THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Voltage Sags Characterisation and Estimation

by

ROBERTO CHOUHY LEBORGNE

Department of Energy and Environment

Division of Electric Power Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2005

Voltage Sags Characterisation and Estimation

ROBERTO CHOUHY LEBORGNE

Department of Energy and Environment,

Division of Electric Power Engineering

Chalmers University of Technology

SE - 412 96 Göteborg - Sweden

Telephone: +46 (0) 31 – 772 1000

Fax: +46 (0) 31 – 772 1633

E-mail: Roberto.leborgne@elteknik.chalmers.se

Web page: www.elteknik.chalmers.se

Chalmers Bibliotek, Reproservice

Göteborg, Sweden 2005

Cariñosamente para Luciana, Catalina y Diana

Abstract

This thesis introduces a voltage sag (dip) characterisation based on instantaneous voltage and phasor analysis. Through the analysis of these quantities the retained voltage, the phase-angle jump and the event duration are obtained.

Voltage sags have so far been characterised by their magnitude and duration. However, for three-phase-unbalanced disturbances more parameters are needed in order to fully characterise the event and to predict the behaviour of sensitive equipments, such as adjustable-speed drives, computers, and programmable-logic controllers.

Voltage sags are regarded as one of the most harmful power quality disturbances due to their costly impact on sensitive loads. A voltage sag is defined as a short duration reduction of the rms voltage. A voltage disturbance is in general considered as a sag when the rms voltage remains below 90% of nominal voltage for a period not exceeding 3 minutes, however, there is no full agreement about these limits.

The presentation of the voltage sag characteristics is also important for the understanding of the event. Several methods for the presentation of sag characteristics are presented in this thesis. Both retained voltage and phase–angle jump are plotted versus time. In addition, a combined representation consisting of the phasor locus, the extreme phasors, and a set of snapshots is introduced.

Unbalanced voltage sags are characterised using the well known ABC classification. A new method using phase-to-neutral instantaneous voltages for the sag classification into ABC categories is proposed.

The method of fault positions is applied to a model of the Brazilian transmission system. The performance of some selected busbars regarding voltage sags is estimated and contrasted to the actual performance obtained by measurements. The strengths and shortcomings of the simulation tool are discussed. The sensitivity of the method of fault positions is analysed in terms of variations on the fault rate, fault type distribution, and fault position.

Keywords:

Power quality, voltage sags (dips), sag characterisation, and sag estimation.

Acknowledgments

This research is funded by the ***Ministerio da Educação do Brasil*** through the ***Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*** (*CAPES)*.

I would like to express my gratitude to my examiner Prof. Jaap Daalder and my supervisor Dr. Daniel Karlsson for their technical support.

I would like to thank Dr. Gabriel Olguin and Dr. Math Bollen for the fruitful discussions and the technical support, and especially my colleague Gabriel for being such a positive person.

Also I would like to express my gratefulness to my colleagues at the Division of Electric Power Engineering; for their friendship and for the good times spent together at coffee-breaks and parties. I recall my colleagues and friends at Universidade Federal de Itajuba (Brazil) for their encouragement and support to confront this adventure in Sweden.

I thank Professor Gonzalo Casaravilla for his kind invitation to present this research at the Universidad de la República (Uruguay).

I addition, I wish to thank all the friends I met in Sweden for their love and support. It would have been impossible to get through this step without their friendship, happiness, and the good time we spent together. And last but not least, I thank my family and friends in Uruguay and Brazil that continuously encourage and support me.

List of Publications

A. Leborgne, R.C., and Karlsson, D., "**Phasor Based Voltage Sag Monitoring and Characterization**", CIRED, Turin, Italy, June 2005.

B. Leborgne, R.C., Karlsson, D. and Olguin, G., "**Analysis of Voltage Sag Phasor Dynamics**", IEEE-PES Power Tech 2005, St Petersburg, Russia, June 2005.

C. Leborgne, R.C., Olguin, G., Bollen, M.H.J., "**The influence of PQ-monitor connection on voltage dip measurements**", IEE MedPower, Cyprus, November 2004.

D. Leborgne, R.C., Olguin, G., Bollen, M.H.J., "**Sensitivity Analysis of Stochastic Assessment of Voltage Dips**", IEEE PowerCon, Singapore, November 2004.

The author has also contributed to the following publications:

Gabriel Olguin, Roberto C. Leborgne and Daniel Karlsson, **"Stochastic Assessment of Voltage Dips; the Method of Fault Positions Versus a Monte Carlo Simulation Approach"**, IEEE-PES Power Tech 2005, St Petersburg, Russia June 2005.

Gabriel Olguin, Roberto C. Leborgne, Jorge Coelho, **"Ensuring Electromagnetic Compatibility by Analytic Study of Voltage Dips Caused by Faults"**, IEEE–IAS VI Induscon, Brazil, 2004.

Table of Contents

1 Introduction

A general introduction to power quality for technical and non-technical readers is introduced. It includes a general overview on power quality disturbances and a more detailed introduction to voltage sags is offered. The motivation for this project is explained. The outline and the main contribution of this thesis are presented.

1.1 Power quality for general readers

Mr Sven Jonsson, an engineering teacher at Chalmers University, woke up and suddenly realized that something wrong was going on... It was a wonderful bright morning. But a winter morning, so he did not expect to see any sunlight that early. He felt he was missing something when he realized that the alarm clock had not gone on. Too late. And while he was jumping from the bed he watched the clock, its numbers were flashing and asking to be set. He wondered why the clock failed during the night while he was having a quick breakfast.

His PC, which is connected to a no-break that can supply reliable energy for one minute in case of an energy shortage, had managed to download a movie during night. Considering this fact Sven concluded that no major blackout had taken place that night, besides, the microwave clock was working well. Sven had a great dilemma to answer! Otherwise he would get into trouble with his boss explaining the reason to be so late that morning.

On his way to Chalmers he heard on the radio that there had been a major storm in southern Sweden the night before. He understood that the storm could be the main cause of his clock problems. Lightning during storms may cause faults in the power lines. These faults cause a voltage reduction in most of the busbars of the system, including the one that supplies electricity to Sven's house, or the one that supplies your home. This power quality event is called voltage sag, and it lasts until the protection of the line trips, disconnecting the faulted line. When this line is the only electrical supply the loads fed by this line undergo a complete electrical outage until the line is successfully reconnected.

Sven found out the origin of his time problems. But now he was concerned about how to solve it. "Is there any reliable energy source?" There is no fully reliable supply. The more reliable the supply the more expensive it is. Therefore we are talking about a cost/benefit compromise. The clock needs to improve its tolerance to voltage sags. As the clock demand is low, a battery supply is enough to keep it working during these power quality events.

Despite the fact that these power quality events have been happening in the power grid since it was built one hundred years ago, the interest of the technical community in this issue has risen during the last two decades. Power quality events began to be disruptive ever since the extended use of sensitive electronic loads such as personal computers, home electronic devices, adjustable speed drives, and industrial automation. The focus of research has been characterisation of power quality disturbances, analysis of equipment electro-magnetic compatibility, and improvement of the equipment's tolerance.

Sven went back to his house, a nice cottage in the beautiful countryside 40 km away from town. It was dark outside because daylight in November is a rarity in the Nordic countries. Therefore, people are dependent on electric lighting after 3 pm.

He rested on the sofa and picked up the book he was reading. After 10 minutes, he started to feel very upset because of light variation. Somebody must be playing with the light switch, he thought. But Sven lives by himself, so there was nobody who could be switching the incandescent lamp near the sofa. It was a power quality disturbance called flicker, which is noticed as a change in light intensity. It has been statistically proven that the level of annoyance follows a normal distribution reaching the maximum value for an oscillation of 9 times per second.

What really bothered Sven was why his incandescent lamp was flickering. Sven was facing a power quality problem for the second time that day. As in the morning, first he wanted to know what the cause of the flicker was, but he also wanted to know how to mitigate the effects of the disturbance.

He remembered that near his home there was a factory with several arc furnaces where steel is melted. These arc furnaces demand a huge amount of current that varies considerably during the melting process. The current variation produces a voltage variation that is proportional to the network impedance. The network impedance is related to the strength of the network. In other words, networks with a huge amount of energy generation and energy transmission capacity have a low impedance. A strong network handles high energy-demands variation very well with minimum voltage variation.

Sven's cottage is far away from town and electric energy is supplied by long distribution lines. These distribution lines have a high impedance. As a consequence of the network weakness and the high variation of the neighbour's energy demand, Sven was facing a voltage fluctuation. This fluctuation provokes a light intensity variation called flicker. This problem is seldom in cities, because the distribution networks are stronger and capable to handle high demand variations.

Flicker analysis is not a simple issue and the first researches were conducted in the sixties. As incandescent lamps have been used since the origins of the electric systems, customers endured flicker disturbance for decades. Many utilities, concerned about this power quality disturbance, are working to satisfy customer demands. The solutions are not cheap; some examples are increasing the power generation capacity, installing new transmission lines, and relocating heavy variable loads such as arc furnaces.

Sven was concerned about his domestic problem and did not want to wait years for a solution coming from the utility. He thought that probably the voltage variation was not simultaneous in all the three phases of the distribution system. Considering that his house has a three-phase supply, he connected the lamps to different phases, after making some little changes in the electrical wiring of the house. As a result, the variation of luminescence of each lamp was compensated by the others. Sven felt very proud of solving his flicker problem with a minimum of cost.

Sven was reading a letter from a friend who owns a small factory. His friend was concerned with a problem he was facing in many production lines in his factory. He noticed that many motors used in the paper mill were suffering overheating, which reduces the lifetime of motors dramatically. The expected lifetime of the motors is 20 years. However, he reported that after 5 years he started to replace the motors because of the degradation caused by that overheating. Therefore he wondered what was wrong with the motor specification.

Sven answered his friend why the motors were failing so early. Sven wrote that because of the increase of voltage harmonics in the network most of the motors are experiencing this fast ageing, and failing before completing half of their lifetime. He also explained that these voltage harmonics are a common disturbance in industrial electric networks where there are many power electronic loads. These power electronic loads are the main source of harmonics in electric networks.

Then, Sven described this power quality disturbance and wrote: "Harmonic distortion is characterised by the harmonic spectrum, where all frequencies are represented by the magnitude of the signal. There are filters that mitigate the harmonic distortion. The filters are tuned to eliminate a specific harmonic. We need to evaluate the harmonic spectrum in your factory to design the suitable filters to reduce the harmonic distortion and extend the lifetime of your motors to the expected 20 years. This solution will be possible if the cost of the filters is lower than the cost of motor replacement".

This thesis presents an investigation on the characterisation and evaluation of voltage sags, the power quality disturbance that caused the malfunction of Sven's alarm clock.

1.2 Motivation for the project

Until the sixties the main concern of consumers of electricity was the continuity of the supply, this means, the reliability of the supply. Nowadays consumers not only want reliability, but also quality. For example, a consumer that is connected to the same bus that supplies a large motor may face sudden voltage reductions (voltage sags) every time the motor is started. Depending on the sensitivity of the consumer's loads this voltage sag may lead to a failure or disconnection of some loads or the entire plant. Although the supply is not interrupted the consumer experiences a disturbance that causes an outage of the plant. Examples of very sensitive end users are hospitals, automated manufacturing industries, air traffic control towers, and financial institutions, all of them requiring reliable and high quality electrical supply.

Voltage sags are short-duration reductions in voltage. The most severe voltage sags are due to short-circuits or earth faults and these sags often lead to tripping of sensitive equipment such as adjustable speed drives (ASD), programmable logic controller (PLC), and motor contactors.

In earlier studies, techniques have been developed for the analysis of voltage sags as experienced by three-phase equipments. These studies point out that three-phase sag characterisation must be superior over existing methods in order to describe appropriately this kind of events. These extended characterisation methods should be considered for the stochastic and statistical prediction of voltage sags, for the analysis of voltage sag propagation, and for the estimation of equipment sensitivity.

The voltage sag extended characterisation is needed to decide about mitigation methods and to obtain performance indicators for transmission and distribution networks. This information is extremely important considering the new power system management in de-regulated environments, where many transmission and distribution companies exchange electric energy and also power quality disturbances.

Currently, voltage sag statistics are almost exclusively obtained by using power-quality monitoring. Obtaining accurate results is expensive and time consuming. The aim of this project is to develop techniques for attaining an extended voltage sag characterisation and the sag statistics to evaluate the performance of the power system in terms of site and system indices.

1.3 Aim and thesis outline

The objective of this research is to investigate the voltage sag characterisation and estimation. Deterministic fault estimation combined with stochastic assessment of faults is used to evaluate the system performance, as an alternative to power-quality monitoring. The main limitation of this method is that only voltage sags caused by short circuit and earth faults are considered.

An algorithm for a comprehensive voltage sag characterisation in terms of retained voltage, phase-angle jump, duration, and sag type is developed and applied to field measurements. These measurements were done using power-quality monitors (PQ-monitor) and phasor measurement units (PMU).

The three-phase voltage sag characterisation methods are analysed. And a new method for the classification of voltage sag in the A, B, C, D, E, F, and G types is introduced. This method is based on the relation between phase-to-phase (PP) and phase-to-neutral voltages (PN).

The method of fault positions is analysed for the stochastic estimation of voltage sags. A sensitivity assessment of the method in terms of fault rate, fault type, and fault position, is performed.

Section 1 is a general introduction to power quality for technical and non-technical readers. The motivation for this project is explained and the outline and the main contributions of this thesis are highlighted.

In Section 2 a literature review on power quality is offered. A historical retrospective of the research on power quality is introduced including: definitions, effects on loads, power quality in de-regulated markets, power quality surveys, and standardisation. A literature review on voltage sags, including: definitions, effects on loads, and some mitigation approaches is also presented.

Section 3 contains a general overview of the characterisation of voltage sags. Unbalanced voltage sags are highlighted since they are the most common type of sags on transmission and distribution networks. A method for classification of measured voltage sag in the ABC types is proposed. New methods for voltage sag representation based on phasor analysis are introduced.

Section 4 describes the estimation of voltage sags at site and system levels. The main indices for site and system assessment are presented. The advantages and shortcomings of the indices estimation by monitoring and fault simulation are analysed. The method of fault positions for voltage sag assessment is described and applied to a model of the Brazilian transmission grid. Voltage sag indices obtained by the method of fault positions are compared with the indices obtained by monitoring. The sensitivity of the method of fault positions regarding the main fault uncertainties (fault rate, fault type, and fault location) is analysed. Finally, voltage sag indices obtained from PP and PN voltages are compared.

In Section 5 the preliminary conclusions of this research are presented and future works including the research lines that will lead to the Ph.D. diploma are highlighted.

1.4 Main contribution of this thesis

The main contributions of this research are two aspects of voltage sags: the characterisation and the quantification of the events.

From the characterisation viewpoint, this thesis introduces a method based on the instantaneous voltages and on the phasors analysis. Through the analysis of these quantities the retained voltage, the phase-angle jump, and the event duration are obtained, and three-phase unbalanced sags are classified in ABCD… types.

The presentation of the voltage sag characteristics is also highlighted in this thesis. Several methods for the presentation of these characteristics are introduced. Both retained voltage and phase–angle jump are plotted versus time. In addition, a combined representation in terms of the phasor locus, the extreme phasors, and a set of snapshots is developed.

A new method using phase-to-neutral instantaneous voltages for the sag classification into ABC categories is introduced. The method is based in the theoretical relations between PP and PN voltages. Each type of sag follows a particular relation, described by a curve in the plane PP vs PN.

The quantification of the voltage sags is based on site and system indices. This thesis evaluates the strengths and weaknesses of the method of fault positions for the estimation of these indices. The limitations of the method of fault positions to estimate the short term performance of a specific site or system regarding voltage sags are discussed. However, the method of fault positions is suitable for the assessment of voltage sags in a long term approach.

The accuracy of the assessment of voltage sags using the method of fault positions depends on the quality of the data used for the simulations. This thesis shows the influence of the different choices of fault characteristics in the voltage sag indices. It is shown how the choice of three-phase faults at busbars gives an overestimation of the sag indices. Nevertheless, simulating faults just at busbars can be a rough approach, taking into account that the results will describe a pessimistic scenario.

The influence of the monitored voltages on the sag indices is also reported. The choice between PP and PN voltages affects the results. It is shown that, at distribution busbars the difference in voltage sag indices for PP and PN voltages is rather small. However, at transmission levels the expected number of events may differ greatly depending on the option of voltages.

2 Literature review

In this section a literature review on power quality is presented. A historical retrospective of the research on power quality is given including: definitions, effects on loads, power quality in de-regulated markets, power quality surveys, and standardisation. A literature review on voltage sags including definitions, effects on loads, and some mitigation approaches is part of this section.

2.1 Increasing interest in power quality

The subject of power quality has been present in the technical literature since the 1960s; however the number of publications has increased significantly in the last decade, as shown in Figure 1. The survey at INSPEC was made with the following entries, where sag and dip are considered synonyms:

- power quality AND electric* AND (quality within title)
- power quality AND (sag* within title OR dip* within title)

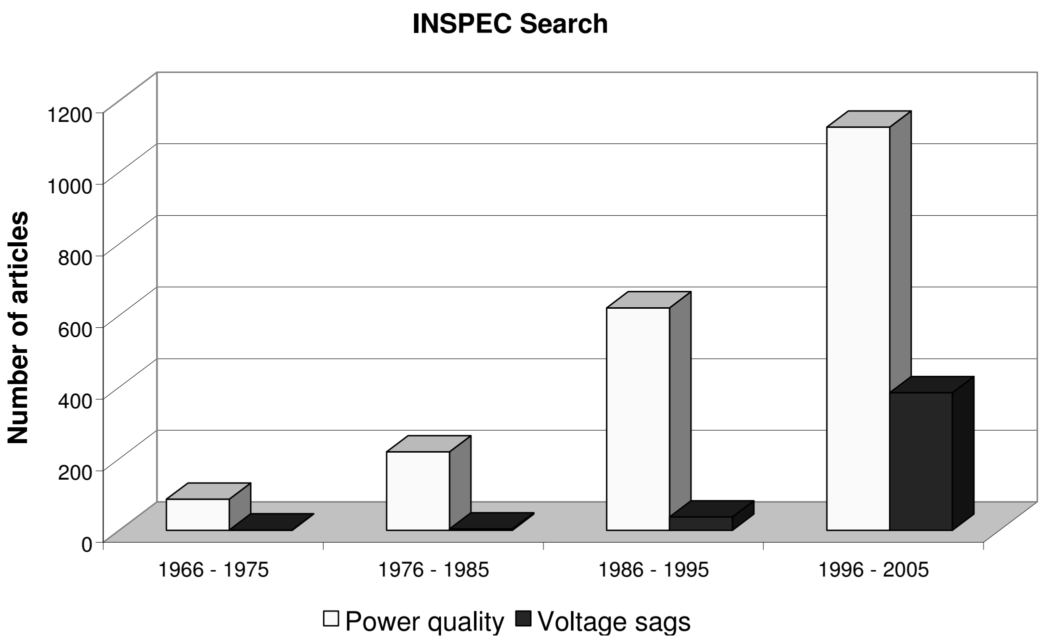


Figure 1 – Statistical analysis of number of publications

Several reasons have been given to explain the current interest in power quality (Bollen, 2000):

- Equipment has become more sensitive to voltage disturbances. Electronic and power electronic loads have become much more sensitive than previous electric equipments. Industrial customers are much more aware of the economical losses that power quality problems may cause in their processes.
- Equipments cause voltage disturbances. Often the same equipment that is sensitive to voltage disturbances will itself cause other voltage disturbances. This is the case with several power converters, whose input current is non-sinusoidal, containing a high level of harmonic distortion. The distortion of the demanded current leads to harmonic components in the supply voltage.
- The need for performance criteria. There is an increasing need for performance criteria to assess the quality of the power supplied. This is especially important for the monopolistic part of the chain formed by generation, transmission, and distribution of electricity. The natural monopoly that transmission and distribution companies possess, even in the deregulated markets, requires a quality framework where compulsory quality levels are given. Regulator bodies will have to create such a quality framework in terms of power quality indices.
- Despite the well known blackouts of 2003, the power supply has become so reliable that in most industrial countries long interruptions and blackouts have become rare phenomena. As a result, an increasing attention is given to second order problems such as short interruptions, voltage sags, harmonic distortion, etc.
- Power quality can be measured. The availability of power quality monitors means that voltage and current quality can actually be monitored on a large scale.

2.2 Power quality definitions

Back in the 1970s the definition of the power quality included limits applied to the fluctuations of frequency and voltage, to the voltage unbalance, voltage transients, voltage harmonics, and power cuts. Moreover, the purposes of quality control were intended to reduce consumers' complaints and increment the electric-power use value as well as to obtain data for better control and planning of power supply systems (Hilger, 1972).

Later Meynaud (1983) claimed that the quality of the electricity delivered by suppliers to consumers could be characterised by two additional factors: one defining the continuity of supply, and the second defining the "quality" of the voltage. He listed the causes and effects of distortion of voltage and discussed the nature, parameters and consequences of rapid voltage variations, voltage sags due to faults and the like, harmonics, voltage asymmetry, and transient overvoltages (spikes).

Today there is not a general agreement about the meaning of power quality. For example, IEEE std. 1100 defines power quality as "the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment". Despite this definition the term power quality is used in a more general way within the Institute of Electrical and Electronics Engineers (IEEE) (Bollen, 2000). IEC has adopted, instead of power quality, the concept of electromagnetic compatibility defined as "the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment".

2.3 Effects on loads

Special installations such as army, aircraft and navy facilities also conducted research in this field, looking for more reliable and secure installations and focusing on reducing malfunction of critical electric devices due to electromagnetic incompatibility. The need for a sine-wave voltage with constant frequency and amplitude was pointed out (Kajihara, (1968), Frichtel and Dougherty, (1970), Hucker, (1970), Giorgi, (1975) and Bertinov et al., (1981)).

Research concerning industrial plant planning and operation regarding the performance of sensitive electric tools under poor power quality conditions are found in the literature since the 1970s. Manufacturers and users of machine tools used to take electric power practically for granted, because circuits were operating with adequate unused capacity. Unfortunately, two simultaneous trends in manufacturing technology made this simple approach increasingly risky. The first was the tremendous growth in the use of electric power in the industry in general. Plant power systems, especially in the oldest facilities, started to be operated at or even beyond their design capacities, with generally adverse consequences to their performance. The changes were qualitative as well as quantitative; in many plants, an increasing part of the total electric load is composed of electric arc furnaces, rectifiers, thyristor converters, and other equipment that are potential contributors to poor power quality. The second trend was towards machine-tool technology that demands high power quality. For these reasons, many engineers started to find that power-system evaluation was a necessity in planning a major new machine-tool installation and design (McFadden, 1969, 1970), (Plette, 1969), (Konstantinov et al., 1977), (Gruzs, 1989) and (McGranaghan, 1995).

Total reliance on sensitive electronic systems for such important functions as data processing, communications, and process control has been taken for granted in commercial, industrial, and governmental activities. These new applications necessitated a new concern towards the quality of the electric supply. Intermittent power disturbances, capable of disrupting electronic equipment were inherent to both commercial and industrial power systems. Any disruption causing downtime and financial loss, power-related or otherwise, was likely to precipitate a study to determine appropriate corrective actions (Key, 1979).

Transmission and distribution utilities are facing an increasing pressure to fully utilize their existing systems because of the rise of capital, fuel, and environmental costs. Simultaneously, standards for quality of supply were under review. To mitigate problems related to poor power quality, customer participation in quality control was proposed to achieve the cheapest overall cost of system operation (Outhred and Schweppe, 1980).

The problems reported in manufacturing processes due to the poor quality of the electric supply have also been studied from an economical point of view, and the losses have been quantified. Reason (1988) analysed that manufacturers of electronic equipment were turning the tables on electric utilities by redefining the meaning of power quality. The quality of the power delivered by utilities had steadily improved over the years, but sensitive electronic equipment needed a high-quality power delivery system that extended all the way to the point of use. The author argues that in too many cases, manufacturers tried to place the onus on the utility as the party solely responsible for power quality. He showed that in fact, the causes of power quality problems were usually found in incorrect wiring of the customer's premises.

Kurbatskii and Yaramenko (1990) emphasised the deleterious effects of a low quality electric energy on the functioning and safety of the individual electric installations served by a distribution system and on the system itself. The authors estimated that the financial losses incurred by the individual undertakings ranged from £20,000 to £200,000 (sterling pounds) in the course of one year.

2.4 Power quality in de-regulated markets

The characteristics and sensitivity of end use equipment within customer facilities ultimately define power quality requirements. Improving the energy efficiency and productivity of industrial and commercial facilities can sometimes result in the use of technology that either causes power quality problems or is sensitive to power quality variations. Historically, utilities have only become involved in power quality problems that they caused to their customers. In the de-regulated environment, the responsibilities of utilities and customers are blurred. Who will be responsible for the quality of the power delivered in the de-regulated power industry? What are the power quality requirements at the interface between the transmission company and the distribution company? What is the base level of power quality that must be supplied by the distribution company to the end use customers? What kinds of enhanced power quality services can the energy service company offer to the end use customers? The answers to all these questions must be developed in terms of the contracts between the different entities resulting from the utility industry de-regulation (McGranaghan et al., 1998).

Meanwhile in Australia, generation companies, transmission companies, distribution companies, the market operator and electricity users have to obey the regulations set up by the Office of the Regulator General (ORG). The requirements related to quality of supply are defined in the System and the Distribution Code. ORG has several instruments including large penalties to execute the regulations defined by the Codes. This creates a new legal situation. There are several avenues for customers' complaints on quality of supply. The competitive electricity markets are generally more customer oriented (Mielczarski and Michalik, 1998).

2.5 Power quality surveys

Many countries have done their own power quality surveys to evaluate the performance of the electric grid. Based upon reviewed Romanian standards and original research results and information, Popescu (1983) proposed the items for a new Romanian standard concerning the quality of the delivered electric power. The emphasis was laid on the quality indices of the electric voltage in distorted condition.

In 1986, the Duke Power Company implemented a power system disturbance policy. The policy identified ways in which Duke could work with customers to resolve disturbance problems. Monitoring and investigating power quality were important elements in solving the power-disturbance problem. Duke relied upon instruments that ranged from a simple strip-chart recorder to an eight-channel computer-based waveform recording system with software for extensive waveform analysis (Dagenhart et al, 1987). As well in the USA, Hairabedian (1989) described a system that was designed to survey power disturbances at representative sites across the country. Disturbance data gathered from remote power monitors were transmitted over telephone lines to a central personal computer to be processed and saved in a database for further analysis and study.

Between 1990 and 1995 the National Power Laboratory developed a power quality study. This five-year study of power line disturbances monitored a 120 volt AC electrical service at the point of utilization using 50 special remote disturbance monitors at 235 sites in ten geographic regions of the United States and Canada. The total database of the study was approximately 1800 monitor months (Jurewicz, 1990), (Dorr, 1992).

Electricité de France has been involved in a policy to improve the quality of its supply. Measuring tools have been progressively developed for this purpose. The aim of the *QUALIMAT* project was to explain the relationships between customer satisfaction and the physical quality of the electricity supply. Physical measurements of the supply disturbances affecting the customers on their premises and assessment of their satisfaction, by way of conventional surveys, were conducted simultaneously. A new apparatus, known as the *QUALITY METER*, has been used for physical measurements (Fouilloux et al., 1991).

Delaney et al. (1994) describe a major UK distribution power quality survey on the various distribution voltage levels of one Regional Electricity Company. This project was created in response to increasing customer concerns over power quality.

Prior to 1990, very little information was available on the frequency of voltage sags and their origins at the Canadian grid (i.e. did the voltage sag originate in the utility's system or within the industrial facilities electric system?). In 1991, the Canadian Electrical Association took a pro-active approach to power quality problems and initiated a three year "Canadian National Power

Quality Survey" involving twenty-two utilities. The survey results provided a basic knowledge for designing and utilizing voltage sag mitigating technologies (Koval and Hughes, 1996).

More recently some developing countries have also made power quality surveys. For example, the Electric Power Research Institute (EPRI-USA) has investigated the power quality in an electric utility in India. As a result of this investigation, plans were offered for the creation of a power quality park, with special distribution features to maximize customer productivity (Banerjee et al., 1998).

Brazil also runs a project to evaluate the sag performance of Brazilian network busbars. The Brazilian electric energy market can be characterised as a functionally unbundled model, which implies that generation, transmission, distribution, and commercialization activities are segregated. Considering the ample institutional experience in Brazil, the Brazilian Independent System Operator (ONS*)* has been working to bring into force all the previous concerns with respect to the question of power quality. To this end and with the support of the Brazilian Electric Energy Regulating Agency (*ANEEL), ONS* has been stimulating a broad debate about power quality with the participation of market players that require access to the transmission system, government organs, universities, and research centres. It has been observed that the amount of information about voltage sags available in Brazil is not sufficient to safely derive conclusions. Therefore, a measurement survey as pilot project has been initiated. This project has as its prime motivation the assessment of the quality of power at the end consumer and has striven to achieve the immediate objectives of identifying the main causes and mechanisms of sag propagation in the system, as well as to define and characterise the phenomenon and its indices (Macedo Correia and Oliveira Campones do Brasil, 2003).

2.6 Power quality standardisation

The standardisation of power quality is also a long and never-ending story. Deloux (1974) claimed that international standardisation had done little towards drawing up detailed requirements to ensure the electromagnetic compatibility between the network and the loads connected, in the event of disturbed voltage. From this point of view the situation was changing considerably, as he reported at the European Committee for Electrotechnical Standardization (CENELEC). It was necessary to define quality criteria, develop suitable means of measuring quality and ratify recommendations and standards. A large-scale international standardising work primarily concerned with voltages and voltage quality, has been running since then (Lonngren, 1974).

Heikkila (1976) also claimed that the lack of international standards implied the need for national recommendations and regulations concerning devices causing harmonics. The increasing occurrence of harmonics in electricity networks deteriorates the quality of supply, provokes telephone interferences, and increases losses in networks and consumer devices. Furthermore, the criteria for harmonic evaluation were defined by using spectral methods, determining the length and frequency of measurements (Konstantinov et al., 1978).

The International Union of Producers and Distributors of Electrical Energy (UNIPEDE) issued one of the first standards on power quality. It is a report that outlines the quality of the electricity supply in terms of noise spikes, variation of voltage levels and audio and radio frequency contents (Colding, 1982).

In the former USSR the reduction of the quality of the electric energy in a power system was causing electromagnetic damage. The economical evaluation was done using the damage cost function. For the damage reduction, maximum permissible values of the quality factors for the USSR were stated (Valov, 1984). The prerequisites for electromagnetic compatibility between the system and the loads were similar to those required for energy quality meters, and were regulated by the GOST Standard 13109-87 (Kartashev and Kryuchkov, 1992).

McEachern (1993) claimed the need of standards regarding power quality in order to determine the power quality status of distribution systems; unfortunately, he concluded there were not standards, at least not in 1993. Many different groups were working towards this goal, including IEEE, IEC (International Electrotechnical Commission), ANSI (American National Standards Institute), CBEMA (Computer and Business Equipment Manufacturers Association), and EPRI.

As a consequence of the de-regulation process that most countries were experiencing in the energy business, power quality became a discussion issue. For instance, the analysis of the electric power quality in Romania demonstrated the necessity to take actions in order to observe the international standards. On the basis of proposals, resulting from the surveys carried out at the country power grid, the committee has in view the achievement of some measures to improve the electric power quality. For example, starting a permanent monitoring of the voltage values, the voltage sags and the short interruptions, calculating the minimal short circuit power required in the nodes where the nonlinear loads are connected; drawing up a regulation concerning the selection of the nodes which do not observe the limit values of the asymmetry coefficient (<2%) and the distortion coefficient (<80%); updating the standard PE 142/80 regarding the flicker, the voltage fluctuations and its completion with an emission limits' allotting methodology; and drawing up complete regulations in order to monitor each quality index, starting with those who are the object of the contract requirements (Albert and Lavrov, 1997).

At the other side of the world, Argentina has developed explicit power quality regulations. At the beginning of the 1990's, public distribution companies were privatised in the area of Gran Buenos Aires. Detailed regulations regarding continuity of supply and voltage profile were then established. In addition, regulations regarding voltage disturbances were established at the end of 1996, for the purpose of controlling the level of disturbance in the power networks and users disturbance injection, particularly regarding harmonics and flicker. The bases of these new regulations are international standards that have been adapted to form a set of reference levels, emission limits and measurement and control procedures (Roman and Ubeda, 1998).

A historical review on the standards related to power quality at the Institute of Electrical and Electronic Engineers is given below:
ANSI/IEEE Std 519-1981 "IEEE guide for harmonic control and reactive compensation of static power converters"
IEEE Std C57.18-10-1998 "IEEE standard practices and requirements for semiconductor power rectifier transformers"
IEEE Std C62.48-1995 "IEEE guide on interactions between power system disturbances and surge-protective devices"
IEEE Std 493-1997, "Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems", Appendix N
IEEE Std 493-1997 "IEEE recommended practice for the design of reliable industrial and commercial power systems", Chapter 9
IEEE Std 519-1992 "IEEE recommended practices and requirements for harmonic control in electrical power systems"
IEEE Std 1100-1999 "IEEE recommended practice for powering and grounding electronic equipment"
IEEE Std 1124-2003 "IEEE guide for the analysis and definition of DC-side harmonic performance of HVDC transmission systems"
IEEE Standard 1159-1995, "IEEE recommended practice for monitoring electric power quality".

IEEE Std 1159.3-2003 "IEEE recommended practice for the transfer of power quality data"
IEEE Std 1250-1995 "IEEE guide for service to equipment sensitive to momentary voltage disturbances"
IEEE Std 1346-1998 "IEEE recommended practice for evaluating electric power system compatibility with electronic process equipment"
IEEE Std 1531-2003 "IEEE Guide for Application and Specification of Harmonic Filters"
IEEE Standard 1564 draft 6, "Recommended Practice for the Establishment of Voltage Sags Indices"

The IEC has presented a standard on electromagnetic compatibility (IEC 61000, 1990), which covers most of the power quality issues. This document consists of 6 parts, named: General, Environment, Limits, Testing and measurements techniques, Installation and mitigation guidelines, and Generic standards. Electromagnetic disturbances are classified by IEC as shown in Table 1.

Table 1 – Classification of electromagnetic phenomena according IEC

Conducted low-frequency	Harmonics and inter-harmonics
	Signal systems (power line carrier)
	Voltage fluctuations
	Voltage sags and interruptions
	Voltage imbalance
	Power-frequency variations
	Induced low-frequency voltages
	DC in AC networks
Radiated low-frequency	Magnetic fields
	Electric fields
Conducted high-frequency	Induced continuous wave voltages or currents
	Unidirectional transients
	Oscillatory transients
Radiated high-frequency	Magnetic fields
	Electric fields
	Electromagnetic fields
	Continuous waves
	Transients

2.7 Literature review on voltage sags

As mentioned in Section 2.1, voltage sags and voltage dips are considered synonyms in this thesis. This assumption is based on the similarity of the definitions found in the standards commented here. According to the Standard IEEE 1346-1998 a voltage sag is "a decrease in rms voltage or current at the power frequency for duration of 0.5 cycle to 1 minute". The IEC has the following definition for a dip (IEC 61000-2-1, 1990). "A voltage dip is a sudden reduction of the voltage at a point in the electrical system, followed by a voltage recovery after a short period of time, from half a cycle to a few seconds". From the previous definitions it is evident that both voltage sag and voltage dip refer to the same disturbance. Moreover, the draft Technical Report for Electromagnetic Compatibility (IEC 61000-2-8, 2002) regarding voltage dips and short interruption on public electric power systems states, "voltage sag is an alternative name for the phenomenon voltage dip".

The interest in voltage sags is new in the power quality area. The main concern about voltage sags is their effect on sensitive electrical devices, such as personal computers, adjustable speed drives, programmable logic controllers, and other power electronic equipments. After having briefly defined voltage sags, and recalled to mind their repercussions, Mestres (1972) described the arrangements made by *Electricité de France* for facilitating the qualitative analysis of the service in the field of short power supply breaks. Another early research developed by Poeata et al. (1978) investigated the possibilities of calculating the effects of voltage sags on the industrial consumer using digital simulation.

Later, Wagner et al. (1990) presented a case study involving monitoring power quality disturbances at a representative plant and identifying the disturbances that disrupt production. The sensitivities of representative electronic control equipment to the identified disturbances were measured and then projected to form a plant disturbance threshold. Voltage sags were the only disturbance to directly cause lost production and were the most common disturbance at 68% of the total number of events recorded. Two programmable logic controllers (PLC) and a computerized numerically controlled lathe (CNC) were tested with a sag generator to determine the sensitivity of the equipment. The most sensitive components failed when the voltage dropped to 80-86% of rated voltage. On the other hand, the least sensitive loads failed when the voltage dropped to 30% of the rated voltage. From the test results, the calculated sag threshold to affect production at the utility point of common coupling (PCC) was 87% of the nominal voltage for more than 8.3 ms.

Tosato et al. (1991) also investigated the problems posed by voltage sags to industrial power electronic loads. Voltage sag generation and propagation in power systems were analysed and discussed. Proper methods for addressing the problem in public networks and customer plants were analysed. A fast-response, low-cost static booster system was proposed as an effective method to relieve most of the consequences for industrial power loads. Simulation results of the proposed circuit were also reported and discussed.

McGranaghan (1995) analysed the effects of voltage sags in process industry applications. The author described the causes of voltage sags in affecting process industries, their impacts on equipment operation, and possible solutions. The definition proposed focuses on system faults as the major cause of voltage sags. The sensitivity of different types of process industry equipment, including adjustable speed drives, programmable logic controllers, and motor contactors was analysed. The author also described the available methods of power conditioning for these sensitive equipments.

Heine et al. (2002) developed a method for estimating the frequency and cost of voltage sags. The annual number and cost of voltage sags were determined for five Finnish distribution companies. The method of fault positions was applied for the calculation of voltage sag frequency. The economic consequences were assessed by multiplying the sag frequency and cost by the number of customers. The cost of a single voltage sag was determined from a survey that had been carried out in three Nordic countries in the mid 1990s. In addition, they estimated the total annual sag-related cost for each of the companies considered in this study and for each customer category. Finally they concluded that the total cost per company appeared to be much higher than had generally been assumed.

Leborgne et al. (2003) investigated an alternative method for the characterisation of industrial process sensitivity to voltage sags using a power quality monitoring system. Several methods used for voltage sag characterisation were analysed. The load behaviour was classified for all sags recorded by the power quality monitor. As a result, a method based on the sag magnitude for the characterisation of load sensitivity was presented. It was concluded that the loads were sensitive to sag magnitudes below 0.70 pu.

Stockman et al. (2004) described the vulnerability of variable speed drives (VSD) to voltage sags on a theoretical basis. Then, three embedded mitigation methods were addressed in theory to protect textile processes against voltage sags, and practical measurements with a sag generator were shown. The use of embedded solutions such as kinetic buffering and boost convertor increased the voltage sag immunity of the process. Finally, two processes in the textile industry were described, and a brief cost-benefit analysis of the solutions was performed.

Djokic et al. (2005) discussed the sensitivity of adjustable speed drives (ASD) to voltage sags and short interruptions on the basis of extensive test results. Existing standards and previously published works were critically reviewed, and a description of test procedures needed for appropriate assessment of ASD sensitivity was presented. The following tests were performed: sensitivity to rectangular three-phase, two-phase, and single-phase voltage sags with ideal and nonideal supply characteristics, as well as sensitivity to nonrectangular-balanced three-phase voltage sags similar to those caused by the starting of large motors. The results demonstrated that although the behaviour of this equipment has a rather complex pattern, a simple representation of ASD sensitivity to various types of voltage sags and short interruption can be established.

Research about mitigation methods for voltage sags are also found in the literature. Johns and Morgan (1994) proposed that the voltage sag impact on industrial processes can be mitigated using ridethrough coordination. The utility predicted for the new plant site: the depth, duration and number of expected sags; and the number of expected outages. The predictions were provided so they could be included in the new machinery quotations. Because the ridethrough predictions for the machinery at the new plant site were known up front and site specific, mitigating the effects of voltage sag could be built into the machinery and did not necessarily require UPS type equipment. Management weighed additional purchase cost with long term downtime cost based on the machine vs. utility specifications and selected the best economic alternative.

Gomez and Campetelli (2000) proposed the voltage sag mitigation by using current-limiting fuses. The authors analysed the coordination of the voltage sag equipment susceptibility curves and the specific energy of the current-limiting fuses. There are several fuse types, which allow the best selection to be made for the reduction of the voltage sag duration, using the fuse energy control characteristic.

Tosato and Quaia (2000) also presented a mitigation solution by the reduction of fault-clearing time. The reduction of the clearing time of the lines' protection equipment may lead to a substantial power quality improvement because the majority of sensitive industrial processes (including computer systems, power electronics and variable speed drives) are capable of riding through a sag of very limited duration (typically below a half period). This possibility exists with modern technologies. Later, Tosato (2001) presented the fault-current limitation as a way to limit the expected voltage sag amplitude and improve the system power quality. Since the depth of the voltage sag is proportional to the fault current, limiting fault current by means of a device connected at the beginning of the most exposed radial feeders is proposed.

Sannino and Svensson (2000) proposed the mitigation of voltage sags based in the application of power electronic devices. A series-connected voltage source converter (VSC) for voltage sag mitigation using vector control and a filter compensation algorithm was presented. The series-connected VSC, which is characterised by a fast control logic, based on the decomposition of the unbalanced supply voltages into instantaneous positive and negative sequence components in two different rotating dq-coordinate systems was proposed. Furthermore, its performance was improved through the implementation of an algorithm to compensate for the steady-state voltage drop on the converter output filter.

Woodley and Sezi (2000) presented another solution for sag mitigation using power electronic devices. The authors described a multi-module dynamic voltage regulator (DVR) that demonstrated its benefits in protecting large sensitive customer loads from supply system disturbances providing a practical means to minimize down-time in large industrial facilities. They have successfully illustrated the ability to parallel standard 2 MVA DVR modules at 4 MVA and 6 MVA power levels. With the ability to combine up to ten modules, solutions now exist to protect sensitive distribution-voltage served loads of up to 40 MVA from voltage sag/swell events.

Yun et al. (2000) introduced voltage sag mitigation by using feeder transfer in power distribution systems. The paper proposed a method using the switching for sectionalizing points of distribution networks. Customers connected to busbars affected by a voltage sag are switched to another busbar supplied by another source.

Macken et al. (2004) analysed the incidence of distributed generation for voltage sags mitigation. Two solutions are presented to prevent sensitive equipment from disruptive operation. Both solutions make use of distributed generation systems to maintain the voltage across the equipment in the presence of voltage sags. The emphasis of this paper is on the transient response of the solutions for both balanced as well as unbalanced voltage sags.

Degeneff et al. (2000) stated that the "cost" of poor quality of power depends upon many factors but generally varies from 50 to 400 U$S/kVA.year. The authors analysed the numerous mitigation methods proposed, e.g., uninterruptible power supply (UPS), ferroresonant transformers, static transfer switches, transformers with electronic tap-changers, and static voltage compensators (SVC). Finally, they presented a comparison of the total owning cost of various equipment options. The total owning cost is found by combining the investment cost of the equipment, with the present value of the operating cost, and the addition cost incurred due to limitations of the device. The ratings addressed in this research were from 20 kVA and 400 kVA.

Dettloff (2000) analysed another way to mitigate the economical cost of voltage sags to end users. The author describes the special manufacturing contracts between energy provider and customers taking into account the power quality performance. In 1995, Detroit Edison entered into long-term pricing and service quality agreements with the Chrysler Corporation, the Ford Motor Company, and the General Motors. The terms are specified in an agreement known as the Special Manufacturing Contract (SMC). The service agreement covers voltage interruptions and voltage sags. Detroit Edison became liable for interruptions that exceeded performance targets effective from January 1995. The voltage sag amendment to the SMC, effective from January 1998, makes Detroit Edison liable to the customers if voltage sag measures exceed performance targets. Detroit Edison has installed a power quality monitoring system at 58 customers' locations throughout its territory. The power quality monitoring system allows Detroit Edison to determine the frequency and severity of voltage sags at the selected locations. This paper presents the purpose and rules of the voltage sag agreements. It explains the definition of a sag score. The sag agreements define what a qualifying sag is.

The utility companies increased interest to assess their performance regarding voltage sags is also found in the literature. One of the first references in this field was authored by Ermakov and Cherepov (1983), when the authors proposed a statistical analysis of voltage surges and sags at the Soviet Union network. The quality of the voltage was assessed with the aid of a statistical analyser, which measured the amplitude distribution of the surges and sags, in relation to a nominal level.

Marquet (1992) introduced a software for the determination of depth, duration and number of voltage sags in medium voltage networks at *Electricité de France*. These results enabled customers to know the voltage sag indices at any location in the network, indicating the minimum ridethrough needed by the loads to be unaffected by voltage sags.

Sabin et al. (1999) presented the performance of a distribution grid based on a monitoring survey. This work describes the methods for collecting, characterising, and analysing rms voltage variation measurements during a distribution system power quality monitoring program. The measurements were collected from the primary distribution systems of 24 utilities in different geographic regions of the United States.

Thallam and Heydt (2000) introduced a set of indices to evaluate grid performance for three-phase voltage sags. The electric power acceptability curves are an empirical set of curves that represent the intensity and duration of bus voltage disturbances. Alternatives for the assessment of voltage sags, such as voltage sag energy, are proposed.

The complex issues involving voltage sags are the consequence of the different requirements of the utility customers, equipment manufacturers, and the distribution utilities. In the environment of the new competitive market in electricity, equipment manufacturers and distribution utilities have made efforts towards achieving the satisfaction of their customers. The contribution of power quality standards is very important, although the definitions and criteria for the power quality analyses are not well defined yet (Ribeiro, 1999).

This section has dealt with a literature review on power quality issues. The Inspec publication data base has been used to show the increased interest in this topic in the last decade and the relevance of voltage sags among other disturbances. Now that the reader has been introduced through this historical review of power quality and voltage sags, the next sections present the specific aspect of voltage sags that has been analysed in this project.

3 Voltage sag characterisation

This section presents an overview of the characterisation of voltage sags. Unbalanced voltage sags are highlighted since they are the most common type of sags on transmission and distribution networks. A method for classification of three-phase voltage sags is proposed. New methods for voltage sag representation based on phasor analysis are introduced.

3.1 Magnitude and duration

Magnitude and duration are the two most important sag characteristics. Sag magnitude is defined as the minimum rms voltage. Alternatively, sag magnitude may be defined as the amplitude of the voltage drop, leading to a opposite meaning, as shown in Figure 2. Therefore it is necessary to specify if magnitude refers to the retained voltage or to the drop of the voltage (IEEE P1564). The expressions "retained voltage", "remaining voltage", and "residual voltage" are considered synonyms in this thesis.

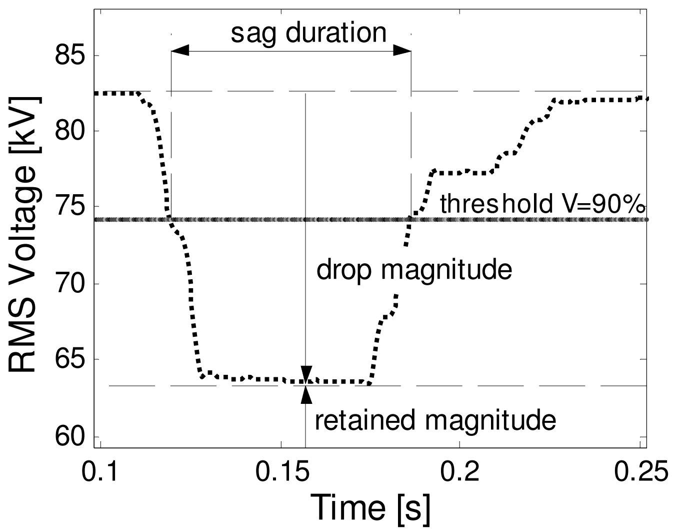


Figure 2 –Voltage sag magnitude and duration. The detection threshold (V=90%) is also represented

The voltage sag duration is the period of time in which the voltage is lower than a stated limit, as shown in Figure 2. Normally, sag duration is less than 1 s (IEEE Std. 493, 1997).

According to IEEE Std 1159 (1995), sag magnitudes range from 10% to 90% of nominal voltage and sag durations from half-cycle to 1 min. Furthermore, sags may be classified by their duration as shown in Table 2. All events whose retained voltage is less than 0.1 per unit are classified as interruptions and should not be considered voltage sags according to IEEE Std 1159 (1995).

Table 2 – Classification of voltage sags according IEEE 1159

Type of Sag	Duration	Magnitude
Instantaneous	0.5 - 30 cycles	0.1 - 0.9 pu
Momentary	30 cycles - 3 s	0.1 - 0.9 pu
Temporary	3 s – 1 min	0.1 - 0.9 pu

The power system voltage is described by a sine wave. A voltage sag can be seen as a reduction in the amplitude of the waveform. Figure 3 shows the voltage waveform during a fault-caused sag, sampled at 32 points per cycle. The amplitude of the instantaneous voltage can also be used to characterise the sag magnitude.

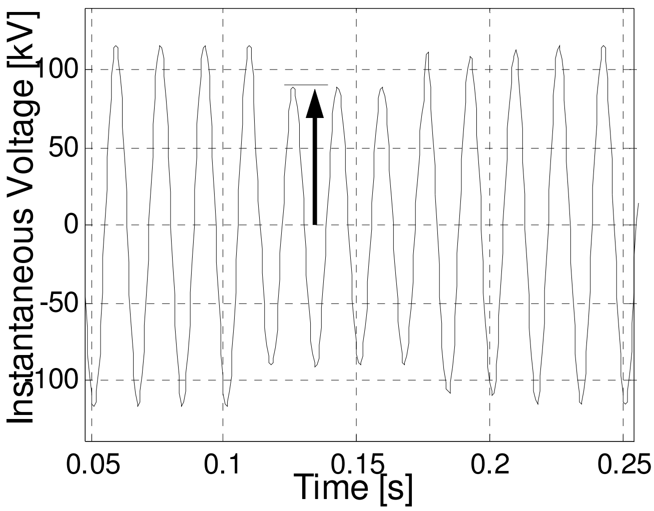


Figure 3 – Voltage waveform during voltage sag

Considering that voltage sag is defined as a reduction of the rms voltage, it is natural to use the rms voltage to define the voltage sag magnitude. The rms voltage is calculated using (2.1).

$$V_{rms}(k) = \sqrt{\frac{1}{N} \sum_{i=k-N+1}^{k} v_i^2} \tag{2.1}$$

Here N is the number of samples per cycle, v_i is the instantaneous sampled voltage and k is the instant when the rms voltage is estimated. Here rms voltage is post estimated; rms voltage is calculated with the previous N instantaneous voltage samples. Moreover, this algorithm is called one-cycle window, meaning that rms values are estimated with one cycle of instantaneous values.

Alternatively it is possible to estimate the rms value using only half a cycle of instantaneous values. This algorithm (2.2) is called half-cycle window.

$$V_{rms(1/2)}(k) = \sqrt{\frac{2}{N} \sum_{i=k-(N/2)+1}^{k} v_i^2} \tag{2.2}$$

The half cycle algorithm is more sensitive to changes in the voltage and has a faster response to detect an event. However, the half-cycle algorithm shows oscillations when there is a second harmonic component in the voltage signal. Figure 4 shows the rms voltage estimation using one-cycle and half-cycle algorithms. It also shows that the half-cycle algorithm is faster to detect the starting and ending of the events. Nevertheless, the event duration does not change considerably, both algorithms provide similar results. Furthermore, it can be verified that duration differences are rather small, and do not affect the estimation of sag indices (Kagan et al., 2000).

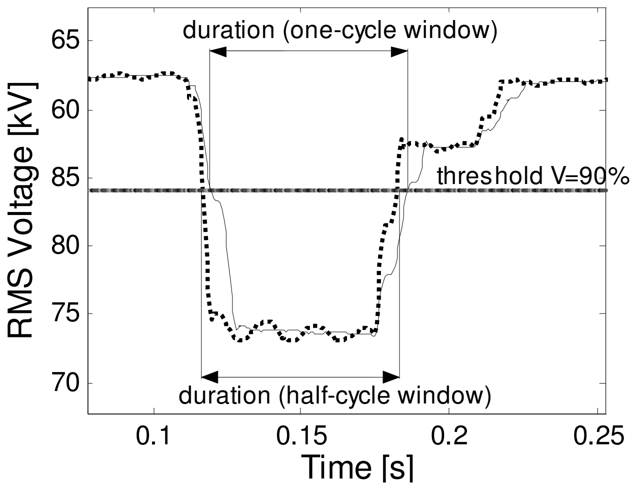


Figure 4 – Influence of rms algorithm on the sag duration, 1/2 cycle algorithm (dotted line) and 1 cycle algorithm (solid line), the threshold (V=90%) is also represented

The rms voltage is not a constant value during the event. In this thesis the voltage sag magnitude is characterised by the minimum rms value during the event, as it is shown in Figure 5. However, for sags that greatly differ from the rectangular shape the recommendation is to consider a set of thresholds and estimate the related duration for each selected threshold (Brooks et al., 1998).

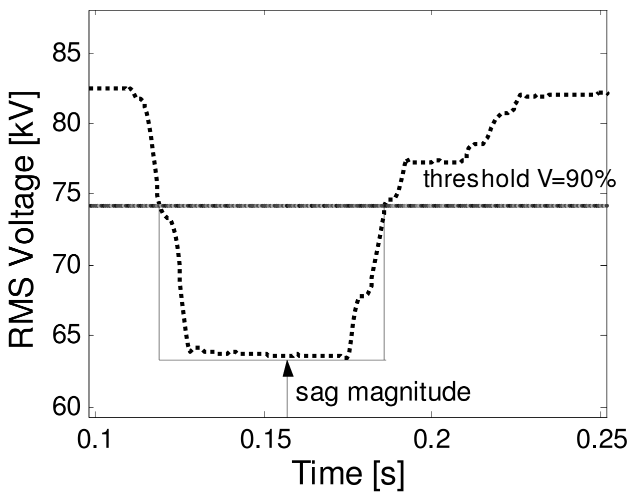


Figure 5 – Voltage sag magnitude characterisation (solid line) and rms voltage dynamic behaviour (dotted line), the threshold (V=90%) is also represented

It is also possible to consider the fundamental voltage to characterise the sag. The fundamental voltage is a complex quantity obtained by the decomposition of the instantaneous voltage in its Fourier components, where the second component of the series corresponds to the fundamental frequency signal (50 or 60Hz). The rms value of the fundamental voltage behaves similarly as the rms value of the complete voltage, as shown in Figure 6. This similarity is seen for normal voltage conditions (acceptable harmonic levels). In addition, voltage sag magnitude and duration estimated by fundamental voltage are enough accurate for most sag analysis (Ohrstrom and Soder, 2003).

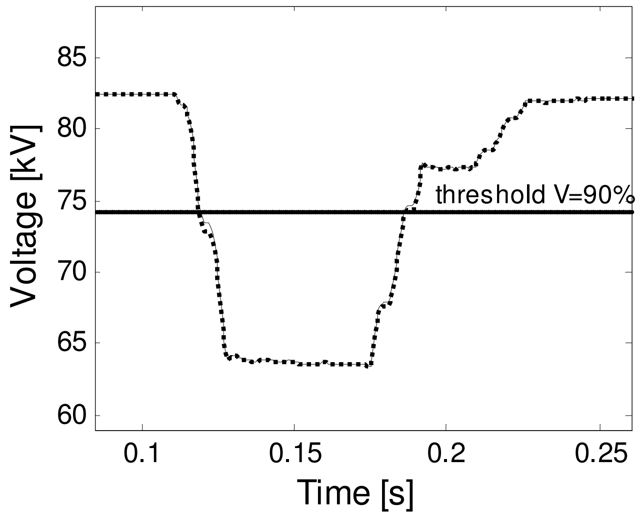


Figure 6 – rms voltage (solid line) and rms of fundamental voltage (dotted line), sag from Figure 3, the threshold (V=90%) is also represented

The fundamental voltage is obtained using the Fast Fourier transformation (FFT), where FFT is an efficient algorithm for computing the Discrete Fourier Transformation (DFT). DFT is the appropriate Fourier analysis for sampled vector data, such as the instantaneous voltage.

3.2 Phase-angle jump

An event in the power system, like a short-circuit or a fault, affects not only the magnitude of the voltage phasors but also the angle of the phasors. The change in the phasor angle is called phase-angle jump (paj) associated with the voltage sag. The phase-angle jump is seen as a shift in the zero crossing of instantaneous voltage and it is a cause of failure of power electronic converters that use phase-angle information for their firing control (Bollen, 2000).

The phase-angle jump (Ψ) is the difference between the actual voltage-angle (arg[$V(t)$]) and the reference voltage-angle ($\Phi_o(t)$).

The reference voltage may be chosen as the pre-event complex voltage (*V(0)*) keeping a constant rotation speed of $2\pi f_o$ (rad/s), as shown in (2.3).

$$\phi_o(t) = \arg[V(0)] + 2\pi f_o t \tag{2.3}$$

Here $V(0)$ is the pre-event complex voltage and f_o is the pre-event voltage frequency.

Finally, the phase-angle jump is estimated as the difference of the actual voltage angle and the reference angle, as shown in (2.4).

$$\psi(t) = \arg[V(t)] - \phi_o(t) \tag{2.4}$$

A schematic representation of the phase-angle jump estimated using equations (2.3) and (2.4) is shown in Figure 7. The reference angle ($\Phi_o(t)$) follows a straight line because it rotates with constant speed ($2\pi f_o$). The actual angle coincides with the reference angle until the starting of the event. Then the actual angle diverges from the reference angle causing the phase-angle jump. After the event the actual angle may not coincide with the reference one. The actual angle may keep a constant shift if the actual frequency is the same as the pre-event frequency, otherwise the actual angle diverges constantly with respect to the reference angle.

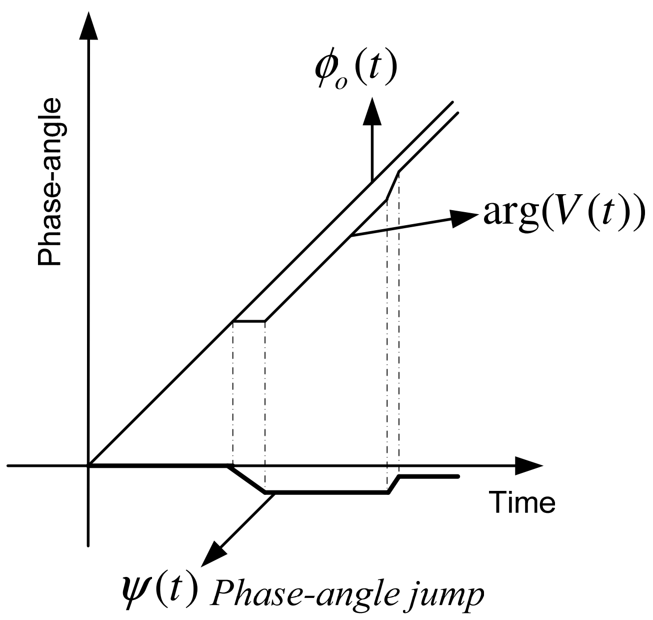


Figure 7 – Phase-angle jump schematic representation

The phase-angle jump can be obtained from measured instantaneous voltages and from simulated sags, using time domain analysis tools such as EMTP/ATP programs. In these cases, when instantaneous voltage is available, the complex voltages may be obtained using the Discrete Fourier Transformation. Once the complex voltages are known the voltage angle is easily estimated.

The algorithm presented above has been applied to the voltage sag shown in Figure 3. The estimated phase-angle jump is shown in Figure 8. The starting and ending sag transitions must be neglected to estimate the maximum absolute deviation of phase-angle (-2 degrees) because they are a consequence of the Fourier Transformation algorithm applied to a non-periodic signal and do not represent the physical reality.

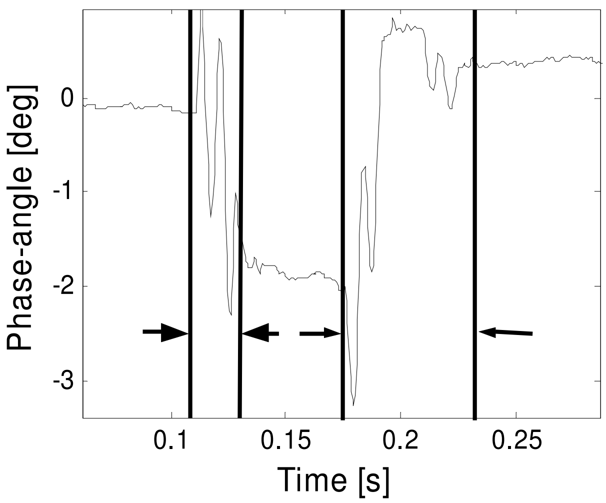


Figure 8 – Phase-angle jump estimation for the sag shown in Figure 3; the starting and ending transient periods, indicated by the arrows, should be neglected to estimate phase-angle jump

3.3 Three-phase events

The voltage sags observed in transmission and distribution networks generally affect more than one of the voltage phases. Moreover, each of the three phases perceives different voltage sag characteristics. Figure 9 shows an unbalanced voltage sag, where two phases are affected. In addition, the voltage sag has different magnitude and duration in each phase, indicated as V1, T1, V2, and T2 in Figure 9.

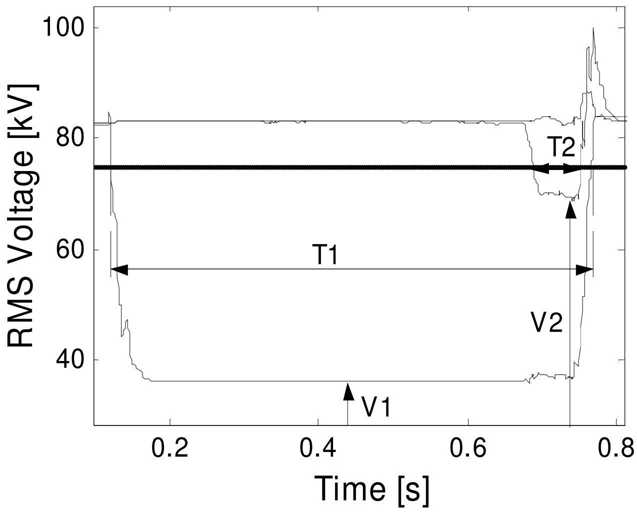


Figure 9 – Unbalanced voltage sag

Two different philosophies to characterise three-phase voltage sags can be found in the literature. One approach is to consider each phase individually and treat the three-phase event as three single phase events; estimating magnitude, phase-angle jump and duration for each single event (Martinez and Arnedo, 2004).

A more common approach considers the three-phase sag as one individual event. Single event-characteristics are obtained as a result of the phase aggregation. The lowest voltage and the longest duration may be chosen to characterise the three-phase sag (Bollen and Zhang, 2003). This method of aggregation has several consequences:

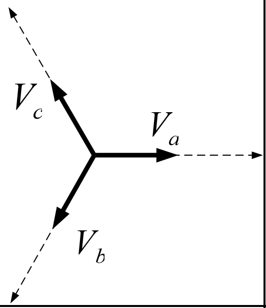
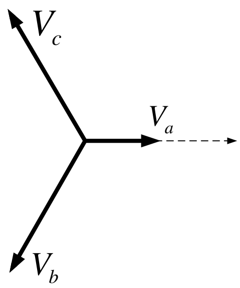
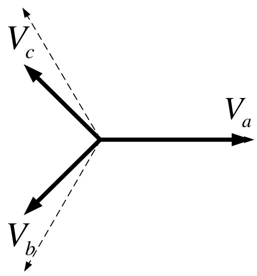
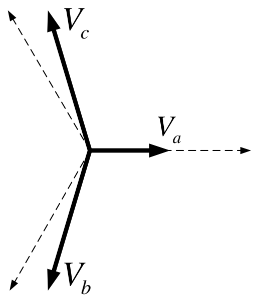
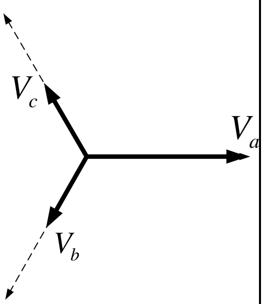
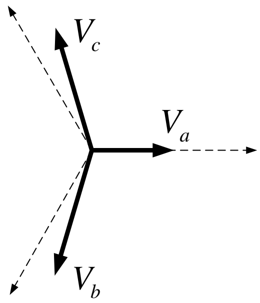
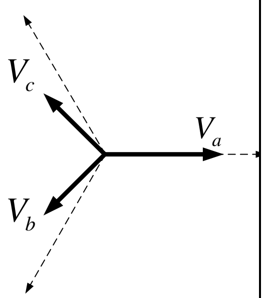
- An event where only one phase experiences a voltage sag is characterised as severe as an event where all three-phases experience the same sag.
- It is not possible to analyse the propagation of voltage sags through a transformer, and predict the effects on the loads connected on the other side of transformers.
- There is no clear relation between phase-to-phase and phase-to-neutral voltage sag, or delta and star connected monitors.
- Some information is lost, thus it is more difficult to investigate the cause of the voltage sag as for example the fault type and the fault location that causes the event.

Bollen and Zhang (2003) developed two methods to obtain three-phase voltage sag characterisation called “ABC classification” and “symmetrical components classification”. Due to its simplicity the

ABC classification is more used than the symmetrical components classification. However, this classification is based on a simplified model of the network and the authors do not recommend its use for the classification of voltage sags obtained from measured instantaneous voltages.

In the ABC classification seven types of voltage sags are distinguished. The complex voltages and the phasor diagram of each type of sag are shown in Table 3.

Table 3 – Three-phase voltage sags according the ABC classification

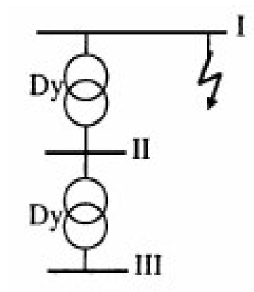
Type A $\overline{V}_a = V$ $\overline{V}_b = -\frac{1}{2}V - j\frac{\sqrt{3}}{2}V$ $\overline{V}_c = -\frac{1}{2}V + j\frac{\sqrt{3}}{2}V$ 	Type B $\overline{V}_a = V$ $\overline{V}_b = -\frac{1}{2}E_1 - j\frac{\sqrt{3}}{2}\overline{E}_1$ $\overline{V}_c = -\frac{1}{2}E_1 + j\frac{\sqrt{3}}{2}\overline{E}_1$ 
Type C $\overline{V}_a = E_1$ $\overline{V}_b = -\frac{1}{2}E_1 - j\frac{\sqrt{3}}{2}V$ $\overline{V}_c = -\frac{1}{2}E_1 + j\frac{\sqrt{3}}{2}V$ 	Type D $\overline{V}_a = V$ $\overline{V}_b = -\frac{1}{2}V - j\frac{\sqrt{3}}{2}E_1$ $\overline{V}_c = -\frac{1}{2}V + j\frac{\sqrt{3}}{2}E_1$ 
Type E $\overline{V}_a = E_1$ $\overline{V}_b = -\frac{1}{2}V - j\frac{\sqrt{3}}{2}V$ $\overline{V}_c = -\frac{1}{2}V + j\frac{\sqrt{3}}{2}V$ 	Type F $\overline{V}_a = V$ $\overline{V}_b = -\frac{1}{2}V - j(\frac{\sqrt{3}}{6}V + \frac{\sqrt{3}}{3}E_1)$ $\overline{V}_c = -\frac{1}{2}V + j(\frac{\sqrt{3}}{6}V + \frac{\sqrt{3}}{3}E_1)$ 
Type G $\overline{V}_a = \frac{2}{3}E_1 + \frac{1}{3}V$ $\overline{V}_b = -\frac{1}{3}E_1 - \frac{1}{6}V - j\frac{\sqrt{3}}{2}V$ $\overline{V}_c = -\frac{1}{3}E_1 - \frac{1}{6}V + j\frac{\sqrt{3}}{2}V$ 	

The pre-event voltage in phase A is denoted as E_1, recalling to the equivalence between phase A voltage and positive sequence voltage in a balanced system. The voltage in the phase that experienced the sag or between the phases that experienced the sag is indicated as V.

The sag types shown in Table 3 are drawn considering phase A as the reference phase. It means that another set of equivalent equations can be derived if phase B or C are set as the reference phase.

The ABC classification was developed, among other reasons, to analyse the propagation of a voltage sag from transmission to distributions levels, when the disturbance propagates through a transformer. The generation and propagation of the different types of voltage sags are indicated in Table 4.

Table 4 – Voltage sag types propagation through delta-star transformer



Location / Voltage sag type			
Fault type	**I**	**II**	**III**
LLL	A	A	A
LG	B	C	D
LL	C	D	C
LLG	E	F	G

For instance, when there is a LLG fault at the location I, a sag type E is seen at this location. However, at location II below a delta-star transformer the same event is seen as a sag type F and at location III below another delta-star connected transformer the sag is observed as type G.

The symmetrical components classification is based on a systematic analysis of each type of fault using the symmetrical components theory. An example is given in Appendix 1. Voltage sags in one phase (type D) and voltage sags in two phases (type C) are distinguished in this method. Symmetrical three-phase sags are considered a limit case. Figure 10 shows the classification of voltage sags according to the symmetrical components method.

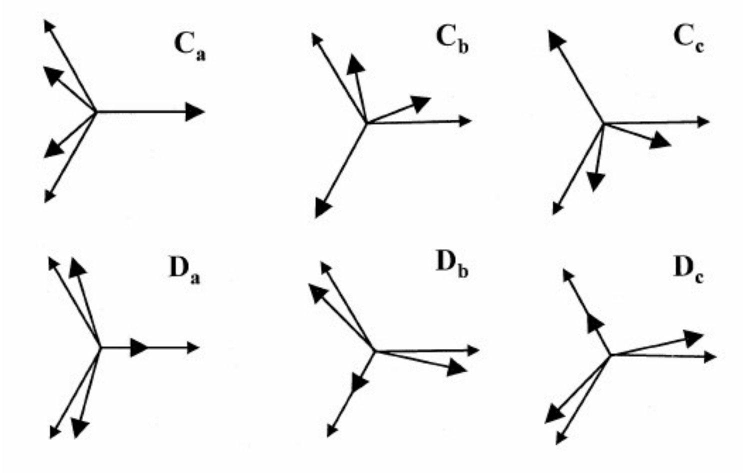


Figure 10 – Voltage sag classification according to the symmetrical components method

The type of voltage sag can be obtained comparing phase-to-neutral and phase-to-phase voltages, estimated in per-unit after removing the zero sequence component, according to the first column of Table 5. That is to say, if the lowest voltage is between phases A and B (V_{AB}) the sag is classified as type C_C.

Table 5 – Symmetrical-components classification of voltage sags

Sag in phases	**Sag Type**	**Characteristic voltage (V_{Ch})**	**PN factor (F)**
BC	C_a	$V_{Ch} = U_1 - U_2$	$F = U_1 + U_2$
CA	C_b	$V_{Ch} = U_1 - a^2 U_2$	$F = U_1 + a^2 U_2$
AB	C_c	$V_{Ch} = U_1 - aU_2$	$F = U_1 + aU_2$
A	D_a	$V_{Ch} = U_1 + U_2$	$F = U_1 - U_2$
B	D_b	$V_{Ch} = U_1 + a^2 U_2$	$F = U_1 - a^2 U_2$
C	D_c	$V_{Ch} = U_1 + a^2 U_2$	$F = U_1 - a^2 U_2$

The first column of Table 5 identifies the voltage that experiences the most severe drop; the second column shows the sag classification, and the third and fourth columns introduce the equations to obtain characteristic voltage (V_{Ch}) and the PN-factor (F). The PN-factor is an additional phasor that quantifies an unbalanced sag when the system's positive and negative sequence impedance are not equal. A detailed description of the derivation of these equations can be found in Bollen and Zhang (2003).

The ABC and the symmetrical-component classification methods are equivalent and the characterisation parameters can be converted from one method to the other as shown in Table 6.

Table 6 – Conversion of characterisation from ABC to symmetrical component classification

ABC method	Symmetrical component method	Characteristic voltage	PN factor	Zero-sequence voltage
A	Any	$V_{Ch} = \overline{V}$	$F = \overline{V}$	0
B	D_a	$V_{Ch} = \frac{1}{3}\overline{E}_1 + \frac{2}{3}\overline{V}$	$F = \overline{E}_1$	$U_0 = \frac{1}{3}\overline{V} - \frac{1}{3}\overline{E}_1$
C	C_a	$V_{Ch} = \overline{V}$	$F = \overline{E}_1$	0
D	D_a	$V_{Ch} = \overline{V}$	$F = \overline{E}_1$	0
E	C_a	$V_{Ch} = \overline{V}$	$F = \frac{2}{3}\overline{E}_1 + \frac{1}{3}\overline{V}$	$U_0 = \frac{1}{3}\overline{V} - \frac{1}{3}\overline{E}_1$
F	D_a	$V_{Ch} = \overline{V}$	$F = \frac{2}{3}\overline{E}_1 + \frac{1}{3}\overline{V}$	0
G	C_a	$V_{Ch} = \overline{V}$	$F = \frac{2}{3}\overline{E}_1 + \frac{1}{3}\overline{V}$	0

3.4 Obtaining voltage sag type from instantaneous voltages

This section is partially covered by the paper C in Appendix 3.

Obtaining the voltage sag type from measured voltages is not as straightforward as described in Section 3.3. One of the main problems is that the theory presented is developed for a simplified system model. When actual voltages are analysed the voltage sag classification is not so evident. In this section a new method to classify three-phase voltage sags is developed.

When instantaneous phase-to-neutral (PN) voltages are available phase-to-phase (PP) instantaneous voltages can be obtained as the difference of the instantaneous PN voltages. Then PN and PP complex voltages can be obtained using the Fast Fourier Transformation. The relation between the minimum PN and the minimum PP voltages expressed in per unit will be used to characterise the three-phase unbalance sags.

A theoretical relation between the minimum PN and the minimum PP voltage can be derived for each type of sag using the equations shown in Table 3. It has been considered pre-fault voltage equal 1 per unit ($\overline{E}_1 = 1pu$) and PP minimum voltage has been divided by the $\sqrt{3}$ factor.

Voltage sags type A are symmetrical, all phases experience the same retained voltage and phase-angle jump. Hence, PN and PP retained voltages are equal in per unit, as stated in (2.5).

$$V_{PP} = V_{PN} \quad \text{[pu]} \qquad (2.5)$$

Voltage sags type B are not common because they are seen only when a LG fault occurs at the same voltage level or at a location connected by star-star transformer grounded at both sides. Otherwise the zero sequence voltage is filtered and the sag transforms to another type as shown in Table 4. The relation between PP and PN voltage for type C sag is given by (2.6).

$$V_{PP} = \frac{\sqrt{\left(\frac{1}{2}V_{PN}\right)^2 + \frac{3}{4}}}{\sqrt{3}} \quad \text{[pu]} \qquad (2.6)$$

Voltage sag type C is seen as a reduction of the voltage in two phases. They are caused by a LL fault or by the propagation of a sag type B through a delta-star connected transformer. In this case PP and PN voltages are related by (2.7).

$$V_{PP}^2 = \frac{4}{3}V_{PN}^2 - \frac{1}{3} \quad \text{[pu]} \qquad (2.7)$$

It can be derived from (2.7) that the minimum PN voltage magnitude is 0.5 pu. When this happens, PP voltage magnitude is zero.

A voltage sag type D is caused by the propagation of a type C sag through a delta-star windings connected transformer. This type of sag is observed as a voltage drop in one phase. Equation (2.8) expresses the relation between the PP and PN voltage. Considering an extreme situation PN voltage can be zero, and in this case PP voltage is 0.5 pu.

$$V_{PP}^2 = \frac{1}{4} + \frac{3}{4} V_{PN}^2 \quad \text{[pu]} \qquad (2.8)$$

Voltage sag type E shows a symmetrical relation between PP and PN voltage. The relation between these voltages is the same as for type A sags, and was given in (2.5). These sags are as rare as type B sags since they can be seen only when a LLG fault is located at the same voltage level as the monitored point, or when the fault propagates through a star-star connected transformer grounded at both sides.

Voltage sag type F is also a reduction in one phase voltage. It is caused by the propagation of a LLG fault through a delta-star connected transformer. The relation between PP and PN voltage is given by (2.9). For this type of sag, when the PN voltage is zero, the minimum PP voltage is 1/3.

$$3V_{PP}^2 = (2 + \frac{1}{3}) V_{PN}^2 + \frac{1}{3} V_{PN} + \frac{1}{3} \quad \text{[pu]} \qquad (2.9)$$

Finally, for type G sags, the relation between the PP and PN voltages is given by (2.10). These sags are obtained by the propagation of a sag type F through a delta-star connected transformer. For this type of sag the minimum PN voltage is 1/3, when PP voltage is zero.

$$V_{PP} = -0.0707 + \frac{\sqrt{3.112 V_{PN}^2 - 0.327}}{1.556} \quad \text{[pu]} \qquad (2.10)$$

These theoretical relations, that identify each type of voltage sag, are plotted and presented in Figure 11, where each curve is named with the letter that identifies the sag (A, B, C, D, E, F, and G) according to the ABC classification.

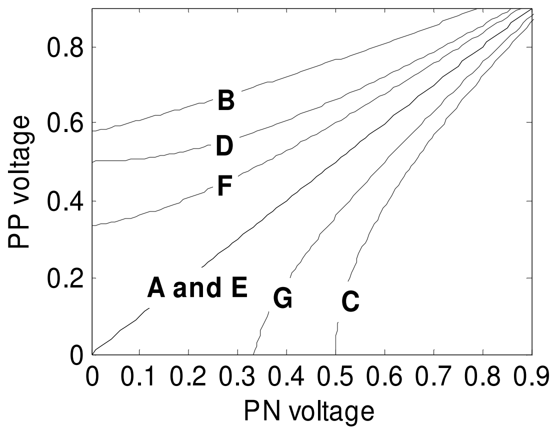


Figure 11 – Theoretical curves for each type of voltage sag

In order to test the applicability of this method voltage sags are generated by the simulation of faults in a transmission grid. The results are presented in four plots, one for each type of fault (LG, LL, LLG, and LLL), as shown in Figure 12. The obtained sags can be characterised by the proximity to the reference curves. The dispersion observed in the plotted sags can be explained as an effect of the sag propagation through transformers that change the sag type.

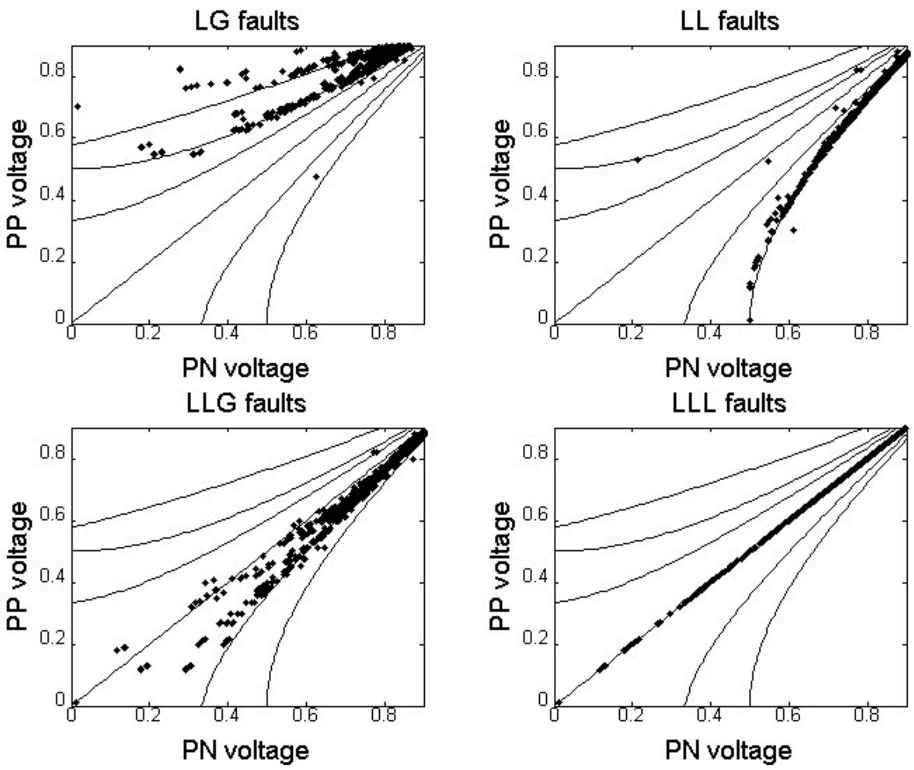


Figure 12 – Classification of three-phase voltage sags

The type of fault that caused the voltage sag can be identified observing the region of the chart where the sag is plotted. Therefore, this method has two direct applications, characterisation of three-phase sags and classification of the sag source (type of fault).

3.5 Phasor based voltage sag characterisation

This section is extracted from papers A and B in Appendix 3.

The analysis of power system in frequency domain is based on the assumption that the frequency (f) remains constant and that all electrical entities have the same frequency. Under these conditions the voltages are represented by complex values known as phasors. These phasors keep a constant magnitude whereas the angle varies constantly at a speed of $2\pi f$ [rad/s].

During a sag-event the magnitude and angle of the voltage-phasors are affected. Previous studies have focused on the magnitude variation, which was considered to be the most important parameter for sensitive loads. Recently studies on voltage sags also started to include the phase-angle variation, which is also responsible for malfunctions of electronic devices such as three-phase converters.

During the sag the voltage phasors can be assessed through the independent analysis of magnitude and phase-angle versus time respectively, as shown in Figure 13. This event was recorded at a sample rate of 32 points per cycle. Voltage magnitude and phase-angle are obtained applying the Discrete Fourier Transformation over a window of one cycle of the instantaneous voltage. The results are updated for each new sampled voltage. Thus, the algorithm is applied 32 times every 16.6 ms (f=60Hz) obtaining a quasi-continuous estimation of magnitude and phase-angle jump (paj).

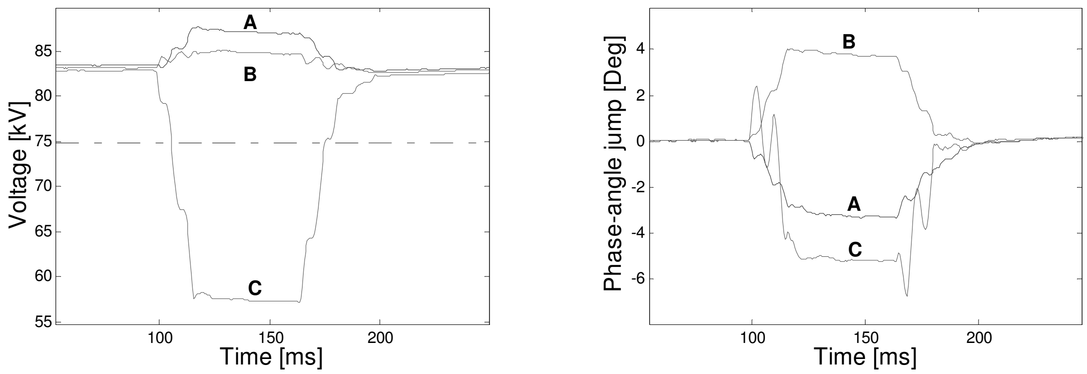


Figure 13 – Voltage sag represented by rms voltage variation and phase-angle variation

Alternatively, the phasors can also be analysed in a two-dimensional chart where the imaginary part is plotted versus the real part, as shown in Figure 14. In this chart both the path that the phasors follow during the event (phasor locus), and the phasors that experienced the maximum phase-angle jump (paj) as well as the deepest sag (extreme phasors) can be seen. The pre-event phasors (dashed lines), the pre-event phasor magnitude (external circle), and the sag threshold (internal circle) are also represented.

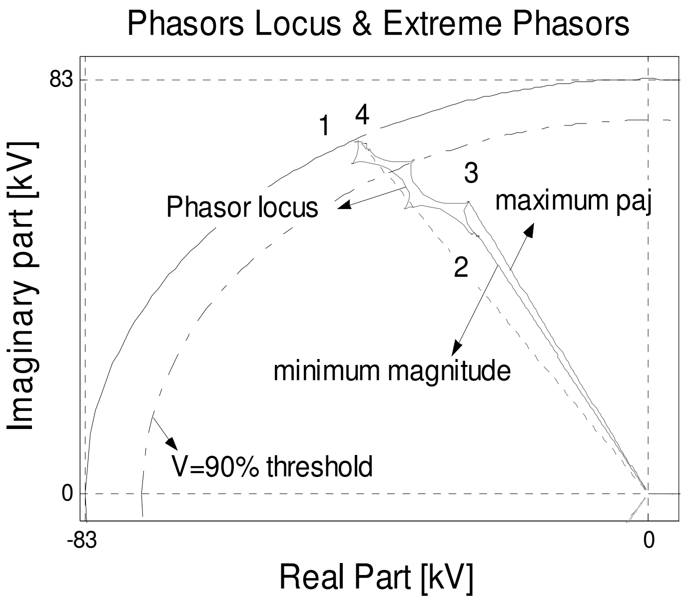


Figure 14 – Voltage sag phasor characterisation including: threshold V=90%, maximum paj, minimum magnitude, and phasor locus (1-2-3-4)

It can be observed that the maximum phase-angle jump and the minimum retained voltage phasors do not coincide. Thus, two phasors are the candidates to characterise the sag. The choice of the phasor that will best represent the severity of the sag depends on the sensitivity of the load. Some loads might be more sensitive to the phase-angle jump than to the voltage drop. For such kind of loads the severity of the sag should be represented by the phasor that shows the largest angle jump. This representation of voltage sags, combined with load behaviour, might improve the understanding of the loads ridethrough capability and reduce the cost of the mitigation technique.

In order to reintroduce the time reference while keeping the visual effect from the chart of the phasors, the during-event phasors can be seen in a sequence of snapshots, as shown in Figure 15. In this figure, it can be observed how the phasors "move" during the event. The first and last graphs show the precise time when one of the phasors intersects the sag threshold (V=90%). These 6 snapshots are selected to give a good understanding on how the phasors behave during this voltage sag, nevertheless more than 100 snapshots are available to describe this sag-event.

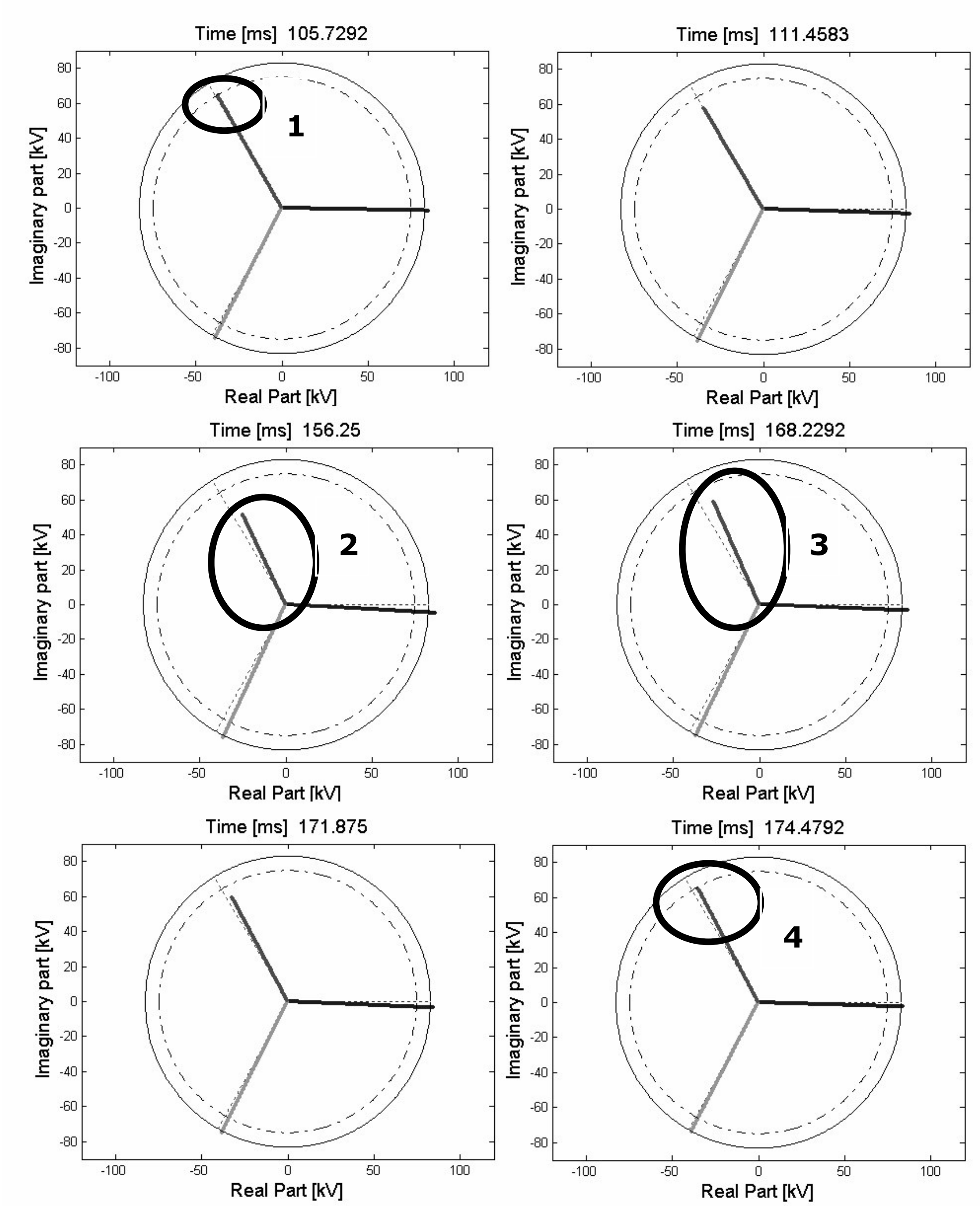


Figure 15 – Voltage sag view by a sequence of phasors snapshots: voltage sag initiation (1), minimum magnitude (2), maximum phase-angle jump (3), voltage sag ending (4)

This kind of visual representation is becoming more common in power system analysis as a consequence of the installation of phasor measurement units (PMU).

4 Voltage sag estimation

This section contains a general introduction to the estimation of voltage sags at site and system levels. The main indices for site and system assessment are presented. The advantages and shortcomings of the indices estimation by monitoring and fault simulation are analysed. The method of fault positions for voltage sag assessment is described and applied to a model of the Brazilian transmission grid. Voltage sag indices obtained by the method of fault positions are compared with the indices obtained by monitoring. The sensitivity of the method of fault positions regarding the main fault uncertainties (fault rate, fault type, and fault location) is analysed. Finally, voltage sag indices obtained from phase-to-neutral and phase-to-phase voltages are compared.

4.1 Sag indices

Voltage sags indices are the set of values used to describe the performance of a given site or system regarding voltage sags. In order to obtain this performance a five step method is recommended (IEEE Std 1564 draft 6, 2004):

- Obtain instantaneous voltages.
- Calculate event characteristics as a function of time.
- Calculate single event characteristics.
- Calculate site indices from the single event-characteristics of the events registered during a period of time.
- Calculate system indices from the site indices.

Instantaneous voltages can be obtained from either measurement devices or time-domain simulation. Voltage sag measurements are time consuming and the results might vary considerably from year to year. This variation is due to the likelihood of faults in the power system. The number of voltage sags is strongly linked to the number of faults in the power grid; this number however varies considerably from year to year.

Frequency-domain simulation provides an approximation of single event-characteristics for fault-caused events. The retained voltage can be estimated from the symmetrical component network model, and the event duration can be assessed considering the fault-clearing time. Once the single event-characteristics are estimated, a statistical approach can be used to estimate the site and system indices.

The main index to evaluate voltage sags is the SARFI (IEEE P1564, 2004). This is an acronym for System Average rms Variation Frequency Index, in other words, it provides the number of voltage sags within a certain retained voltage and duration interval for a location during a certain period of time (one year).

There are two types of SARFI indices. The SARFI-x refers to a certain sag threshold (x=90%, 70%, 50%, etc). This index indicates the number of voltage sags with a retained voltage below x%. The SARFI-curve indicates the number of events below a certain reference curve of sensitivity (CBEMA, ITIC, SEMI), the curves are shown in Figure 16.

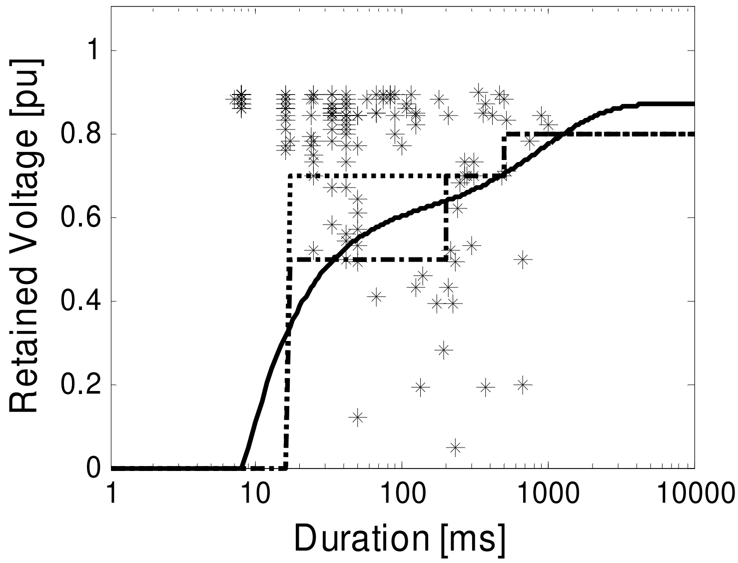


Figure 16 – Voltage sags and the reference curves, CBEMA (solid line), ITIC (dotted line), and SEMI (dash-dotted line)

In order to show how these indices are estimated, the results of a voltage sag survey are presented in Table 7. This survey was carried out in a distribution grid that supplied an industrial customer having sensitive processes. Voltage sag measurements were taken at 138 kV, 13.8 kV and 440 V during a period of approximately one year. Here, only a few events are shown. The complete table is presented in Appendix 2. This table presents the single event characteristics for a one-year monitoring period.

Table 7 - Voltage sag monitoring on a 13.8 kV busbar, the complete table is presented in Appendix 2

Date@time	Retained voltage (%)	Duration (ms)
30/04/2002@17:47:05,133	**88**	**8**
03/05/2002@19:59:07,797	**87**	**108**
03/05/2002@19:59:10,922	**89**	**467**
03/05/2002@19:59:11,297	**84**	**892**
03/05/2002@20:00:01,938	**83**	**517**
03/05/2002@20:00:36,130	**89**	**8**
13/03/2003@15:32:47.552	**86**	**16**
17/03/2003@11:03:35.727	**84**	**49**
22/03/2003@17:42:12.185	**70**	**25**
29/03/2003@17:34:16.539	**87**	**16**
30/03/2003@08:52:25.672	**86**	**33**
04/04/2003@10:05:15.096	**87**	**41**
15/04/2003@11:24:52.627	**89**	**8**
16/04/2003@09:17:15.708	**67**	**33**
16/04/2003@09:17:17.924	**89**	**8**
02/05/2003@15:41:34.690	**87**	**8**
05/05/2003@06:12:23.031	**77**	**16**

A scatter plot allows to visualise the events and the tolerance reference curves (CBEMA, ITIC and SEMI), as shown in Figure 16. As can be expected most of the events are shallow sags, these sags are above the sensitive curves. The severe sags are the ones below the tolerance curves.

The SARFI values are presented in Table 8. The SARFI-90 is the total number of events registered during the one-year period; this number is statistically interesting when comparing different sites but it is not related to load sensitivity.

Table 8 – SARFI estimation

$SARFI_{90}$	$SARFI_{70}$	$SARFI_{CBEMA}$	$SARFI_{ITIC}$	$SARFI_{SEMI}$
150	30	20	32	21

There is also another index obtained from the statistical analysis of the single event retained voltages. This index is known as VDA, the acronym of Voltage Dip Amplitude (di Perna, C. D., G. Olguin, et al., 2004). The indices derived from the VDA are the expected value of VDA (*μ[VDA]*), the 95th percentile (*$CP95_{VDA}$*) and the 5th percentile (*$CP5_{VDA}$*). The expected value of VDA is obtained by the average of the retained voltage of all voltage sags registered at the analysed site. The 5th percentile is a retained voltage indicating that 5% of the voltage sags have a retained voltage below this value. It is important to recall that both *μ[VDA]* and *CPx_{VDA}* depend on the sag threshold considered, as only events with a retained voltage below the sag threshold are considered for the statistical analysis. The results from the survey are presented in Table 9.

Table 9 – VDA indices estimation

$CP5_{VDA}$	**μ[VDA]**	**$CP95_{VDA}$**
0.39 pu	0.77 pu	0.89 pu

A more complete view of site and system performance is obtained by the cumulative frequency distribution of the voltage sag retained voltages, as shown in Figure 17. This curve allows comparing different sites and deriving conclusions about their strength. Weak busbars experience more severe voltage sags while strong busbars suffers more shallow events (Olguin and Bollen, 2003).

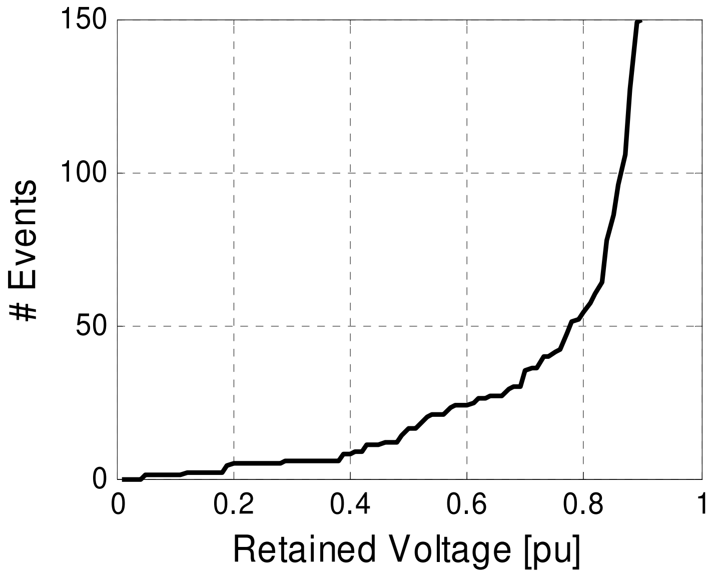


Figure 17 – Cumulative frequency distribution of event retained voltages

As can be seen in Figure 17, most of the voltage sags are shallow; they are risk-free even for sensitive equipments. Half of the events have a retained voltage higher than 0.84 per unit. However, the index $CP5_{VDA}$ expresses that 5% of the sags may have a retained voltage less that 0.39 per unit, meaning that equipment with high tolerance to voltage sags will certainly fail many times every year.

4.2 Monitoring voltage sags

The main limitation a monitoring program has in order to estimate the site indices is the monitoring time needed to obtain accurate results. The minimum required time of monitoring for a given level of accuracy can be estimated considering that the time between events is exponentially distributed. This means that the probability of an event to happen in the next minute is independent of the time elapsed since the last event. Under this condition the number of events within a certain period of time is a random variable that follows the Poisson distribution. For an expected number of n voltage sags per year the minimum monitoring time to limit the error ε is given approximate by $time > 4/n\varepsilon^2$. This implies that, for an expected number of 150 sags per year, to obtain an accurate result (error less than 10%) the minimum monitoring period should be around 3 years. This result is extended for other scenarios of expected number of sags and required accuracy in Table 10.

Table 10 – Minimum monitoring period to obtain a given accuracy (Bollen, 2000)

Sag frequency	50% Error	10% Error	2% Error
1 per day	2 weeks	1 year	25 years
1 per week	4 months	7 years	200 years
1 per month	1 year	30 years	800 years

A study done by Leborgne et al. (2003) shows that an industry having many sensitive processes was affected by 42 voltage sags during one year but only 5 were severe (retained voltage below 0.70 per unit). Considering these results, it can be concluded that sag measurements gives a rough approximation of the performance of a site for shallow sags with an accuracy of about 30%. On the other hand, to predict the number of severe sags whose retained voltage is below 0.70 per unit (less than 10 events per year), one year monitoring term is not enough and the results are affected by great uncertainty, in this case the error is about 90%. This means that the results of a one-year monitoring period should not be used to forecast the number of equipment malfunction due to voltage sags.

4.3 Simulating voltage sags

Considering that most of the severe voltage sags are caused by faults and short-circuits in transmission and distribution networks, fault simulation has been the most popular tool for voltage sags estimation (Bollen, 2000).

Both time-domain and frequency-domain tools are suitable for voltage sag assessment through fault simulation. Time-domain tools require detailed network models and are more time consuming. However, a complete description of the instantaneous voltage during the event is obtained (Martinez and Arnedo, 2004). Therefore, all event characteristics can be attained.

Frequency-domain tools are the most popular for voltage sag assessment due to their easy application and simple network modelling (Olguin, 2003). The voltage sag magnitude can be obtained using these tools, whereas the sag duration can be estimated using the fault-clearing time.

One of the first papers proposing this method was written by Conrad, Little, et al. (1991). Later Qader, Bollen, et al. (1999) published an investigation were this method, applied to the England and Wales transmission grid, was called method of fault positions. Then this method was largely extended by Bollen (2000) to include the effect of motor re-acceleration and generator outages.

The method of fault positions for voltage sag assessment consists in simulating faults at numerous points of the system, estimating the retained voltage of a selected number of busbars. Each fault location is associated with a fault frequency so each estimated retained voltage is also associated with a frequency, permitting the statistical analysis of the retained voltages in the analysed busbar. The algorithm for this method can be summarized as follows:

- Select the region of the network were the faults will be simulated, as shown in Figure 18.

- Divide this region in small segments so that a fault at any point within a segment should result in a similar retained voltage.
- The fault frequency (number of faults per year) of each segment is estimated. Normally the line fault rate is divided by the number of segments, so that all segments within a transmission line have the same fault rate. For instance, (3.1) represents a vector containing the fault rates of each segment for all the fault positions to be simulated.

$$\boldsymbol{\lambda} = \left[\lambda_1, \lambda_2, ...\lambda_k, ...\lambda_N, ...\lambda_{Fp}\right] \tag{3.1}$$

- Using a suitable network model, the sag characteristics at the analysed busbar are estimated for each simulated fault.

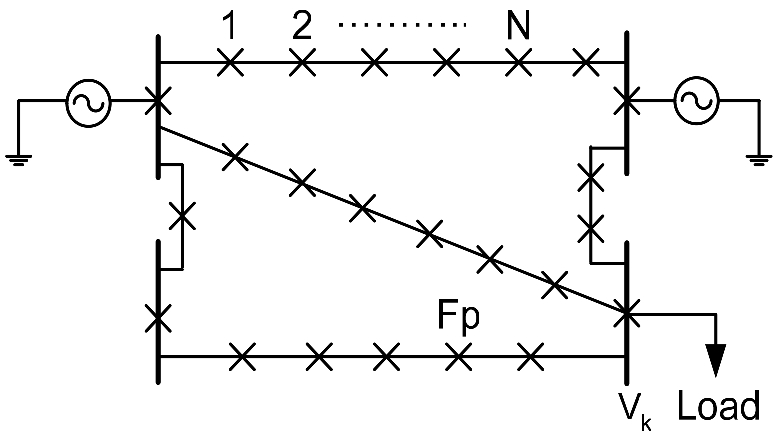


Figure 18 – Schematic network indicating all fault positions used for the estimation of voltage sags

As described in the last bullet, the user should choose a suitable network model reflecting the purpose of the research. For voltage sag assessment based on the retained voltage, a symmetrical-component model of the network will give enough accurate results. These results include retained voltage and the expected number of sags per year as shown in Table 11. When a more complete sag characterisation is needed, a time domain simulation tool should be implemented in order to obtain the instantaneous voltages during the event.

Table 11 – Retained voltages at busbar k for a simulated fault at location f and the frequency **(λ)** (events per year) of each event

Retained voltage (V_{kf}) at busbar *k*	**Frequency (λ)**
V_{k1}	λ_1
V_{k2}	λ_2
...	...
V_{kN}	λ_N
...	...
V_{kFp}	λ_{Fp}

For instance, when a fault is simulated at position N, the retained voltage at busbar k is V_{kN} and this sag is expected to happen λ_N times per year.

4.4 Case study – Brazilian transmission grid

This section is partially covered by the paper D in Appendix 3.

In order to investigate the performance of the method of fault positions for voltage sag assessment in a large transmission system, a model of the Brazilian transmission grid is used. The main characteristics of this system are presented in Table 12. The selection of this system was made considering:

- Size of the system.
- Availability of the system symmetrical-components model.
- Availability of monitoring results for further comparisons.

Table 12 – Brazilian transmission network characteristics

	230 kV	**345 kV**	**440 kV**	**500 kV**	**Total**
Lines #	518	113	33	129	793
Length [km]	30976	10296	5408	17554	64234
Busbars #	409	74	20	153	656

The symmetrical-components model of the Brazilian transmission system is accessible on the internet home page of the Brazilian System Operator (ONS, 2003). The transmission model available is continuously updated with respect to new installations. This study was done considering the model available in December 2003. Figure 19 shows the present Brazilian transmission grid controlled centrally by the independent system operator (ONS).

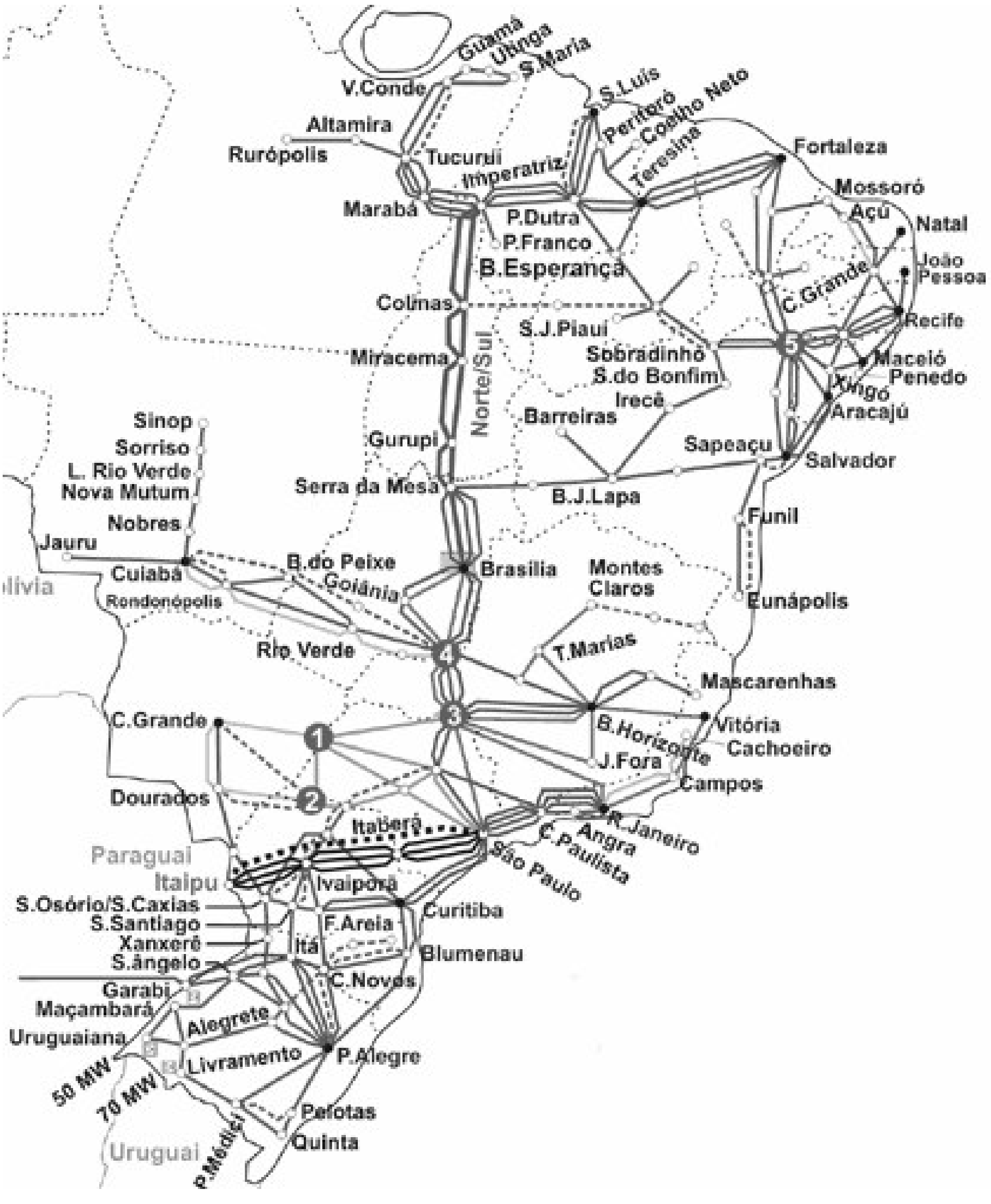


Figure 19 – Brazilian transmission grid

The Brazilian transmission network is a continental network, having a geographical extension of 6000 km from north to south. The total load demand is about 60 GW, while the generation capacity is 90 GW. The main generation comes from hydroelectric plants (68 GW), followed by thermoelectric plants (20 GW), and nuclear generation plants (2 GW).

The method of fault positions was applied to a model of the Brazilian transmission grid. For the **reference case** a total of 793 symmetrical and unsymmetrical faults were simulated. The fault position was the middle point of each transmission line for this simulation. Four types of faults were simulated at each fault position: LLL, LLG, LL, LG faults. The minimum retained voltage was used to characterise the unbalanced sags.

The fault-rate and the fault-type distribution at different voltage levels corresponding to the **reference case** are shown in Table 13. The values are typical values for the Brazilian grid (Carvalho Filho, et al., 2002).

Table 13 - Fault rates and fault distribution for the reference case

Transmission Voltage [kV]	**Faults/ 100km. year**	**LLL**	**LLG**	**LL**	**LG**
500	2.09	1 %	4 %	1 %	94 %
440	1.1	1 %	5 %	2 %	92 %
345	1.1	1 %	5 %	2 %	92 %
230	1.9	2 %	15 %	3 %	80 %

The simulation results were statistically analysed in order to obtain the site indices for a selected number of busbars. The estimated site and system indices are SARFI-90 and $\mu[VDA]$, as shown in Table 14. The system SARFI-90 index was estimated averaging the sites SARFI-90. The system $\mu[VDA]$ index was estimated by the weighted average of the sites $\mu[VDA]$. The weight factor of each site is its own SARFI-90 index.

Table 14 – Sag indices estimated by the method of fault positions

Voltage level	Busbar	SARFI-90 (sags per year)	$\mu[VDA]$ (per unit)
<34,5 kV	B5420	13	0.78
<34,5 kV	B1944	16	0.83
<34,5 kV	B7360	70	0.78
<34,5 kV	**System index**	**33**	**0.79**
69 kV	B2519	56	0.83
69 kV	B1103	12	0.88
69 kV	B6247	13	0.77
69 kV	B2671	69	0.75
69 kV	B5284	9	0.78
69 kV	**System index**	**32**	**0.79**
138 kV	B2515	56	0.83
138 kV	B1250	29	0.84
138 kV	B5463	14	0.77
138 kV	B1405	27	0.81
138 kV	B1385	37	0.85
138 kV	B1941	17	0.83
138 kV	B2620	55	0.74
138 kV	B5924	19	0.74
138 kV	**System index**	**32**	**0.80**
230 kV	B1563	28	0.79
230 kV	B5962	19	0.71
230 kV	B5994	26	0.77
230 kV	B5283	12	0.76
230 kV	B7350	70	0.78
230 kV	**System index**	**31**	**0.77**
440 kV	B1404	28	0.78
440 kV	B1383	39	0.82
440 kV	**System index**	**34**	**0.80**

The Brazilian Independent System Operator ran a voltage sag survey during 2001 and 2002. A total of 55 busbars were monitored during a period of time within these two years. The monitored locations are distributed as follows: 22 busbars at <34.5 kV, 16 busbars at 69-88 kV, 9 busbars at 138-161 kV, 6 busbars at 230 kV, and 2 busbars at 440 kV. Unfortunately the monitoring period of many locations were just a few months, affecting the results due to the seasonal characteristic of the faults in that transmission network. The frequency of faults is highly dependent on the weather conditions. The results are shown in Table 15.

Table 15 – Sag indices obtained by monitoring

Voltage level	**SARFI-90 (sags per month)**	**$\mu[VDA]$ (per unit)**
<34,5 kV	11.2	0.77
69-88 kV	5.8	0.78
138-161 kV	5.8	0.77
230 kV	3.6	0.69
440-500 kV	1.2	0.23

Results from the use of the method of fault positions and monitoring are shown in Table 16 for comparison. The monitoring results from Table 15 are expanded for one-year monitoring. Average values of the simulated system indices are extracted from Table 14.

Table 16 – Comparison of results from simulation and monitoring

Voltage level	**Monitored SARFI-90 (sags per year) (2001-02)**	**Simulated SARFI-90 (sags per year)**	**Monitored $\mu[VDA]$ (per unit) (2001-02)**	**Simulated $\mu[VDA]$ (per unit)**
<34,5 kV	134	33	0.77	0.79
69-88 kV	66	32	0.78	0.79
138-161 kV	66	32	0.77	0.80
230 kV	43	31	0.69	0.77
440-500 kV	14	34	0.23	0.80

As shown in the table, monitored and simulated results strongly diverge. The main reasons for the divergence are:

- The monitoring period was too short and failed to include the effect of the seasonal variation of the fault frequency.
- Long-term average fault rates are used for the application of the method of fault positions, but the actual number of

faults varies considerably from year to year. This is one of the key factors to explain the large difference in the number of sags obtained by simulation and by monitoring.

- Faults at distribution level were not simulated, resulting in an underestimation of the number of event at distribution voltages (34.5 – 161 kV).

The method of fault positions is suitable for the assessment of voltage sags in a long term approach, but fails to describe the site and system next year behaviour. Nevertheless, it can be used to obtain an indication of the expected number of events and their average retained voltage. Long term analysis using this method will match better with the actual performance than short term analysis. When some adjustments are done in the fault rate to better describe the monitored period, the difference between measured and simulated SARFI-90 index may be reduced down to 10% (Carvalho Filho et al., 2002).

4.5 Sensitivity analysis of the method of fault positions

This section is partially included in paper D, Appendix 3.

The accuracy of the assessment of voltage sags using the method of fault positions depends on the quality of the data used for the simulations. The expected number of voltage sags at a given observation busbar is directly related to the number of faults occurring within the electrical nearness. This electrical nearness is known as the exposed area and it usually includes different voltage levels. Many surveys have been published pertaining to transmission line outages over a period of time (McGranaghan and Roettger, 2001) (IEEE Std 497, 1997). It has been pointed out that faults are strongly correlated to severe weather conditions or poor maintenance. The number of faults or the fault rates used for the sag assessment must be as close as possible to the statistical fault rate of the simulated system.

In order to analyse the variation of voltage sag indices (SARFI-90 and $\mu[VDA]$) various cases are simulated and the results are compared to the **reference case**, introduced in the previous section. A first case considers a 50% increased fault rate for all transmission lines. Then, four different cases show the effect of a partial 50% increased fault rate for each transmission level, one at the time. The variation of the system index SARFI-90, with respect to the results shown in Table 14, is presented in Table 17.

Table 17 – System SARFI-90 variation for different fault rate scenarios

Fault rate is increased by 50% in:	System SARFI-90 variation				
	<34,5 kV	69 kV	138 kV	230 kV	440 kV
Case 1 - All kV	50 %	50 %	50 %	50 %	50 %
Case 2 - 500 kV	15 %	16 %	8 %	9 %	0.3 %
Case 3 - 440 kV	0 %	2 %	12 %	39 %	35 %
Case 4 - 345 kV	0 %	7 %	8 %	3 %	13 %
Case 5 - 230 kV	35 %	26 %	22 %	34 %	2 %

As shown in Table 17 the index variation depends on which fault rate is changed. For instance, when the 440 kV transmission lines fault rate is increased by 50%, the most affected system index is the 440 kV system (35%). On the other extreme, the 34.5 kV system index does not change (0%); meaning that there are no 440 kV transmission-lines within the 34.5 kV sites exposed area for a threshold of 90%. In other words, whatever fault rate is adopted for the 440 kV lines, the SARFI-90 for the 34.5 kV system will not change.

Faults occurring at power systems may be symmetrical (LLL) or unsymmetrical (LG, LL, and LLG); leading to balanced and unbalanced voltage sags respectively. Balanced sags show the same retained voltage in every phase, whereas unbalanced sags show different retained voltages. The minimum voltage characterise unbalanced sags. It is well known that the majority of faults are LG; usually more than 70% of the total number of faults, however, the exact combination of symmetrical and unsymmetrical faults is an uncertainty when estimating voltage sags.

The assessment of voltage sags can be performed based exclusively on symmetrical faults but accurate results require a reasonable combination of symmetrical and unsymmetrical faults. Two new additional scenarios are simulated to analyse the variation of the sag indices. A first scenario considers only symmetrical faults (LLL), a second one takes exclusively unsymmetrical LG faults. The estimated SARFI-90 for both scenarios is plotted in Figure 20.

The expected number of sags (SARFI-90) is much higher when only three-phase faults are simulated. For example, for busbar B1103 the SARFI-90 is three times higher than the **reference case**, when only three-phase faults are simulated. Nevertheless, for a rough and conservative voltage sag assessment, simulating just three-phase faults can be an option. Instead, if only LG faults are considered, the SARFI-90 will be slightly underestimated.

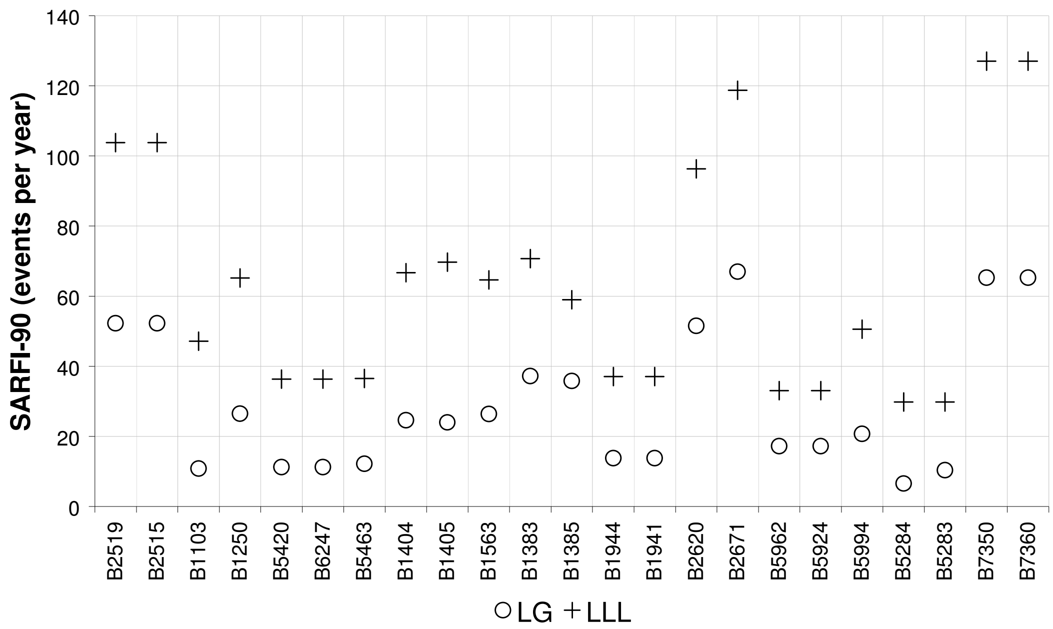


Figure 20 – SARFI-90 estimated for LG and LLL faults

The variation of SARFI-90 regarding the reference case is lower when LG faults are simulated because in the **reference case** most of the faults are LG.

The method of fault positions can be performed considering faults only at busbars. The main advantage of this approach is the simplicity. When faults are simulated at different locations in the transmission lines, fictitious nodes must be created at these locations, making the simulation longer and more engineering work is required. Applying all the faults at busbars makes the computation process easy, but the results are less accurate. Simulating faults at busbars gives large SARFI-90 and lower expected VDA, as can be derived from Figure 21 and Figure 22.

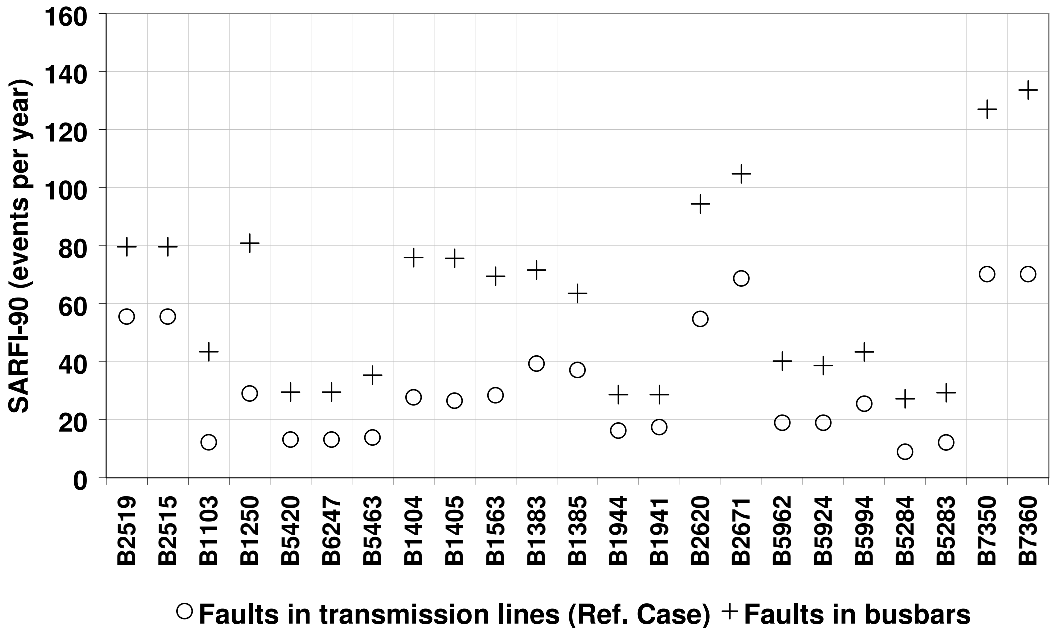


Figure 21 – SARFI-90 for faults at busbars (+) and for faults at transmission lines (o)

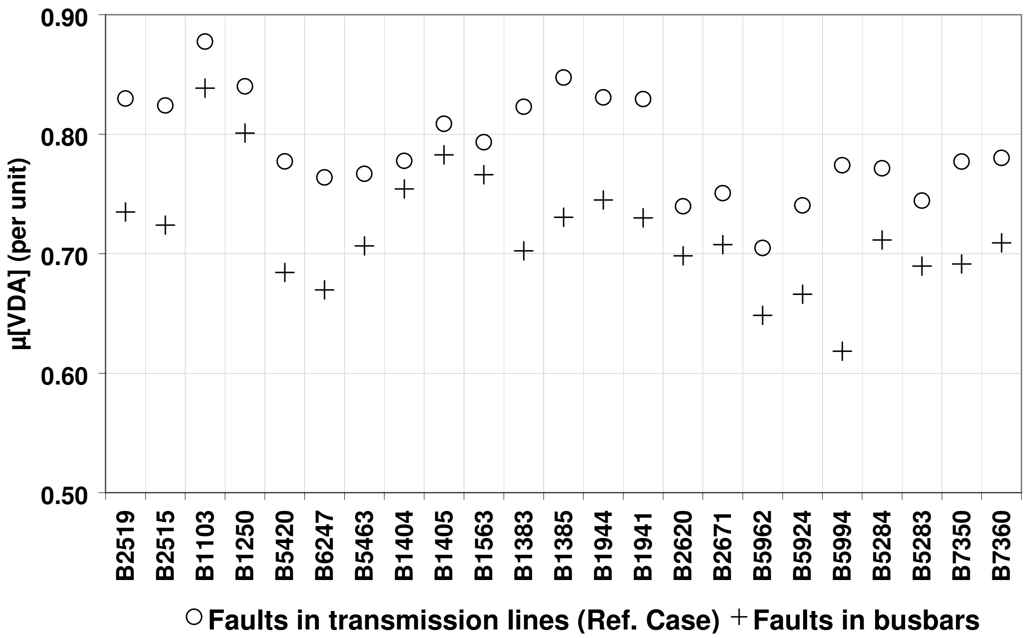


Figure 22 - *μ[VDA]* for faults at busbars (+) and for faults at transmission lines (o)

It is clear that simulating faults only at busbars leads to an overestimation of the voltage sag indices. This simulation approach results in both an overestimation of the number of events (SARFI-90) and an underestimation of the expected retained voltage (*μ[VDA]*). Nevertheless, simulating faults at busbars can be a first approach, taking into account that the results will be a pessimistic scenario.

4.6 Phase-to-neutral vs phase-to-phase voltage sags

This section is included in paper C, Appendix 3.

Voltage sag indices are estimated based on monitoring or fault simulation. The choice between phase-to-phase (PP) and phase-to-neutral (PN) voltage affects the results.

In order to investigate the influence of the choice between PP and PN on the sag assessment, a new set of simulations, using the method of fault positions, is performed. The same Brazilian network as described in Section 4.5 is used. A new fault statistic is considered, as shown in Table 18. Faults are located at busbars and transmission lines.

Table 18 – New fault statistics

Transmission Voltage	Fault/ 100km.year	LLL	LLG	LL	LG
500 kV	1.14	1.5 %	6 %	5.5 %	87 %
440 kV	1.14	1.5 %	6 %	5.5 %	87 %
345 kV	1.98	3.5 %	1.5 %	5.5 %	90 %
230 kV	1.57	4 %	6 %	14 %	76 %

In order to describe the performance of the analysed sites, the SARFI-90 and *μ[VDA]* are estimated for both PP and PN voltages. The estimated values of SARFI-90 are presented in Figure 23 and the obtained values of *μ[VDA]* are shown in Figure 24.

Most of the 23 busbars show the same tendency, PN voltage sags are more frequent and severe than PP ones. For instance, 70 PN sags per year with an average VDA of 0.74 pu, are expected at busbar B1383 (440 kV). However, only 53 PP sags with an average VDA of 0.82 pu are expected at the same B1383 busbar.

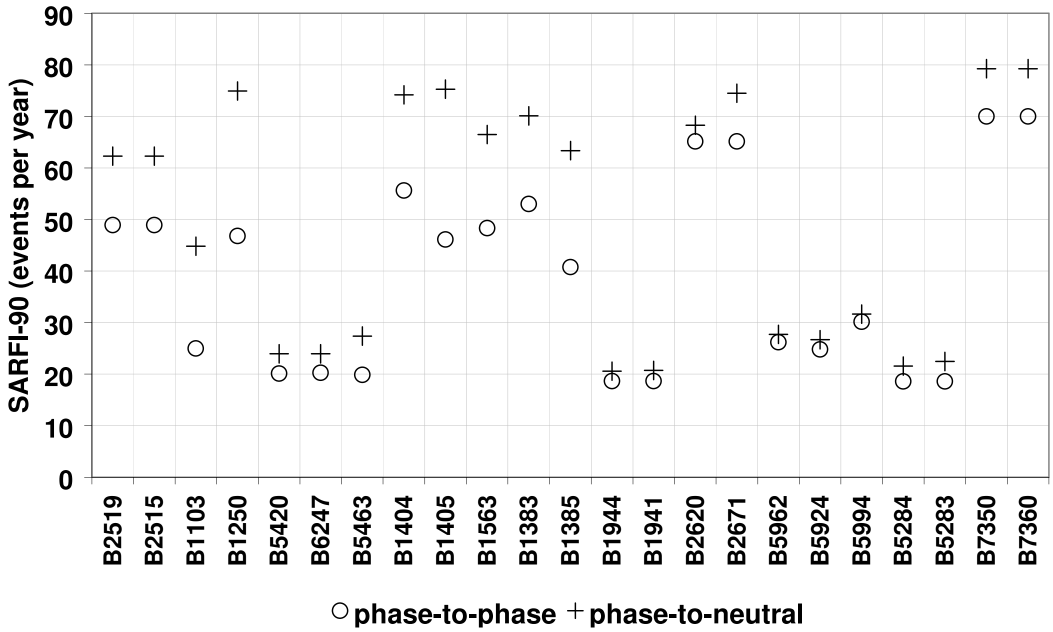


Figure 23 – SARFI-90 for PN and PP voltage sags

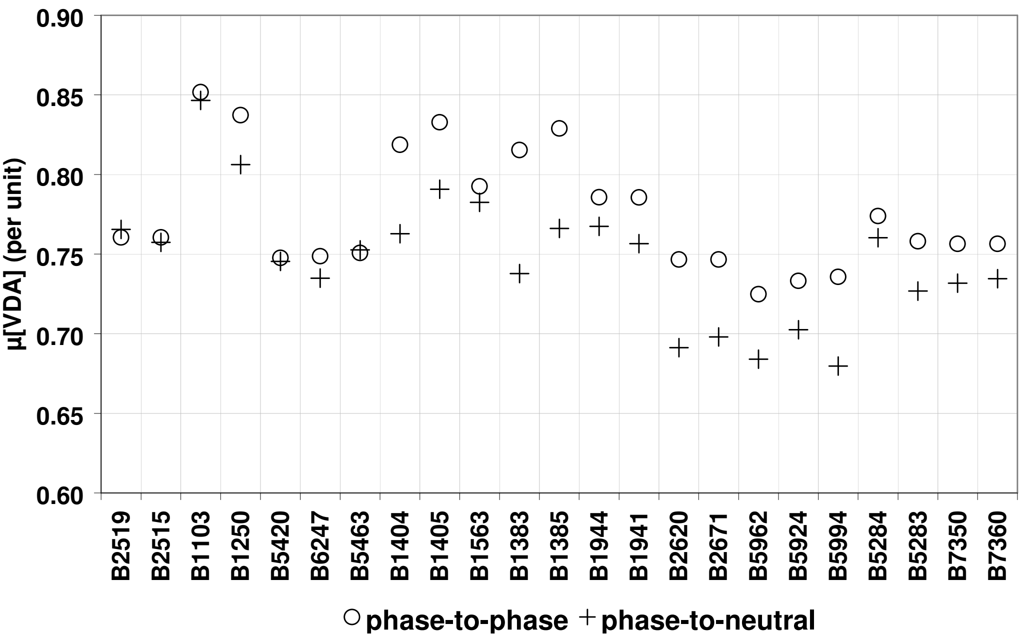


Figure 24 - *μ[VDA]* for PN and PP voltage sags

Generally, at distribution busbars the difference in voltage sag indices for PP and PN voltages is rather small. For instance, the distribution busbar B5420 expects 20 sags per year having an average retained voltage of 0.75 pu for PP voltages, whereas for PN voltages the expected number of events is 24 having an average retained voltage of 0.75 pu.

5 Conclusion and future work

A summary of this research is presented and the main conclusions are highlighted in this section. Proposals for future work are also described.

5.1 Summary and conclusions

A **voltage sag characterisation** method using the instantaneous and phasor voltages is presented in this thesis. The voltage sags are characterised through the retained voltage, the phase-angle jump and the event duration.

Several methods for the presentation of the sag characteristics are shown in this thesis. The retained voltage and the phase–angle jump are plotted versus time. Additionally, voltage sag are described in terms of the phasor locus, the extreme phasors, and a set of phasors snapshots.

A novel method using phase-to-neutral instantaneous voltages for the classification of three-phase sags into ABC categories is introduced. The method is based in the theoretical relations between phase-to-neutral (PN) and phase-to-phase (PP) retained voltages. Each type of sag follows a particular relation, described as a curve that divides the plane PN vs PP in excluded regions.

In order to **estimate voltage-sag site and system indices** the method of fault positions is implemented in a model of the Brazilian transmission grid. The site and system indices are compared with the indices obtained in a voltage sag monitoring survey. Monitored and simulated results strongly diverge. The monitoring period was short and failed to include the effect of the seasonal variation of the fault frequency. Long-term average fault rates are used for the application of the method of fault positions, but the actual number of faults varies considerably from year to year. This is one of the key factors to explain the large difference in the number of sags obtained by simulation and by monitoring. Faults at distribution level were not simulated, resulting in an underestimation of the number of event at distribution voltages.

The method of fault positions is suitable for the assessment of voltage sags in a long term approach, but fails to estimate the site and system voltage sag indices for the next short term period. Nevertheless, it can be used to obtain an indication of the expected number of events and their average retained voltage. Long term analysis using this method will match better with the actual performance than short term analysis. When certain adjustments are made in the fault rate to better describe the monitored period the difference between measured and simulated SARFI-90 index may be reduced down to 10%.

The accuracy of the assessment of voltage sags using the method of fault positions depends on the quality of the data used for the simulations. The expected number of voltage sags at a given observation busbar is directly related to the number of faults occurring within the electrical nearness. This electrical nearness is known as the exposed area and it usually includes different voltage levels.

Faults occurring at power systems are symmetrical (LLL) or unsymmetrical (LG, LL, and LLG); leading to balanced and unbalanced voltage sags respectively. Balanced sags show the same retained voltage in every phase, whereas unbalanced sags show different retained voltages. The minimum retained voltage may characterise unbalanced sags. It is well known that most of the faults are LG; usually more than 70% of the total number of faults, however, the relation between symmetrical and unsymmetrical faults is uncertain.

The assessment of voltage sags can be performed based exclusively on symmetrical faults but accurate results require a reasonable combination of symmetrical and unsymmetrical faults. The expected number of sags is much higher when only three-phase faults are simulated, reaching for some busbars more than three times the number of sags obtained from a reasonably mix of faults. Nevertheless, for a rough and conservative voltage sag assessment, simulating just LLL faults can be an option. Instead, if only LG faults are considered, the number of voltage sags will be slightly underestimated.

Simulating faults at busbars gives a larger number of expected sags and a lower average retained voltage. It is clear that simulating faults only at busbars leads to an overestimation of the voltage sag indices. Nevertheless, simulating faults exclusively at busbars can be a first approach, taking into account that the results will be a pessimistic scenario.

The choice between phase-to-phase (PP) and phase-to-neutral (PN) voltage affected the sag assessment. A set of simulations, using the method of fault positions, has been performed with the aim of investigating the influence of the choice between PP and PN voltage on the voltage sag assessment. The analysed busbars show the same tendency: PN voltage sags are more frequent and more severe than PP ones. Generally, at distribution busbars the difference in voltage sag indices for PP and PN voltages is rather small. For instance, one of the analysed busbars expects 20 sags per year having an average retained voltage of 0.75 pu for PP voltages, whereas for PN voltages the expected number of events is 24 per year, having an average retained voltage of 0.75 pu.

5.2 Future Work

Considering the continuation of this PhD research the following topics are highlighted:

1. Voltage **sags origin detection**. Develop a method to estimate the location of the fault, upstream or downstream of the distribution utility busbar connection to the transmission grid. This is a crucial point to establish responsibilities for the lack of power quality in de-regulated environments. The algorithm should consider different grid configurations including distributed generation (DG).

2. Economical assessment of mitigation techniques using **real options** analysis. The use of real options analysis seems to be more adequate than the conventional financial analysis based on discounted cash flow for the assessment of mitigation procedures. The intensive uses of power electronics on many mitigation solutions indicate the possibility of considering other applications for the mitigation devices. These new applications lead to a more complex economical analysis where real options may be more successful to drive the utilities' decision makers.

References

Albert, H. and G. Lavrov (1997). "Aspects regarding the approach of the electric power quality issue in Romania." Buletinul ISPE 40(2): 66-73.

Banerjee, B. B., S. Joglakar, et al. (1998). Power quality park prospects in Mumbai, India. Proceedings of 1998 Power Quality Conference, 1998, Hyderabad, India, IEEE.

Bertinov, A. I., S. R. Mizyurin, et al. (1981). "Quality of electric energy in supply systems on board aircraft and methods for its improvement." Elektrichestvo(6): 32-6.

Bollen, M. H. J. (2000). Understanding Power Quality Problems, Voltage Sags and Interruptions. New York, IEEE Press.

Bollen, M. H. J. and L. D. Zhang (2003). "Different methods for classification of three-phase unbalanced voltage dips due to faults." Electric Power Systems Research 66(1): 59-69.

Brooks, D. L., R. C. Dugan, et al. (1998). "Indices for assessing utility distribution system RMS variation performance." IEEE Transactions on Power Delivery 13(1): 254-9.

Carvalho Filho, J. M., J. P. G. Abreu, et al. (2002). Comparative analysis between measurements and simulations of voltage sags. 2002 International Conference on Harmonics and Quality of Power, 6-9 Oct. 2002, Rio de Janeiro, Brazil, IEEE.

Colding, S. (1982). "What quality can be demanded from the electricity supply." Elteknik med Aktuell Elektronik 25(2): 20-2.

Conrad, L., K. Little, et al. (1991). "Predicting and preventing problems associated with remote fault-clearing voltage dips." IEEE Transactions on Industry Applications 27(1, pt.1): 167-72.

Dagenhart, J. B., J. G. Dalton, et al. (1987). "New techniques developed to ensure quality power." Transmission and Distribution 39(5): 48, 50, 52, 55, 56.

Degeneff, R. C., R. Barss, et al. (2000). Reducing the effect of sags and momentary interruptions: a total owning cost prospective. Proceedings of 2000 International Conference on Harmonics and Quality of Power, 1-4 Oct. 2000, Orlando, FL, USA, IEEE.

Delaney, E. J., D. R. Mueller, et al. (1994). A major UK distribution power quality survey. 1994 Universities Power Engineering Conference (UPEC), 14-16 Sept. 1994, Galway, Ireland, Univ. Coll. Galway.

Deloux, G. (1974). International standardization and electric power supply network disturbances. International Conference on Sources and Effects of Power System Disturbances, 22-24 April 1974, London, UK, IEE.

Dettloff, A. (2000). Power quality performance component of the special manufacturing contracts between energy provider and customer. 2000 Power Engineering Society Summer Meeting, 16-20 July 2000, Seattle, WA, USA, IEEE.

di Perna, C. D., G. Olguin, et al. (2004). On probabilistic system indices for voltage dips. 2004 International Conference on Probabilistic Methods Applied to Power Systems, 12-16 Sept. 2004, Ames, IA, USA, IEEE.

Djokic, S. Z., K. Stockman, et al. (2005). "Sensitivity of AC adjustable speed drives to voltage sags and short interruptions." IEEE Transactions on Power Delivery 20(1): 494-505.

Dorr, D. S. (1992). Power quality study-1990 to 1995-initial results. APEC '92. Seventh Annual Applied Power Electronics Conference and Exposition. Conference Proceedings 1992 (Cat. No.92CH3089-0), 23-27 Feb. 1992, Boston, MA, USA, IEEE.

Ermakov, V. F. and V. I. Cherepov (1983). "A statistical analysis of voltage surges and dips." Izvestiya Vysshikh Uchebnykh Zavedenii, Elektromekhanika(3): 97-100.

Fouilloux, J. M., N. Duphil, et al. (1991). Perceived and physical quality of electricity: towards the QUALIMAT. CIRED. 11th International Conference on Electricity Distribution 1991, 22-26 April 1991, Liege, Belgium, AIM.

Frichtel, J. S. and J. W. Dougherty (1970). Specific avionic system benefits through improved electric power quality. 1970 proceedings of the national aerospace electronics conference, 18-20 May 1970, Dayton, OH, USA, IEEE.

Giorgi, E. (1975). "High quality electric power." Naval Research Reviews 28(4): 23-34.

Gomez, J. C. and G. N. Campetelli (2000). Voltage sag mitigation by current limiting fuses. Proceedings of World Congress on Industrial Applications of Electrical Energy and 35th IEEE-IAS Annual Meeting, 8-12 Oct. 2000, Rome, Italy, IEEE.

Gruzs, T. M. (1989). Power quality-a shared responsibility. Power Quality '89. Official Proceedings of the First International Conference, 15-20 Oct. 1989, Long Beach, CA, USA, Intertec Commun.

Hairabedian, B. (1989). A system for surveying power quality. Conference Record. IEEE Instrumentation and Measurement Technology Conference (Cat. No.89CH2707-8), 25-27 April 1989, Washington, DC, USA, IEEE.

Heikkila, H. (1976). "Harmonics in a power system." Saehkoe 49(1): 27-30.

Heine, P., P. Pohjanheimo, et al. (2002). "A method for estimating the frequency and cost of voltage sags." IEEE Transactions on Power Systems 17(2): 290-6.

Hilger, C.-H. (1972). "What is the quality of electric power?" Elektroteknikeren 68(19): 418-22.

Hucker, D. J. (1970). Aircraft a.c. electric system power quality. 1970 proceedings of the national aerospace electronics conference, 18-20 May 1970, Dayton, OH, USA, IEEE.

IEEE Std C57.18-10-1998 “IEEE standard practices and requirements for semiconductor power rectifier transformers”

IEEE Std C62.48-1995 “IEEE guide on interactions between power system disturbances and surge-protective devices”

IEEE Std 493-1997, “Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems”, Appendix N

IEEE Std 493-1997 "IEEE recommended practice for the design of reliable industrial and commercial power systems", Chapter 9

IEEE Std 519-1992 "IEEE recommended practices and requirements for harmonic control in electrical power systems"

IEEE Std 1100-1999 "IEEE recommended practice for powering and grounding electronic equipment"

IEEE Std 1124-2003 "IEEE guide for the analysis and definition of DC-side harmonic performance of HVDC transmission systems"

IEEE Standard 1159-1995, "IEEE recommended practice for monitoring electric power quality".

IEEE Std 1159.3-2003 "IEEE recommended practice for the transfer of power quality data"

IEEE Std 1250-1995 "IEEE guide for service to equipment sensitive to momentary voltage disturbances"

IEEE Std 1346-1998 "IEEE recommended practice for evaluating electric power system compatibility with electronic process equipment"

IEEE Std 1531-2003 "IEEE Guide for Application and Specification of Harmonic Filters"

IEEE Standard 1564 draft 6, "Recommended Practice for the Establishment of Voltage Sags Indices"

Johns, M. and L. Morgan (1994). Voltage sag mitigation through ridethrough coordination. Proceedings of 1994 IEEE/IAS Annual Textile, Fiber and Film Industry Technical Conference, 4-5 May 1994, Greenville, SC, USA, IEEE.

Jurewicz, R. E. (1990). Power quality study-1990 to 1995. INTELEC: Twelfth International Telecommunications Energy Conference (Cat. No.90CH2928-0), 21-25 Oct. 1990, Orlando, FL, USA, IEEE.

Kagan, N., E. L. Ferrari, et al. (2000). Influence of RMS variation measurement protocols on electrical system performance indices for voltage sags and swells. Proceedings of 2000 International Conference on Harmonics and Quality of Power, 1-4 Oct. 2000, Orlando, FL, USA, IEEE.

Kajihara, H. H. (1968). "Quality Power for Electronics." Electro-Technology 82(2): 46.

Kartashev, I. I. and D. B. Kryuchkov (1992). "Voltage quality analyser." Promyshlennaya Energetika(2): 27-30.

Key, T. S. (1979). "Diagnosing power quality related computer problems." IEEE Transactions on Industry Applications IA-15(4): 381-93.

Konstantinov, B. A., I. V. Zhezhelenko, et al. (1977). "Power quality and electromagnetic compatibility of electrical gear in industry." Elektrichestvo(3): 1-8.

Konstantinov, B. A., I. V. Zhezhelenko, et al. (1978). "A system of indices and standardising the quality of electric energy." Elektrichestvo(9): 11-19.

Koval, D. O. and M. B. Hughes (1996). Frequency of voltage sags at industrial and commercial sites in Canada. Proceedings of 1996 Canadian Conference on Electrical and Computer Engineering, 26-29 May 1996, Calgary, Alta., Canada, IEEE.

Kurbatskii, V. G. and V. N. Yaramenko (1990). "Economic appraisal of the effect of the quality of electrical energy on the operation of electrical equipment." Promyshlennaya Energetika(4): 12-14.

Leborgne, R. C., J. M. C. Filho, et al. (2003). Alternative methodology for characterization of industrial process sensitivity to voltage sags. 2003 IEEE Bologna PowerTech, 23-26 June 2003, Bologna, Italy, IEEE.

Lonngren, K. (1974). "Quality of electricity supply." Saehkoe 47(3): 118-23.

Macken, K. J. P., M. H. J. Bollen, et al. (2004). "Mitigation of voltage dips through distributed generation systems." IEEE Transactions on Industry Applications 40(6): 1686-93.

Macedo Correia, D. and D. de Oliveira Campones do Brasil (2003). Pilot project for the evaluation of the sag performance of some Brazilian network busbars. CIGRE/IEEE PES International Symposium. Quality and Security of Electric Power Delivery Systems, 8-10 Oct. 2003, Montreal, Que., Canada, IEEE.

Marquet, J. (1992). CREUTENSI: software for determination of depth, duration and number of voltage dips (sags) on medium voltage networks, EDF-Electricite de France, Clamart, France. 93NR00001: 10.

Martinez, J. A. and J. Martin-Arnedo (2004). "Voltage sag stochastic prediction using an electromagnetic transients program." IEEE Transactions on Power Delivery 19(4): 1975-82.

McEachern, A. (1993). "Power quality: how bad is bad?" Electrical Construction and Maintenance 92(2): 26, 30, 32.

McFadden, R. H. (1969). "How does plant power distribution design affect today's machine tools?" Electrical Construction Design: 21-8.

McFadden, R. H. (1970). Power system analysis-what it can do for industrial plants. IEEE conference record of 1970 5th annual meeting of the IEEE industry and general applications group, 5-8 Oct. 1970, Chicago, IL, USA, IEEE.

McGranaghan, M. (1995). Effects of voltage sags in process industry applications. Proceedings of Stockholm Power Tech International Symposium on Electric Power Engineering, 18-22 June 1995, Stockholm, Sweden, IEEE.

McGranaghan, M., B. W. Kennedy, et al. (1998). Power quality contracts in a competitive electric utility industry. Proceedings of 1998 International Conference on Harmonics and Quality of Power, 14-16 Oct. 1998, Athens, Greece, IEEE.

McGranaghan, M. and B. Roettger (2001). Benchmarking International Transmission System Fault Performance. PQA Conference.

Mestres, C. (1972). "Computer power supply, analysis of service quality in voltage dips field." Revue Générale de l'Electricité 81(9): 531-6.

Meynaud, P. (1983). The quality of the voltage in the supply of electrical energy. 2 Colloque National et Exposition sur la Compatibilité Electromagnetique (2nd National Colloquium and Exposition on Electromagnetic Compatibility), 1-3 June 1983, Tregastel, France, CNET.

Mielczarski, W. and G. Michalik (1998). Regulation of power quality in competitive electricity markets. Proceedings of 1998 International

Conference on Harmonics and Quality of Power, 14-16 Oct. 1998, Athens, Greece, IEEE.

Olguin, G. (2003). Stochastic Assessment of voltage Dips Caused by Faults in Large Transmission System. Department of Electric Power Engineering. Gothenburg, Chalmers University of Technology: 113.

Olguin, G. and M. H. J. Bollen (2003). Stochastic assessment of unbalanced voltage dips in large transmission systems. 2003 IEEE Bologna PowerTech, 23-26 June 2003, Bologna, Italy, IEEE.

ONS - Operador Nacional do Sistema Interligado (Brasil), (2003) http://www.ons.org.br/ons/sin/index.htm).

Ohrstrom, M. and L. Soder (2003). A comparison of two methods used for voltage dip characterization. 2003 IEEE Bologna PowerTech, 23-26 June 2003, Bologna, Italy, IEEE.

Outhred, H. and F. C. Schweppe (1980). Quality of supply pricing for electric power systems. IEEE 1980 Power Engineering Society Winter Meeting, 3-8 Feb. 1980, New York, NY, USA, IEEE.

Plette, D. L. (1969). The effects of improved power quality on utilization equipment. Proceedings of national aerospace electronics conference, 19-21 May 1969, Dayton, OH, USA, IEEE.

Poeata, A., D. Ivas, et al. (1978). "Possibilities of calculating the effects of voltage dips on the industrial consumer on using digital simulation." Buletinul Institutului de Studii si Proiectari Energetice 21(1-2): 53-61.

Popescu, M. and F. Popescu (1983). "The quality of delivered electric power. Quality indices of the electric voltage in the presence of a deforming regime." Energetica 31(4): 182-9.

Qader, M. R., M. H. J. Bollen, et al. (1999). "Stochastic prediction of voltage sags in a large transmission system." IEEE Transactions on Industry Applications 35(1): 152-62.

Reason, J. (1988). "End-use power quality: new demand on utilities." Electrical World 202(11): 43-46.

Ribeiro, T. N. (1999). Power quality issues relating of IEEE and IEC standards. Proceedings of Conference on Electrical Machines, Converters and Systems, 14-16 Sept. 1999, Lisbon, Portugal, Inst. Superior Tecnico.

Roman, T. G. S. and J. R. Ubeda (1998). "Power quality regulation in Argentina: flicker and harmonics." IEEE Transactions on Power Delivery 13(3): 895-901.

Sabin, D. D., T. E. Grebe, et al. (1999). RMS voltage variation statistical analysis for a survey of distribution system power quality performance. IEEE Power Engineering Society. 1999 Winter Meeting, 31 Jan.-4 Feb. 1999, New York, NY, USA, IEEE.

Sannino, A. and J. Svensson (2000). A series-connected voltage source converter for voltage sag mitigation using vector control and a filter compensation algorithm. Proceedings of World Congress on Industrial Applications of Electrical Energy and 35th IEEE-IAS Annual Meeting, 8-12 Oct. 2000, Rome, Italy, IEEE.

Stockman, K., M. Didden, et al. (2004). "Bag the sags." IEEE Industry Applications Magazine 10(5): 59-65.

Thallam, R. S. and G. T. Heydt (2000). Power acceptability and voltage sag indices in the three phase sense. 2000 Power Engineering Society Summer Meeting, 16-20 July 2000, Seattle, WA, USA, IEEE.

Tosato, F. (2001). "Voltage sags mitigation on distribution utilities." European Transactions on Electrical Power 11(1): 17-21.

Tosato, F., G. Giadrossi, et al. (1991). The problems posed by voltage supply dips to industrial power electronic loads. 6th Mediterranean Electrotechnical Conference. Proceedings. (Cat. No.91CH2964-5), 22-24 May 1991, LJubljana, Slovenia, IEEE.

Tosato, F. and S. Quaia (2000). "Equipment fault-clearing time reduction: an approach to utility voltage sag mitigation." Elektrotehniski Vestnik 67(5): 294-9.

Wagner, V. E., A. A. Andreshak, et al. (1990). "Power quality and factory automation." IEEE Transactions on Industry Applications 26(4): 620-6.

Valov, B. M. (1984). "The normalization of the quality of the electric energy in the USSR." Elektrie 38(8): 284-6.

Woodley, N. H. and T. Sezi (2000). Voltage sag and swell mitigation using a static series compensation device. Proceedings of International Conference for Power Electronics, Drives, Motion and Control and Power Quality, 6-8 June 2000, Nurnberg, Germany, ZM Commun. GMBH.

Yun, S.-Y., J.-H. Oh, et al. (2000). Mitigation of voltage sag using feeder transfer in power distribution system. 2000 Power Engineering Society Summer Meeting, 16-20 July 2000, Seattle, WA, USA, IEEE.

Appendix 1: Sag classification

The symmetrical component classification of voltage sags is based on a systematic analysis of faults. The basic model for a distribution system is shown in Figure 25.

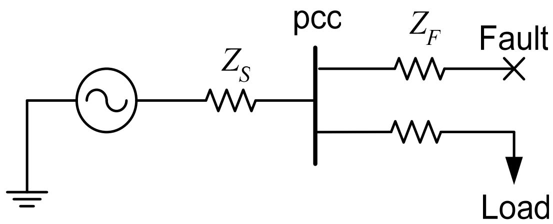


Figure 25 – Basic model for fault analysis

For a symmetric three-phase fault the voltage at the point-of-common-coupling (pcc) can be estimated using a simple voltage-divider model represented by the equation (A.1). In this case the fault impedance is not considered.

$$U = \frac{Z_F}{Z_F + Z_S} E_1 \tag{A.1}$$

Here U is the retained voltage at pcc, E_1 is the pre-fault voltage in phase A, Z_F is the feeder impedance and Z_S is the source impedance.

If we consider a line-to-line fault (LL) between phases B and C the voltage and current at fault position are described by (A.2):

$$\begin{aligned} V_B &= V_C \\ I_A &= 0 \\ I_B &= I_F = -I_C \end{aligned} \tag{A.2}$$

Where V_B and V_C are the phasor voltages at phase B and C, I_A and I_B are the phasor currents at phase A and B, and I_F is the fault current.

Applying symmetrical components theory, equation (A.3), to the boundary conditions shown in (A.2) the symmetrical voltages and currents at the fault location are obtained (A.4).

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{j120^o} & e^{j240^o} \\ 1 & e^{j240^o} & e^{j120^o} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{A.3}$$

$$\begin{aligned} V_1 &= V_2 \\ I_0 &= 0 \\ I_1 &= I_F \end{aligned} \tag{A.4}$$

The set of equations (A.4) expresses that positive and negative sequence voltages are equal at the fault location. It also indicates that the zero sequence components are not present in the LL faults. This is obvious because this fault does not provide any return path for the zero sequence current, as shown in Figure 26.

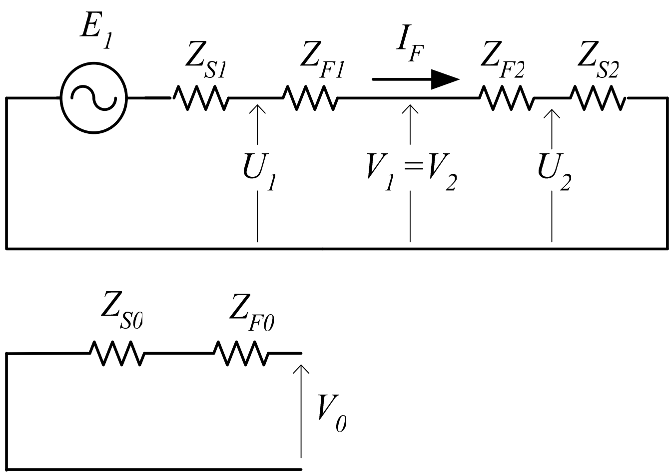


Figure 26 – Symmetrical component model for LL fault

Considering the distribution grid from Figure 25, each of the Thevenin impedances seen from the fault location is the sum of the source and the feeder sequence impedances as shown in Figure 26.

The fault current is straightforward calculated using equation (A.5), which is easily derived from the Figure 26.

$$I_F = E_1 \frac{1}{Z_1 + Z_2} = E_1 \frac{1}{Z_{S1} + Z_{F1} + Z_{S2} + Z_{F2}} \tag{A.5}$$

Once the fault current is known the sequence voltages at pcc (U_1 and U_2) are estimated using the equation (A.6).

$$U_1 = E_1 - Z_{S1} I_F = E_1 \left(1 - \frac{Z_{S1}}{Z_{S1} + Z_{F1} + Z_{S2} + Z_{F2}} \right)$$
$$U_2 = Z_{S2} I_F = E_1 \frac{Z_{S2}}{Z_{S1} + Z_{F1} + Z_{S2} + Z_{F2}} \qquad \text{(A.6)}$$

Where Z_1 is the Thevenin positive sequence impedance and Z_2 is the Thevenin negative sequence impedance seen from the fault position.

Considering now the difference and the sum of positive and negative sequence voltages a new set of expressions is obtained (A.7).

$$U_1 - U_2 = \frac{Z_{F1} + Z_{F2}}{Z_{S1} + Z_{F1} + Z_{S2} + Z_{F2}} E_1$$
$$U_1 + U_2 = \left(1 - \frac{Z_{S1} - Z_{S2}}{Z_{S1} + Z_{F1} + Z_{S2} + Z_{F2}} \right) E_1 \qquad \text{(A.7)}$$

The difference of U_1 and U_2 is called characteristic voltage (V_{Ch}) and the sum is called PN-factor (F). In general positive and negative sequence impedances are very similar. Therefore, the equations (A.7) are approximate by (A.8):

$$V_{Ch} = U_1 - U_2 \cong \frac{Z_{F1}}{Z_{S1} + Z_{F1}} E_1$$
$$F = U_1 + U_2 \cong E_1 \qquad \text{(A.8)}$$

A LL fault affecting phases B and C causes a voltage sag between these phases. Using the symmetrical-component classification this event is characterised by three parameters: characteristic voltage (V_{Ch}), PN-factor (F), and by the sag type C_a.

Appendix 2: Sag survey

Table 19 - Voltage sag survey on a distribution feeder 13.8 kV.

Date	Retained voltage (%)	Duration (ms)
30/04/2002@17:47:05,133	88	8
03/05/2002@19:59:07,797	87	108
03/05/2002@19:59:10,922	89	467
03/05/2002@19:59:11,297	84	892
03/05/2002@20:00:01,938	83	517
03/05/2002@20:00:36,130	89	8
03/05/2002@20:03:15,318	89	25
07/05/2002@15:00:49,921	88	58
13/05/2002@11:44:36,516	83	33
19/05/2002@10:14:47,201	73	25
19/05/2002@10:24:48,236	89	41
21/05/2002@03:55:51,739	88	8
12/06/2002@05:11:02,615	85	358
12/06/2002@06:04:21,416	88	500
17/07/2002@07:35:26,046	89	33
17/07/2002@07:35:26,054	81	41
27/07/2002@07:58:41.924	84	41
29/07/2002@14:50:23,319	39	175
01/08/2002@23:10:43,611	70	266
01/08/2002@23:32:34,540	88	16
02/08/2002@12:56:06,179	70	307
02/08/2002@23:18:06,356	70	283
03/08/2002@10:59:49,981	81	16
04/08/2002@06:40:37,418	86	108
04/08/2002@13:26:50,374	68	250
06/08/2002@10:41:28.942	90	341
09/08/2002@15:03:15.261	80	41
09/08/2002@15:03:17.760	71	526
09/08/2002@15:03:20.217	70	491
09/08/2002@19:10:44.346	82	125
26/08/2002@18:17:26.380	89	33
26/08/2002@18:17:28.564	86	42
26/08/2002@18:38:10.649	87	33
30/08/2002@02:17:46.953	87	41
06/09/2002@13:45:07.255	89	83
06/09/2002@19:28:40.893	77	100
06/09/2002@19:28:45.116	88	8
07/09/2002@03:22:40.736	82	41
07/09/2002@03:47:08.028	73	274
07/09/2002@03:56:16.495	58	33
07/09/2002@03:56:23.045	53	50
07/09/2002@03:56:37.217	39	225
07/09/2002@03:58:04.859	88	8
07/09/2002@03:59:36.364	88	8
07/09/2002@05:27:31.638	88	83
07/09/2002@05:58:59.848	89	16
07/09/2002@10:29:52.366	89	83

10/09/2002@14:25:06.805	**88**	**8**
14/09/2002@10:55:33.598	**89**	**16**
22/09/2002@11:52:16.395	**88**	**8**
29/09/2002@23:16:52.778	**84**	**208**
29/09/2002@23:29:37.507	**84**	**41**
01/10/2002@11:34:14.952	**87**	**33**
01/10/2002@11:34:21.304	**78**	**25**
01/10/2002@11:34:34.873	**89**	**25**
02/10/2002@16:07:46.578	**28**	**191**
02/10/2002@16:08:47.421	**52**	**25**
09/10/2002@09:02:17.733	**78**	**17**
13/10/2002@06:42:39.683	**67**	**41**
13/10/2002@06:42:41.866	**62**	**242**
13/10/2002@06:42:43.882	**43**	**124**
13/10/2002@06:42:43.890	**19**	**133**
13/10/2002@06:46:07.354	**54**	**41**
13/10/2002@06:46:25.175	**78**	**751**
14/10/2002@14:11:15.955	**86**	**33**
15/10/2002@11:43:48.323	**73**	**41**
22/10/2002@00:35:10.786	**86**	**8**
25/10/2002@20:54:41.023	**88**	**16**
27/10/2002@23:38:49.016	**84**	**124**
27/10/2002@23:38:51.107	**84**	**33**
27/10/2002@23:38:53.356	**85**	**66**
28/10/2002@14:20:10.026	**84**	**16**
28/10/2002@14:32:21.382	**88**	**8**
28/10/2002@14:37:59.658	**86**	**8**
28/10/2002@14:38:55.146	**84**	**24**
28/10/2002@15:45:13.101	**88**	**74**
28/10/2002@17:17:24.554	**83**	**16**
28/10/2002@19:10:36.002	**89**	**8**
29/10/2002@08:47:47.527	**19**	**374**
29/10/2002@23:28:58.172	**12**	**50**
10/11/2002@07:01:33.826	**41**	**66**
10/11/2002@08:31:20.532	**50**	**683**
15/11/2002@08:44:22.260	**84**	**41**
19/11/2002@07:58:29.741	**89**	**8**
21/11/2002@12:11:03.534	**88**	**41**
28/11/2002@09:51:22.499	**20**	**676**
02/12/2002@15:01:31.271	**89**	**66**
03/12/2002@14:13:14.876	**85**	**33**
03/12/2002@14:13:20.900	**85**	**33**
03/12/2002@14:13:33.416	**85**	**125**
03/12/2002@20:16:23.202	**88**	**25**
03/12/2002@20:38:01.465	**77**	**41**
03/12/2002@20:39:16.766	**85**	**33**
04/12/2002@16:47:19.630	**86**	**16**
04/12/2002@16:51:15.519	**89**	**8**
05/12/2002@16:54:46.196	**85**	**33**
09/12/2002@10:04:30.876	**5**	**233**
10/12/2002@00:58:14.887	**85**	**66**
13/12/2002@17:19:49.705	**87**	**375**
13/12/2002@19:28:50.180	**89**	**116**
16/12/2002@16:33:48.405	**88**	**183**
16/12/2002@16:33:48.921	**84**	**416**

20/12/2002@13:08:04.212	**75**	**25**
24/12/2002@09:49:44.187	**81**	**33**
29/12/2002@16:52:59.156	**57**	**50**
29/12/2002@16:53:01.371	**52**	**216**
29/12/2002@16:53:03.420	**46**	**141**
17/01/2003@19:26:08.085	**78**	**33**
18/01/2003@11:02:56.733	**77**	**50**
18/01/2003@11:03:14.740	**84**	**49**
21/01/2003@01:14:03.341	**80**	**91**
22/01/2003@13:08:37.338	**87**	**8**
27/01/2003@17:29:42.013	**86**	**16**
30/01/2003@18:36:15.122	**84**	**91**
30/01/2003@18:36:15.130	**82**	**1007**
30/01/2003@20:54:11.114	**89**	**91**
01/02/2003@18:49:39.081	**89**	**8**
02/02/2003@17:06:14.839	**86**	**33**
02/02/2003@17:29:15.444	**84**	**33**
06/02/2003@17:21:24.394	**88**	**7**
06/02/2003@17:57:44.323	**61**	**50**
16/02/2003@15:25:10.936	**87**	**8**
16/02/2003@15:25:13.153	**88**	**16**
16/02/2003@15:25:15.346	**89**	**8**
17/02/2003@16:04:54.384	**83**	**41**
19/02/2003@01:14:29.651	**88**	**24**
22/02/2003@13:06:09.463	**64**	**50**
22/02/2003@13:06:12.037	**73**	**308**
22/02/2003@13:36:05.849	**56**	**41**
22/02/2003@13:36:08.109	**53**	**300**
22/02/2003@13:36:10.251	**43**	**208**
22/02/2003@13:37:44.386	**79**	**24**
26/02/2003@11:41:04.220	**88**	**8**
04/03/2003@15:54:26.801	**50**	**41**
04/03/2003@15:54:28.727	**49**	**49**
04/03/2003@15:54:30.902	**49**	**233**
05/03/2003@00:59:44.399	**77**	**24**
05/03/2003@02:12:19.687	**76**	**16**
13/03/2003@15:32:42.863	**89**	**74**
13/03/2003@15:32:47.552	**86**	**16**
17/03/2003@11:03:35.727	**84**	**49**
22/03/2003@17:42:12.185	**70**	**25**
29/03/2003@17:34:16.539	**87**	**16**
30/03/2003@08:52:25.672	**86**	**33**
04/04/2003@10:05:15.096	**87**	**41**
15/04/2003@11:24:52.627	**89**	**8**
16/04/2003@09:17:15.708	**67**	**33**
16/04/2003@09:17:17.924	**89**	**8**
02/05/2003@15:41:34.690	**87**	**8**
05/05/2003@06:12:23.031	**77**	**16**

Appendix 3: Published papers

PAPER A

Leborgne, R.C., and Karlsson, D., "**Phasor Based Voltage Sag Monitoring and Characterization**", CIRED, Turin, Italy, June 2005.

PAPER B

Leborgne, R.C., Karlsson, D. and Olguin, G., "**Analysis of Voltage Sag Phasor Dynamics**", IEEE-PES Power Tech 2005, St Petersburg, Russia, June 2005.

PAPER C

Leborgne, R.C., Olguin, G., Bollen, M.H.J., "**The influence of PQ-monitor connection on voltage dip measurements**", IEE MedPower, Cyprus, November 2004.

PAPER D

Leborgne, R.C., Olguin, G., Bollen, M.H.J., "**Sensitivity Analysis of Stochastic Assessment of Voltage Dips**", IEEE PowerCon, Singapore, November 2004.