Distorted power is not a conservative quantity, thus it cannot be interpreted as the previous components. The distorted powers in the test case 17 are 49.54kVA, 15.44kVA and

52.69kVA for the feeder, Induction and DC group respectively. The powers confirm the previous analysis.

The contributions for each current component are:

Active currents

Induction group is alone in the group G_α, its contribution is $\rho_{(Ind,\alpha)} = 1.0$. The contributions of group G_β are $\rho_{(Feeder,\beta)} = 0.87$ and $\rho_{(DC,\beta)} = 0.13$. This means that the 87% of the current in the Induction machine group interacts with the feeder, the DC group interacts 13%.

Displaced currents

The feeder is in the group G_α, its contribution is $\rho_{(Feeder,\alpha)} = 1.0$. The contributions of group G_β are $\rho_{(Ind,\beta)} = 0.26$ and $\rho_{(DC,\beta)} = 0.74$.

Distorted currents

The DC machine group is in the group G_α, its contribution is $\rho_{(Feeder,\alpha)} = 1.0$. The contributions of group G_β are $\rho_{(Feeder,\beta)} = 0.90$ and $\rho_{(Ind,\beta)} = 0.10$.

4.4.3 Discussion

The Method of disturbances interaction uses the current decomposition proposed in Chapter 2. The advantage of this approach is that each phenomenon is analysed separately. The individual phenomenon analysis provides information about the interaction of all circuits regarding the phenomenon, avoiding the issue identified in the Multi-point method, not capable of distinguishing asymmetry from distortion.

Additionally, the $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ quantifies currents and powers for each component easily. This information serves to determine which disturbance has the major impact on the circuit's condition. As described in Chapter 2, the power factor relates the active power and the apparent power, whose decomposition allows the identification of detrimental power components. The current decomposition procedure proposed in the $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ has been used to describe and quantify the power components of Compact Fluorescent Lamps in [PBP12].

The $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ is not capable of determining the disturbance's origin, it discriminates the components and quantifies them. The next chapter on statistical analysis of indicators proposes a methodology for improving the $\mathcal{M}_{\mathcal{D}}\mathcal{I}$. Nevertheless, the investigation of the method does not stop with this thesis, contributions are expected and well received.

4.5 Summary of the chapter

In this chapter, three currently available method for assessing responsibilities regarding power quality were described, applied and discussed. The methods are the Critical Impedance Method, the Multi-point Method and the Harmonic Pollution Method. Some characteristics of each method were extracted from the discussion, enabling the proposal of a new method called the Method of Disturbances Interaction.

The single section evaluation methods, like the $\mathcal{CIM}$, could provide misleading conclusions, specially when additional customers are connected to the same feeder and disturb the system simultaneously. The assessment of individual frequency components provides potentially contradictory results, further research is required to deal with this issue.

Method based on measurements performed on multiple sites employ more information and provide better results. It has been found that the orthogonal current decomposition improves the methods. Suitable adjustments to the Multi-point Method $\mathcal{M}_{\mathcal{P}}\mathcal{M}$ were proposed.

The Harmonic Pollution Method $\mathcal{HPM}$ founds a classification principle and proposes a simple procedure to distribute the contributions of agents to the harmonic currents. Based on this method and the characteristics of the previously mentioned methods, the Method of Disturbances Interaction $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ was proposed, with the aim of providing an innovative tool to analyse the interaction and propagation of stationary power quality disturbances.

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CHAPTER 5

Statistical Analysis for the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$

No sospecho de nadie,
pero desconfío de todos

Cantinflas

Different characteristics of the responsibilities analysis methods have been presented in the previous chapter. One of the task yet to be solved is the determination of the disturbance's origin. In other words, the disturbance's cause determinations is an unsolved task.

The determination of the cause of an event is one of the most difficult task to be solved. The epidemiology has made significant advances in the determination of disease's causes [Woo99]. Techniques as association, confounding and crossed correlation are typical to analyse information in the search of causes.

The electric power systems have similarities with the living beings and biological systems: individuals live along with many others, interact, depend on each other and exchange energy. Eventually the living systems have the possibility of isolating individuals in order to contain the propagation of diseases. Electric systems rarely are capable of isolating customers or circuits. Electricity is a fundamental production resources, electric power must be available as much as possible.

Despite of any differences between biological and electric power systems, some principles of causality could probably employed to assess power quality. The following list describes briefly some among those principles. No one of them represents a necessary and sufficient condition to determine causality, however their occurrence provides evidence in its favour.

- There should be evidence of a strong association between a risk factor and a disease.
- There should be evidence that exposure to risk factors preceded the onset of a disease.
- There should be a plausible biological (technical, circuital, electromagnetic, etc.) explanation.

- The association should be supported by other investigations in different study settings.
- There should be evidence of reversibility of the effect. This means, if the cause is removed, the effect should disappear, or at least become less likely.
- There should be evidence of dose-response effect, i.e. the greater the amount of exposure to risk factors, the greater the chance of disease.
- There should be no convincing alternative explanations.

The above mentioned principles are supported by statistical tools and can be extended suitably to the analysis of responsibilities in power quality.

In this chapter, a proposal is presented for statistical analysis of power quality indicators based on the Method of Disturbances Interaction $\mathcal{M_DI}$. The proposed techniques can be applied on any other method, special emphasis is made on the $\mathcal{M_DI}$ to explore improvement alternatives. This proposal has been published in [PST12].

5.1 Statistical analysis of $\mathcal{M_DI}$

The indicators extracted from the $\mathcal{M_DI}$ can be used directly to identify the interaction among grouped circuits. Such interaction vary in time as the circuits change their power consumption conditions, thus the indicators must be recorded and evaluated in time.

Stationary disturbances can be assessed by using deterministic and statistical means. The statistical assessment of interaction indicators provides information on probabilities for the disturbances interaction, which lead to a further interpretation of the stationary power quality condition and the disturbance propagation. The $\mathcal{M_DI}$ indicators can be analysed statistically by using the following statistics:

- Conditional probability of a circuit X having a determined contribution at current type k in one interaction group subject to a circuit Y having another determined contribution at the same current type. This statistics is used to assign responsibilities.
- Probability of being assigned into one group (G_α or G_β group. This property has a binomial distribution. It represents the probability of being assigned to a circuits' group with a determined identifiable interaction behavior. Under specific conditions, these groups represent origin or destiny of the assessed disturbance. It happens quite often that a single circuit is assigned to the group G_α, for example in the cases with a single feeder a no other circuit is absorbing the disturbances. This probability means how likely is to be assigned with the responsibility of being disturbed or disturbing.
- Proportion or contribution to the group current effective value. This quantity has a continuous distribution function and is valued from zero to one (no contribution to total contribution, respectively). As a set of circuits can cause the disturbance being received or absorbed by the set of the remaining circuits, these proportions allow to quantify the respective individual contributions.

5.2 Responsibilities assignment

The $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ is not able to assess the origin of disturbances, it can determine where the stationary disturbances are concentrated. In [PST08][PST09][PST10], the origin of disturbances was discussed regarding the assignment of responsibilities. It is possible to cause an undesirable power quality condition when one or several among the following situations meet:

- A device capable of disturbing the system or other devices is switched on.
- A device capable of amplifying a disturbance is switched on.
- A compensating device or a device providing compensation is switched off, either by the operator's command or by a device's authomatic protecting response.
- One or several devices are connected in such a manner that disturbances amplify.

The undesirable power quality conditions can be caused unintentionally by the ordinary operation of the customers or the utilities. Of course, some of the previous situations could appear as result of a wrong operational decision. The previous brief analysis reveals that the disturbance's origin is one issue to be solved and responsibility is a different one. It is not very reasonable to seek for a single guilty agent for any case, most cases involve several interacting agents. Therefore, it is expected that several agents share a certain amount of responsibility.

The events' likelihoods are calculated from the distribution indicators, which are extracted from measurements. For the sake of simplicity, the subindex k, related to the disturbance type, will not be written but implied. In order to assess responsibilities the following definitions and calculations are necessary: If the circuit X is ordered into the group G_α and has the interaction contribution $\rho(X,\alpha) = C \in [0,1]$, the event $R(X,\alpha,C)$ is defined. The following conditional probabilities are constrained to the existence of the conditional event, i.e. that the probability of the conditional event is not zero.

- If the circuit X is ordered into the group G_α and has the interaction contribution $\rho(X,\alpha) = C \in [0,1]$, the event $R(X,\alpha,C)$ is defined. The probability of event R to occur is $P\left(R(X,\alpha,C)\right)$.
- The analysis of responsibilities requires the definition of composed events. Given an event $R(X,\alpha,C)$, its likelihood can be zero for certain contribution values, group ordering or circuit. The evaluation of responsibilities requires that separated events' probabilities exist.
- The conditional probability of $R_X = R(X,\alpha,C_X)$ subject to $R_Y = R(Y,\beta,C_Y)$ is calculated using the Bayes' rule as follows [CL09]:

$$P\left(R_X|R_Y\right) = \frac{P\left(R_X \cap R_Y\right)}{P\left(R_Y\right)} \tag{5.1}$$

The result means how likely is that R_X occurs when R_Y happens.

- The conditional probability of $R_X = R(X, \alpha, C_X)$ subject to:

  $$R_Y = R(Y_1, \beta, C_1) \cap, \ldots, \cap R(Y_m, \beta, C_m)$$

  is calculated as follows:

  $$\begin{aligned} P\left(R_X | R_Y\right) &= \frac{P\left(R_X \cap R_Y\right)}{P\left(R_Y\right)} \\ P\left(R_X | R_Y\right) &= \frac{P\left(R_X \cap R_{Y1} \cap \cdots \cap R_{Ym}\right)}{P\left(R_{Y1} \cap \cdots \cap R_{Ym}\right)} \end{aligned} \tag{5.2}$$

  This probability means how likely is that R_X occurs when the events $R_{Y1} \ldots R_{Ym}$ happen simultaneously.

- The conditional probability of $R_X = R(X_1, \alpha, C_1) \cup, \ldots, \cup R(X_n, \alpha, C_n)$ subject to: $R_Y = R(Y, \beta, C)$ is calculated as follows:

  $$\begin{aligned} P\left(R_X | R_Y\right) &= \frac{P\left(R_X \cap R_Y\right)}{P\left(R_Y\right)} \\ P\left(R_X | R_Y\right) &= \frac{P\left(\left(R_{X1} \cup \cdots \cup R_{Xn}\right) \cap R_Y\right)}{P\left(R_Y\right)} \end{aligned} \tag{5.3}$$

  This probability means how likely is that at least one event among the set R_X occurs when the event R_Y happens.

The above described events and probabilities can be used to assess the responsibilities, based on the observed statistical behavior. As stated before, the evaluation of responsibilities based on composed events requires that separated events' probabilities exist, i.e. each event has an occurrence probability higher than zero. The following basic steps are proposed to assign responsibilities:

1. If the likelihood of an event related to an undesirable condition at circuit X subject to a certain condition at circuit Y_1 is 0%, no responsibility can be assigned to Y_1 because of the condition at X. There is no evidence for the undesirable condition at X to happen due to the condition at Y_1.

2. If the circuit Y_1 is not charged with the responsibility of the condition at X, the remaining circuits must be assessed a their corresponding conditions Y_k until all non responsible circuits are identified.

3. If the likelihood of an event related to an undesirable condition at circuit X subject to a certain condition at circuit Y_k is 100%, the responsibility of the condition at X can be assigned to Y_k. This means that there is evidence for the undesirable condition at X to happen due to the condition at Y_k. Given that the responsibilities are evaluated from interaction indicator, it is possible that the complementary composed event (involving another or more circuits) has a 100% probability. In this case, the responsibility of the undesired condition must be shared among the remaining involved circuits.

4. The probabilities of undesirable conditions can have values between 0% and 100%, which means that the conditions are not completely unlikely nor completely likely to happen either, respectively. The interpretation of this case is that the condition happens with a determined frequency but cannot be classified as a main responsible, it represents an eventual contribution to the undesirable condition.

Additionally, from the contribution indicators, it is possible to determine how often a circuit is ordered into a group and which is the expected value of its contribution. These statistics can be interpreted as follows.

Ordering into a group

The group G_α has the circuit with the highest interaction indicator, the remaining circuits ordered in the same group interact with the circuits of group G_β in the same manner as the circuit with the highest interaction does. Each circuit has a determined probability of being ordered into a group, thus this probability means how often the circuit has a specific interaction behavior.

Expected value of Contribution

The contribution indicator vary in time due to different situations in the system. From the measurements and their corresponding indicators, empirical probability functions can be extracted. The contribution expected value means the expected size of the contribution of each circuit to the disturbance and the undesirable condition, in other words, it presents the contribution's size. The statistical treatment of theses quantities requires special attention, as the contributions are numerically proportions. In [AC98] [AC00] [CCAC+98] [Bro93] some explanations are presented on how confidence intervals for proportions and multinomial probabilities can be determined.

5.3 Application of the Method of Disturbances Interaction

The method proposed in this Chapter has been applied to the Colombia set of measurements, described in the Chapter 3. All stationary phenomena, listed in Table 4.1, were observed during the measurements. Some basic information about each circuit's measurement results is presented in Table 5.1. Mean values along the whole measurement period for voltage unbalance and harmonic distortion are $u_2 = 0.369\%$ and $THD_u = 3.65\%$, respectively. Unbalance was calculated as the ratio of negative to positive sequence fundamental voltages [IEC08]. Voltage distortion was calculated according to [IC10].

Index	S	P	Q	UNB_i	THD_i
	[kVA]	[kW]	[kVAr]	[%]	[%]
Feeder	92.7	83.6	34.5	7.8	19.8
Circuit 1	66.6	60.6	21.9	9.5	19.1
Circuit 2	28.3	23.0	12.6	16.1	26.7

Table 5.1: Powers, unbalance and distortion for the test circuit

5.3.1 Current decomposition

After calculating the current decomposition, the mean values of power components are those presented in Table 5.2.

Comp	S	P	Q_d	Q_{au}	Q_{du}	Q_D
	[kVA]	[kW]	[kVA]	[kVA]	[kVA]	[kVA]
Feeder	92.7	83.3	34.4	6.2	11.5	15.4
Circ1	66.6	60.3	21.7	6.6	8.0	13.4
Circ2	28.3	22.9	12.6	3.6	4.1	6.1

TABLE 5.2: Mean values of power components

5.3.2 Statistical analysis - Ordering into the groups

The results achieved from the application of $\mathcal{M_D I}$ on unbalanced displaced, unbalanced active and distorted components will be shown. No attention was paid to the active and displaced components, as their interpretation responds to the technical common sense of electrical engineering. The Table 5.3 shows how frequently each circuit was assigned to the interaction groups.

Comp	Q_{du}		Q_{au}		Q_D	
Group	G_α	G_β	G_α	G_β	G_α	G_β
Feeder	100.0%	0.0%	40.3%	59.7%	79.0%	21.0%
Circ 1	0.0&	100.0%	54.3%	45.7%	21.0%	79.0%
Circ 2	0.0&	100.0%	5.4%	94.6%	0.0%	100.0%

TABLE 5.3: Circuits ordering into groups for distorted components

The results of Table 5.3 reveal that the Feeder is ordered into the group G_α a high proportion of the time for distorted and displaced unbalanced components. Circuit 1 is assigned to the group G_β a high proportion of the time for the same components. Circuit 2 appears assigned to the group G_β almost all the time for all current components, excepting for the active unbalanced but its frequency at G_α is 5.4% only.

5.3.3 Statistical analysis - Responsibilities assignment

From the values of Table 5.3 and consulting the interaction indicators data base, the probabilities for different events can be calculated.

5.3.3.1 Displaced unbalanced components

The feeder is always ordered into G_α, both circuits into G_β. This situation means that the displaced unbalanced components are interchanged between the feeder and the circuits all the time, no change in interaction condition was observed. The probabilty of not having any component in the feeder is zero, the probability of not having any interaction subject to the presence of any component anywhere is zero as well. The probability of having interaction among all circuits is 100%, therefore all agent are responsible for the displaced unbalanced components. Any compensation must be distributed among all circuits proportionally to the size of their interaction.

5.3.3.2 Distorted components

The feeder appears assigned to both groups, more frequently to G_α than to G_β. Circuit 1 appears assigned to both groups too, but more frequently to G_β than G_α. Circuit 2 is assigned always to G_β. The following events lead to the responsibilities assignment:

- The following events have the values:

  $$P\left(R(F,\alpha,>0)\cup R(2,\beta,>0)|R(1,\beta,>0)\right)=1.0$$

  $$P\left(R(F,\beta,>0)\cup R(2,\beta,>0)|R(1,\alpha,>0)\right)=1.0$$

  This means that there exist distorted components in the Feeder and Circuit 2 regardless what group Circuit 1 is assigned to.

- The following events have the values:

  $$P\left(R(1,\alpha,>0)\cup R(2,\beta,>0)|R(F,\beta,>0)\right)=1.0$$

  $$P\left(R(1,\beta,>0)\cup R(2,\beta,>0)|R(F,\alpha,>0)\right)=1.0$$

  Its meaning is that there exist distorted components in the Circuit 1 and Circuit 2 regardless what group Feeder is assigned to.

- The following events have the values:

  $$P\left(R(F,\alpha,>0)\cup R(1,\beta,>0)|R(1,\beta,>0)\right)=0.79$$

  $$P\left(R(F,\beta,>0)\cup R(1,\alpha,>0)|R(2,\beta,>0)\right)=0.21$$

> This means that the probability of existing components in Feeder or Circuit 1 constrained to the presence of distorted components in Circuit 1 is between 0.21 and 0.79.

Regarding the distorted components, the Feeder and Circuit 1 are responsible for the presence of components in all circuits as the presence of distorted components happens as they have distorted components. Circuit 2 contributes eventually to the presence of distorted components.

5.3.3.3 Active unbalanced components

All circuits are assigned to both groups with different frequencies. The following events lead to the responsibilities assignment:

- The probability of having any interaction in Circuit 1 or 2 when the Feeder is classified into G_α is 1.0, if at least one of them is classified into G_β. Circuit 1 in G_α and Circuit 2 in G_β will have distorted components interaction with 1.0 probability too, if Feeder is in G_β.

- The probability of Circuit 1 and the Feeder having interaction subject to the Circuit 2 in G_α is 1.0 if at least one of them is in G_β. The probability of Circuit 1 and Feeder having interaction subject to Circuit 2 in G_β is 1.0 as well.

- The probability of having interaction with Feeder in any group, Circuit 2 in G_β subject to Circuit 1 in G_α is zero. The probability of having Circuit 1 and 2 in G_α is alwasy 1.0. Additionaly, it was observed that the probability of Circuit 2 in G_β subject to Circuit 1 in G_α is zero. This means that both will interact in the same direction when at least one of them has the highest interaction.

- The remaining events comprise the cases when Circuit 1 and 2 are classified into G_β or they are classified into different groups. These events have probabilities from 8.98% until 88.26%.

This case is quite more complex than the previous ones. If Circuit 1 and 2 have the highest interaction, they both cause the unbalanced active component in the feeder. In other cases, the probabilities of disturbing any circuit varies from zero to 88.26%.

5.3.4 Statistical analysis - expected value of contribution

Once the responsibilities have been assigned, the amount of responsibility is determined using the contribution indicators. For the sake of space, only one example will be shown. The empirical cumulative probability functions corresponding to the contribution indicators in the distorted components interaction cases are displayed in Fig. 5.1. When the Feeder is in G_α, two different distribution functions can be observed for Circuit 1 and 2. The medians are 0.76 and 0.22 for Circuit 1 and 2 respectively, further statistics can be extracted too. This statistics can be employed to dimension a compensation device and distribute its cost or size among the corresponding contribution indicators.

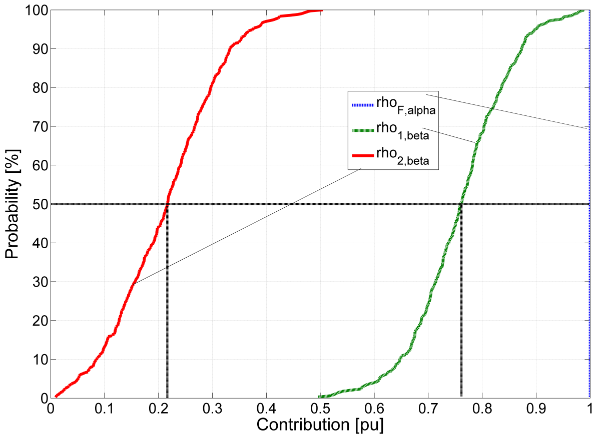

FIGURE 5.1: Contribution indicators of distorted components for Feeder ordered into group G_α

5.4 Summary of the chapter

Different approaches have been proposed in this chapter to assess the temporal dynamic of indicators extracted for responsibilities assignment. Criteria for assigning responsibilities were proposed. The criteria are based on the calculation of probabilities extracted from the indicators provided by the Method of Disturbances Interaction. Further research is required to validate the application of the proposed method in different cases.

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CHAPTER 6

Conclusions

The objectives presented in the doctoral proposal were accomplished. Proof of the objectives' accomplishment can be listed as follows:

- Three methods proposed in the technical literature were investigated, described and implemented. Its usage was illustrated using two test measurements, developed in Colombian and Germany. The studied methods were the Critical Impedance Method, the Multi-point Method and the Harmonic Pollution Method.
- Two test measurement setups were designed and employed to investigate and apply the power quality responsibilities assignment methods. The first one used a medium to low voltage substation located at the Universidad Nacional de Colombia. The second one used the laboratories of the Power Systems Technology and Power Mechatronics Institute of the Ruhr University of Bochum - Germany.
- A method to assess the power quality propagation was proposed. The Method of Disturbances Interaction is based on the reviewed methods and employs the orthogonal decomposition method proposed by the German Professors Manfred Depenbrock and Volker Staudt, named as the FBD electric power theory. The decomposition method is included in the German technical standards DIN 40110-1 and DIN 40110-2.
- Statistical techniques for the treatment, analysis and interpretation of the responsibilities information were studied and applied. Although simulation techniques could help, special emphasis was made on the usage of measurements and electric signals processing procedures.

A doctoral practice was carried out in the Power Systems Technology and Power Mechatronics Institute of the Ruhr University of Bochum - Germany, under the advisory of Professor Volker Staudt. The practice permitted to developed a part of the laboratory work and provided the opportunity of knowing the FBD power theory from his authors.

Four papers were published in international conferences and one paper was published in an international journal. These publications allowed technical discussions with highly acknowledged academic and professional peers, including the authors of the studied methods.

From the doctoral practice and the participation in international conferences, academic and professional exchange opportunities have been found. The most relevant is the participation in the Working Group C4.122 on Power Quality Monitoring in Flexible Power Networks of the CIGRE. Participation in other spaces is being currently explored.

6.1 Conclusions

The analysis of power quality aimed to determined the origin and size of stationary disturbances was studied and summarized in a theoretical realization named Responsibilities Assignment Problem.

The assessment of responsibilities require the definition of reference conditions to determine whether an agent is responsible or not.

Reference conditions to assess responsibilities in power quality must be capable of:

- Identifying the whole characteristics of any disturbance to be assessed.
- Assessing the disturbances regardless the electric power flow condition.
- Treating any agent fairly.
- Suitable measurements are required
- Being harmonised with the current power quality practices.

The revision of electric power definition has supported not only the understanding of stationary power quality disturbances, but also has revealed that disturbances propagation cannot be assessed resorting to traditional power quality indicators. Disturbances propagation analysis requires the consideration of powers and currents decomposed in such a manner, that each disturbance can be investigated individually.

The considered three power quality stationary disturbances can be analysed by means of the method of disturbances interaction. This contribution has no antecedents in the technical literature.

The currently available method for assessing responsibilities use electric power definitions, but all of them do not employ orthogonal current decomposition procedures. The method proposed in this thesis pretends to go further in this direction, providing a method based on principles of orthogonal decomposition.

A minimum accuracy and a suitable frequency bandwidth in the measurements equipment are required for the application of any method to assign responsibilities. Measurements in medium or high voltage levels require in most cases current and voltage and current transducers, moreover many low voltage applications need transducers too. Many transducers are not suited for measuring distorted signals, then the signals received by the registering device (oscilloscope, network analyser, power quality meter, etc.) will differ from actual signals. Special attention must be paid to deal with accuracy and bandwidth issues, contributions from researches are still needed.

The methods for assessing responsibilities can be improved by the utilisation of statistical probabilistic analysis. The definition of conditional events can lead to the determination of causes, supported in statistics and probabilities extracted from measurements.

In accordance with the review of available methods to assess power quality responsibilities, the so called Responsibilities Assignment Problem $\mathcal{R}_{\mathcal{A}}\mathcal{P}$ remains unsolved. Significant advances have been made, but still some issues require contributions. Particularly, the location of disturbing sources has been solved for some cases, further research is required to provide a universal, or at least more general, assessment tool. The quantification of the disturbances has been solved already, the Method of Disturbances Interaction provides an innovative tool to perform this task.

6.2 Contributions

The support of the Power Systems Technology and Power Mechatronics Institute of the Ruhr University of Bochum - Germany, allowed the development of an experimental setup for testing power quality stationary disturbances.

An approximation to electric power theories was necessary for the development of this thesis. The acquired knowledge and its application to power quality analysis does not have antecedents in Colombia, opening a new research area for future electrical engineering students.

A method to assess the contributions of several agents to the power quality conditions at a Point of Common Coupling was presented and tested, the Method of Disturbances Interaction $\mathcal{M}_{\mathcal{D}}\mathcal{I}$.

From the modification of the existing methods using the current decomposition, not only the Multi-point Method can be improved. The application of orthogonal currents decomposition will help to focus on specific phenomena.

6.3 Future work

Development of technical standards in Colombia and on abroad.

The inclusion of methods for assessing analysis of responsibilities in technical standards should be motivated by the participation in technical committees at national and international level. These ideas have been presented and promoted in the following spaces:

- ICONTEC technical committee CT-129 on Power Quality and Electromagnetic Compatibility
- CIGRÉ working group C4.112 on Power Quality Monitoring in Flexible Power Networks
- Proposal of working group creation at IEC through the ICONTEC

Involving of modeling techniques for accounting transformers, cables and lines. Modeling the network elements, the responsibilities assignment problem can be assessed among different points of common coupling.

The extension of the reviewed and developed methods to more complex systems is required. In order to evaluate responsibilities in electric distributions systems, modeling techniques must be employed to transfer the quantities and indicators to different voltage level.

APPENDIX A

Appendix - Publications

The following papers were written from the investigation and results of the doctoral thesis.

1. Pavas A., Staudt V., Torres-Sanchez H. *Discussion on existing methodologies for the responsibilities assignment problem.* Przeglad Elektrotechniczny - Electrical Review, vol. 85, pp. 208-214, 2009.
2. Pavas A., Staudt V., Torres-Saanchez H. *Experimental investigation of existing methodologies for the Responsibilities Assignment Problem.* 2009 IEEE Bucharest PowerTech. Bucharest, Romania. June 28 to July 2. pp 1 -8. 2009.
3. Pavas A., Torres-Sanchez H., Staudt V. *Method of Disturbances Interaction: Novel approach to assess responsibilities for steady state power quality disturbances among customers.* 2010 14th International Conference on Harmonics and Quality of Power (ICHQP). Bergamo, taly. Sept 26-29. pp 1 -9. 2010.
4. Pavas A., Blanco A. M., Parra, E. *Analysing effective lighting devices impact on power quality and electric grid efficiency by means of FBD-power theory.* 2012 IEEE 15th International Conference on Harmonics and Quality of Power (ICHQP). Hong Kong. June 17-29. 2012.
5. Pavas A., Staudt V., Torres-Saanchez H. *Statistical Analysis of Power Quality Disturbances Propagation by Means of the Method of Disturbances Interaction.* IEEE PES Innovative Smart Grid Technolgies Europe 2012 - ISGT Europe 2012. Berlin, Germany. Oct 14-17. 2012.

The first pages of the published papers are listed in the following.

Andrés PAVAS[1], Volker STAUDT[2], Horacio TORRES-SÁNCHEZ[1]

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Discussion on existing methodologies for the responsibilities assignment problem

***Abstract**. This paper introduces the Responsibilities Assignment Problem (RAP} and discusses existing methodologies by theory and examples. The RAP can be understood as the evaluation and determination of the power quality disturbances and of the power quality conditions detriment concerning source and amount. Selected details of this problem are presented in this paper, in order to provide a conceptual background to understand the problem itself and to interpret the characteristics of the currently available assessment methodologies. The existing methodologies are summarized, their principles, characteristics, and application are illustrated by means of an example. From the application results, a comparison of the mentioned methodologies is shown to point out advantages and differences. In the framework of the conference this paper could start and support a discussion about the assignment of responsibilities related to power quality disturbances propagation and improvements of the existing methodologies.*

***Streszczenie.** W artykule przedstawiono Problem Przypisania Odpowiedzialności (RAP - Responsibilities Assignment Problem) i omówiono istniejącą metodologię w teorii oraz na przykładach. RAP może być rozumiany jako szacowanie i wyznaczanie pogorszenia jakości energii elektrycznej oraz warunków negatywnie oddziałujących na źródło i odbiory. Podsumowane zostały istniejące metody, ich zasady, charakterystyka i zastosowanie, zostały one zilustrowane przykładami. Artykuł może stanowić podstawę dyskusji na temat przypisywania odpowiedzialności odnoszącej się do rozprzestrzeniania zaburzeń powodujących pogorszenia jakości energii elektrycznej oraz poprawy istniejących metod. (**Dyskusja istniejącej metodologii dotyczącej problemu przypisania odpowiedzialności**).*

Keywords: Power Quality, Responsibility assignment, Disturbance origin, Harmonics.
Słowa kluczowe: jakość energii, przypisanie odpowiedzialności, przyczyna zaburzeń, harmoniczne

1. Introduction

Nowadays Power Quality is one of the most important issues in Electrical Engineering. The determination of disturbance origin and the knowledge of how these disturbances flow across the electric systems is a very difficult task, for which many researchers have proposed alternatives to find an applicable, reliable and precise solution. There are many details concerning Responsibilities Assignment. In this paper mainly the methodological aspects are treated with the aim of presenting a basic background to lead a technical discussion about this theme.

The Assignment of Responsibilities can be studied, at least at a conceptual level, for each PQ disturbance. Each disturbance has special characteristics, which must be considered in detail to propose a procedure to acquire a solution for the *RAP*. The main concern of this paper is on the *RAP* under stationary conditions for harmonics.

2. Responsibilities Assignment Problem

The *RAP* in Power Quality 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 behaviour, including also 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 *RAP* 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. Currently, the *RAP* is being studied by many researchers from different perspectives, the most important advances use the frequency domain [1][2][5][6].

3. Currently used Methodologies

Many methods have been proposed to find a solution for *RAP*. Although most of them use a specific power definition to analyze the situation in frequency domain, every methodology has a different conceptual approach. In this paper three existing methodologies will be used to illustrate how the *RAP* can be understood und analyzed. Additionally, some indicators extracted from technical standards are presented, which were not directly proposed to assess responsibilities. These technical standards are the German Standards DIN 40110 parts 1 and 2 [8] and the IEEE Standard 1459, which currently is for trial use [10].

A. Critical Impedance Method - CIM

This method was developed by Xu et al [1] 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.1 shows the simplified model to deduce the CIM. Initially the equivalent impedances of the Customer and the Utility are supposed to be purely inductive and the phase angle of the equivalent Utility voltage source is fixed at zero degrees. The method must be applied to each frequency component individually. In Fig. 1 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.

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

Experimental Investigation of existing Methodologies for the Responsibilities Assignment Problem

Andrés Pavas, *GSM, IEEE,* Horacio Torres-Sánchez, *Senior Member, IEEE,*
and Volker Staudt, *Senior Member, IEEE*

***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.

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).

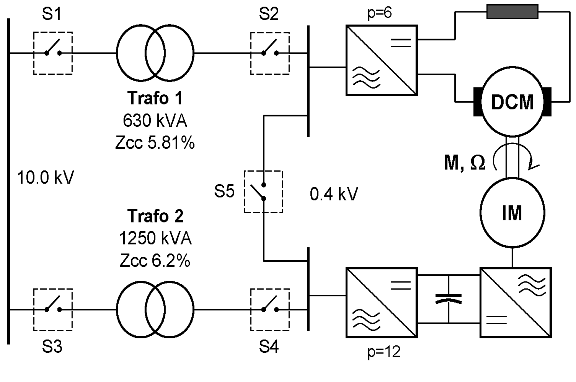

Fig. 1. Laboratory Setup

A schematic diagram of the load setup can be seen in Fig. 1, the two DC Machines are shown as one. The loads are

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Method of Disturbances Interaction: Novel approach to assess responsibilities for steady state power quality disturbances among customers

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***Abstract*—A new method to decompose currents in electrical circuits in order to analyze stationary power quality disturbances is presented in this paper. A set of reference conditions allows the definition of the desirable load behavior regarding power quality. The decomposition permits to analyze separately three stationary phenomena, waveform distortion, asymmetry and phase displacement. A discussion about the problem is responsibilities is presented as well.**

***Index Terms*—Asymmetry, Disturbance origin, harmonics, non-sinusoidal conditions, responsibilities in power quality**

I. INTRODUCTION

SEVERAL methods have been proposed to evaluate the origin of stationary disturbances in Power Quality, most of them resort to different power definitions and power based criteria. Under stationary conditions mainly three phenomena are considered as disturbances: phase displacement, voltage and current assymetry and waveform distortion [1].

The most desired content in electrical power is active power, displacement power related to inductive and capacitive storage elements is undesired but in many cases tolareted and necessary because this power component belongs intrinsicly to the natural bahavior ef electric machines and is required to operate and control electrical power systems.

Asymmetry is a very important disturbance but not the most common one, from the construction and operation of currently existing distribution systems, unbalance indices usually are below the standard limits, nevertheless this disturbnace is part of the power quality stationary condition and needs to be evaluated correspondingly. Waveform distortion is probably the most mentioned charactristic of non-linear load, but of course is not the only one. There is a huge ammount of technical information regarding distortion, in this paper a small contribtion to analyze harmonics is presented.

In this paper a summary of some key features of some currently available disturbance origin identification methods are presented and discussed, reference conditions to identify the load's desirable power quality bahavior is proposed as well. In order to analyze separately the above mentioned stationary power quality disturbances, an orthogonal decomposition and a comparison method are presented, illustrated by means of application examples. A discussion about the resposibilities assignment is proposed and some conslusions are listed.

II. RESPONSIBILITIES ASSIGNMENT PROBLEM

The determination of PQ disturbances origins is a very importan matter for customers and utilities due to its technical and economical relevance. The Responsibilities Assignment Problem $\mathcal{R}_{\mathcal{A}}\mathcal{P}$, presented and described in [2][3], summarizes the tasks to be achived when responsibilities related to power quality detriment must be evaluated. 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, this is customer or utility, belonging to an electric system with respect to a specific Power Quality condition. This paper is focused on the analysis of the three above mentioned stationary power quality disturbances.

Several methods have been proposed to determine whether disturbances come from utilities or from customers, among them [4][5][6][7][8] are listed. Many studies have been carried out to test the usefulness of these methods as well [3][9], showing advantages, disadvantages, desirable and undesirable characteristics. Some interesting highlights are listed below:

- Most of the currently available methods resort to harmonic frequency power components to evaluate responsibilites related to waveform distortion, especially harmonic active power components. It has been shown that harmonic active power might be a hard to measure an a misleading quantity [10][11][12], especially when multiple distortion sources are simultaneously operating.
- Electrical systems modelling is a widely spread activity in electrical engineering and great results have been reached at the moment. Concerning the $\mathcal{R}_{\mathcal{A}}\mathcal{P}$, most of the devices generating disturbances are non-linear and the electrical systems present non-linearities quite often. Due to technical limitations and in order to avoid excesive and, sometimes, unnecessary complexity, linearized models are very frequently employed. Linearized models require assumptions and restrictions, because of that this kind of models provides solutions about particular operating conditions and a method resorting to models for the assessment of responsibilities for the whole operation of a customer or a utility may give uncomplete or even false results.
- Some of the available methods present difficulties by assessing customers with distributed generation or in-plant power supplies.
- Although the target of Power Quality analysis and Re-

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Analysing effective lighting devices impact on power quality and electric grid efficiency by means of FBD-power theory

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***Abstract*—Currently the impact of high efficient lighting devices such as compact fluorescent lamps (CFL) and light emitting diodes (LED) is an important concern for the electrotechnical community. This paper makes a contribution towards determining the impact of these devices on electric grid power quality and efficiency, proposed by means of applying FBD-power theory to the currents absorbed by CFLs and LEDs. An analysis of the waveform distortion regarding the standard IEEE 519 and efficiency detriment quantification are presented.**

***Index Terms*—FBD-Power Theory, CFL, LED's, orthogonal decomposition, efficiency, power quality**

I. Introduction

NOWADAYS a movement from incandescent devices to newly-developed high-efficiency lighting devices has taken place, where compact fluorescent lamps (CFL) and lighting emitting diodes (LED) have been the most commonly used devices in household installations. This change has been motivated by technical and economic reasons [1][2]. The technical ones mainly concern reducing power consumption and improving lighting efficiency. Reduced power consumption has a direct impact on electrical energy billing and the widespread use of these devices worldwide represent a business opportunity, for producers as well as for lighting device sellers [3][4].

Despite the technical and economic advantages of CFLs and LEDs, their power electronics-based drivers produce power quality disturbances that may prejudice neighbouring devices and the system where the lamps are connected. Another negative effect should be noted; CFLs and LEDs involve a pretty low power factor which means that they use electric energy inefficiently, although they transform it into light in a more effective manner than incandescent lamps. According to resolution 182544 (19th December 2010) the Colombian government will ban the production, import, sale and use of inefficient incandescent bulbs from the 31st December 2013. Consequently, a residential customer must replace incandescent bulbs with CFLs or LEDs during the next 2 years [5]. Widespread use of CFLs and LEDs may have a negative impact on electrical grid efficiency and power quality [2][6]; Colombia is not an exception.

Currently there are several possibilities to reduce the impact of CFLs on power quality and energy usage efficiency, many of them are related to high efficient electronic ballasts, which reduce the waveform distortion, some examples are listed in [7] [8]. Nevertheless, the massive usage of CFLs and LEds has already begun in Colombia and efficient lamps with better electric performances are expensive in comparison to the lamps installed in the whole country. Although there are also power factor compensators, such devices are expensive for the average customer, implying that the problem analised in this paper cannot be solved easily.

The use of FBD-power theory has been proposed for analysing these devices possible impact on an electrical network. This power theory has been used recently to assess responsibilities regarding power quality [9][10][11], showing that different phenomena may be assigned to current components, thereby allowing what exists inside the current of a CFL or a LED to be separated and quantified.

This paper presents a current decomposition proposal [11] based on FBD-theory [12][13]. Measurements previously made on efficient lighting devices [2] were used to carry out an efficiency and power quality analysis.

II. Measurements on CFLs and LEDs

Seventy-two samples from different manufactures were tested to obtain the CFL and LED electrical signals. The test circuit is shown in 1, where a Fluke 43B power analyzer was used to measure the electrical variables and a Fluke 190B oscilloscope to obtain the lamps voltage and current signals. Three signal periods were recorded using a 200μs sampling interval.

According to the standards [14][15] and regarding the Universidad Nacional de Colombias available instrumentation and laboratory facilities , the following procedure was used to measure and record the electrical parameters and the CFL and LED signals.

1) Compact Fluorescent Lamps were aged for a period of 100 h of normal operation before the measurements. LEDs did not require any aging prior to testing;

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Statistical Analysis of Power Quality Disturbances Propagation by means of the Method of Disturbances Interaction

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***Abstract*—The determination of power quality disturbances has been studied in the last twenty years from different perspectives. Current decomposition provides a suitable approach to determine how disturbances propagate among circuits. The application of Fryze-Buchholz-Depenbrock - FBD power theory revealed useful results, such application has been called Method of Disturbances Interaction. In this paper a statistical analysis of the indices is presented, showing that indices' statistical behavior provides additional information on the propagation and origin of disturbances. The Method and the statistical analysis is illustrated in a practical application, a discussion and conclusions are listed as well.**

***Index Terms*—Unbalance, Disturbance origin, harmonics, non-sinusoidal conditions, responsibilities in power quality**

I. INTRODUCTION

SMART Grids represent represent currently the tendency for distribution systems' development. Energy efficiency, losses reduction, reliability improvement, voltage regulation and power quality are some of the main concerns to be dealt by smart grids. Power quality disturbances are related in different ways to those concerns by their effects on the network's composing elements. In this sense, the origin of disturbances represent a significant matter in Smart Grids.

Under stationary conditions, mainly three phenomena are considered as disturbances: phase displacement, voltage and current assymetry and waveform distortion [1]. The most desired content in electrical power is the active power. Phase displacement and reactive power, mainly related to inductive and capacitive storage elements, is undesired but in many cases tolareted and necessary. On the other hand, Unbalance is a very important disturbance but not the most common one. From the construction and operation of currently existing distribution systems, unbalance is usually below the standard limits. Nevertheless, this disturbance is part of the power quality stationary condition and needs to be evaluated correspondingly. Finallly, Waveform distortion is probably the most mentioned disturbance regarding power quality, but of course is not the only one. There is a significant amount of technical information regarding distortion, in this paper a small contribution to analyze harmonics is presented too.

Currently there are many proposed methods to evaluate the origin of stationary disturbances in Power Quality, most of them resort to different power definitions and power based criteria, see [2] to [7]. A Method was proposed to assess responsibilities called the Method of Disturbances Interaction $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ [4]. The $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ resorts to a power based current decomposition, capable to provide information about the stationary disturbance content of the signals flowing to all circuits connected to a Point of Common Coupling. Not only disturbances can be assessed by the $\mathcal{M}_{\mathcal{D}}\mathcal{I}$, the power flow can be evaluated as well.

A Statistical assessment of the information extracted from the application of $\mathcal{M}_{\mathcal{D}}\mathcal{I}$ is required in order to determine the regular behavior of the stationary disturbances. This approach is presented in the following paragraphs, showing a novel alternative to assess responsibilities in power quality and providing a new technical tool to solve the needs of the growing and evolving smart grids.

II. RESPONSIBILITIES ASSIGNMENT PROBLEM

The determination of the origins of PQ disturbances is currently one of the most challenging technical unsolved problems in electrical engineering, its technical and economical relevance does not need any detailed explanation. The Responsibilities Assignment Problem - $\mathcal{R}_{\mathcal{A}}\mathcal{P}$, presented and described in [2],[3], summarises the tasks to be performed when responsibilities in power quality need to be evaluated. 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 (i.e.customer or utility) belonging to an electric system, with respect to a specific Power Quality standard or expected condition.

Nowadays there exist several methods to determine whether disturbances come from utilities or from customers. Among them [5] to [9] are listed. Many studies have been carried out to test the usefulness of these methods as well [3],[10], showing advantages, disadvantages, desirable and undesirable characteristics. Some interesting highlights are listed:

- Most of the currently available methods resort to harmonic frequency power components to evaluate responsibilites related to waveform distortion, especially harmonic active power components. It has been shown that harmonic active power might be a hard to measure an a misleading quantity [11]-[13], especially when multiple distorting sources are operating simultaneously.

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