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Power quality data management and reporting methodologies

H. M. S. Chandana Herath
University of Wollongong

Power Quality Data Management and Reporting Methodologies

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H M S Chandana Herath

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To my parents, wife Nimali,

and

son Tharindu

Declaration

Apart from the assistance stated in the acknowledgments and where reference is made in the text this thesis represents the original work of the author. The studies presented here have not been submitted for qualification at any other academic institution.

H.M.S. Chandana Herath

School of Electrical, Computer & Telecommunications Engineering

University of Wollongong

Australia

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Abstract

Deregulation of the Australian electricity supply industry is being accompanied by state regulator requirements for explicit statements on quality of supply backed up with field survey results. The continuous monitoring and storage of every voltage waveform at a selection of key sites will add significant expenses to the associated costs in managing the electricity industry while demanding an enormous quantity of information to be processed. This thesis gives a less comprehensive approach which may be accepted as a standard and consistent method of characterising the supply using simple set of power quality indices. Also presented is a power quality data management and reporting methodology which will give useful feedback to end-users, allowing assessment of operability of equipment as well as to the regulators and utilities, for the comparison of competitive distributor performance. This is supported by a power quality surveys of selected sites within electricity utilities in Australia.

The thesis gives a method of analysis that can be used to conveniently convert the collected raw data into useful knowledge, covering various types of power quality disturbances i.e. continuous or variation type and discrete or event type. Literature suggests that there has been many studies undertaken on continuous disturbance characterisation and related indices. Comprehensive standards have been developed specifying objectives to be met with standard limits for all continuous disturbance types. However, there are no generally acceptable methods for characterisation of discrete disturbances and limits are not well defined in international standards. A generalised method is proposed in this thesis to characterise discrete disturbances

which is essentially based on a Disturbance Severity Indicator (DSI) proportional to the customer complaint rate. Scaled versions of the CBEMA and ITIC curves have been used to give an approximation to customer complaints.

The power quality reporting methodology suggested in this thesis is a consistent approach for power quality data analysis; categorised in to Short term, Medium term and Long term reporting, giving summary indices for each individual disturbance type and a single Unified Power Quality Index (UPQI) for each site and the utility. This approach would give an assessment of power quality rapidly, by means of representative numbers without overlooking important details. These indices, which are the result of characterisation and extraction from a large volume of power quality data, are easy to assess and representative of the actual impact of the disturbances they characterise. A novel methodology is also given to define discrete disturbance limits based on statistical information collected from large scale power quality surveys performed around the world.

Further, Multivariable Linear Regression (MVLR) has been used as a tool to identify hidden patterns and relationships within a large quantity of power quality data in an Australian monitoring campaign. For this, a factor analysis model has been developed using MVLR and complemented with Data Mining techniques; this model reveals the good and bad factors that influence utility power quality. Finally, the power quality data management guidelines and reporting methodologies developed have been applied to representative sites of several Australian utilities, to illustrate their ability to rank sites for power quality improvements and to rank utilities for power quality benchmarking.

Publications arising from the research work of this thesis

Herath, H.M.S.C., Gosbell, V.J., Perera, S., and Stirling, D. "Power Quality (PQ) Survey Factor Analysis using Multivariable Linear Regression (MVLR)," *IEEE International Conference of Harmonics and Quality of Power(ICHQP 2008),* Wollongong, NSW, Australia, Sept. 2008, Paper 1145.

Herath, H.M.S.C., Gosbell, V.J., and Perera, S., "Power Quality (PQ) Survey Reporting: Discrete Disturbance Limits," *IEEE Transactions on Power Delivery,* Vol. 20, No. 2, April 2005, pp. 851-858.

Herath, H.M.S.C., Gosbell, V.J., and Perera, S., "Benchmarking Utilities for the Impact of Voltage Sags on Customers," *IEEE International Conference of Harmonics and Quality of Power(ICHQP 2004),* Lake Placid, New York, USA, 12-15 Sept. 2004, pp. 425-429.

Herath, C., Gosbell, V., and Perera, S., "MV Distribution Voltage Sag Limits for Network Reporting," *Proceedings of Australasian Universities Power Engineering Conference (AUPEC'03)*, Christchurch, New Zealand, September 2003, Paper No. 101.

Herath, C., Gosbell. V., Perera, S., and Robinson, D., "A Transient Index for Reporting Power Quality (PQ) Surveys," *Proceedings of 17th IEE International Conference of Electricity Distribution (CIRED 2003)*, Barcelona, Spain, pp. 2.61-1 - 2.61-5, May 2003.

Gosbell, V.J., Perera, S., and **Herath, H.M.S.C.,** "Unified Power Quality Index (UPQI) for Continuous Disturbances," *10th IEEE International Conference of Harmonics and Quality of Power (ICHQP 2002),* Rio de Janeiro, Brazil, 6-9 October 2002, Vol. 1, pp. 316-321.

V.J. Gosbell, **H.M.S.C. Herath**, B.S.P. Perera and D.A. Robinson "Sources of Error in Unbalance Measurements," *Proceedings of Australasian Universities Power Engineering Conference (AUPEC'02)*, Melbourne, Australia, September 2002, Paper No. 116.

V.J. Gosbell, B.S.P. Perera and **H.M.S.C. Herath** "New Framework for Utility Power Quality Data Analysis," *Proceedings of Australasian Universities Power Engineering Conference (AUPEC'01)*, Perth, Australia, September 2001, pp. 577-582.

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List of abbreviations

ANSI	*American National Standards Institute*
AS/NZS	*Australian/ New Zealand Standards*
ANPQBS	*Australian National Power Quality Benchmark Survey*
CBEMA	*Computer Business Equipment Manufacturers Association*
CEA	*Canadian Electricity Association*
CENELEC	*European Committee for Electrotechnical Standardisation*
DFT	*Discrete Fourier Transform*
DSI	*Disturbance Severity Indicator*
EHV	*Extra high voltage*
EPRI	*Electric Power Research Institute*
ESKOM	*South African Electricity Supply Company*
FFT	*Fast Fourier Transform*
HV	*High voltage*
IEC	*International Electrotechnical Commission*
IEE	*Institution of Electrical Engineers, UK*
IEEE	*Institution of Electrical and Electronic Engineers, USA*
ITIC	*Information Technology Industry Council*
LTNPQS	*Long Term National Power Quality Survey*
LV	*Low voltage*
MML	*Minimum Message Length*
MV	*Medium voltage*
MVLR	*Multivariable Linear Regression*
NEMA	*National Electricity Manufacturers Association, USA*

P_{st}	*Short term flicker severity index*
P_{lt}	*Long term flicker severity index*
PQAT	*Power Quality Analysis Triangle*
RPM	*Reliable Power Meters*
UPQI	*Unified Power Quality Index*
V	*Voltage (V)*
VUF	*Voltage Unbalance Factor*
V_{THD}	*Voltage Total Harmonic Distortion*

Chapter 1

Introduction

1.1 POWER QUALITY MONITORING IN DISTRIBUTION SYSTEMS

Power quality (PQ) is a subject that has captured the interest of both utilities and their customers. A PQ problem can be best described as "Any problem manifested in voltage, current or frequency deviations that results in failure or misoperation of customer's equipment" [1]. Many types of PQ problems have been around for many years and treated independently. Over the last two decades these PQ problems have received considerable attention from researchers and industry where they were treated collectively under the name of power quality. One of the reasons for this appears to be the increased sensitivity of modern equipment that may trip or malfunction due to a single or several combinations of disturbances. Apart from this, there is an increased awareness of power quality issues by end-users that put additional pressures on utilities who are already exposed to an increased competitiveness due to deregulation of electrical power industry. The need for solutions to power quality problems grows rapidly. The ultimate reason for increased awareness of power quality issue is an economic one [2].

During the last two decades or so, many utilities around the world have implemented extensive power quality monitoring programmes to provide their customers a better service as well as to establish an overall understanding about their system and to understand how it reacts to particular PQ disturbances. As a result of continuous monitoring of many sites, a utility produces an enormous amount of PQ data. Advances in storage technologies allow the monitoring systems to collect and store more and more data; however, there is no practical method to conveniently convert the collected raw data into useful knowledge desired by many different readers, i.e. end-users, regulators and utility personnel. There is a need for improved methods in collection, analysis and reporting of very large amounts of measured PQ data.

1.2 MOTIVATION

The present strong interest in PQ arises out of the increased susceptibility of electronic and digital equipment [3] and greater customer expectations in the deregulated market. Problems are most severe in large integrated manufacturing plants with sensitive manufacturing processes and in rural areas where power lines can have relaxed design standards and are more exposed to lightning.

The international approach to power quality control is to ensure compatibility between the level of disturbance on the power supply and the susceptibility of customer equipment. This requires a clear and accurate statement from the utility in relation to actual PQ disturbance level. This can be addressed by using PQ survey data that have been collected by many countries over a period of time in order to establish their actual PQ levels [4-6].

The Australian electricity supply industry has been going through a process of progressive deregulation over the last fifteen years or more. A concern has arisen that the quality of the supply may degrade under the pressure of competition and regulators have increasingly taken steps to define and control minimum levels. In some states, distributors have been requested PQ disturbance level objectives. With very little field data available within Australian utilities, it is hard to develop their own standards, therefore the relevant information have been taken from overseas literature [7]. However, each country has its own practices and local geographical and climatic features and there is no guarantee that the data valid in one country can be re-used elsewhere. As an example of some important differences in practice, in USA low voltage system is mainly single phase with each line serving about 40 households [8], whereas in Australia has a three phase system with sufficient capacity for about 200 or more households.

A review of standards [9-25] reveals that some deviations and new developments are necessary. In the USA, power quality standardisation has been primarily formalised through support of IEEE activities. The Electric Power Research Institute (EPRI) has sponsored work in support of distribution system design improvements and supports the development of standards via IEEE. In Europe, there are also ongoing activities for standardisation and harmonisation among European countries and the IEEE. International Electrotechnical Commission (IEC) is the main body that controls the power quality standardisation activities in Europe while there is another body named European Committee for Electrotechnical Standardisation (CENELEC) [8]. Most of Australian Power Quality standards are adopted IEC standards.

Another difficulty was the lack of an acceptable standard for PQ monitors. They differ in their sampling rate, degree of synchronisation with the supply waveform and how they characterise different types of PQ disturbances. The use of poorly specified monitors will make it difficult to achieve one of the main aims of monitoring schemes, the comparison of sites within a utility and comparison of PQ performance of different utilities. However, the introduction of IEC 61000.4.30: 2003 standard, has given a reasonable solution to the problem, where IEC has recently published the Revision 2 of the IEC 61000-4-30:2007.

There are also developments among state regulators in requiring utilities to establish PQ monitoring campaigns. However, there is no discussion as to whether the methods adopted should be comprehensive or rely on the PQ surveys taken at “a small sample” of sites. There are proposals being considered that may involve monitoring at the sending and far end of every MV (medium voltage) feeder. Although the approach appears to be comprehensive for MV power quality, it takes little notice of the economics or the real need of comprehensive monitoring. As an example, the Integral Energy system, has about 1000 medium voltage feeders, requiring 1500 or so monitors as many of the feeders will have the same supply end. A comprehensive PQ monitor costs about $20,000 that leads to a capital expenditure of $30 million [27]. In addition, there are costs of installation, people to operate the monitoring system, communications infrastructure to bring the data back to a base, data storage facilities and personnel for data processing, report generation and assessment.

The amount of data generated by one monitor sampling three phase voltages with a minimum sampling rate of 4 kHz, and a sampling accuracy of 12 bits gives about 10GB of data per site per week [26]. It is a nontrivial exercise to establish a means of storing the data in a form that can be intelligently used. Extension of this approach to the much more extensive LV (low voltage system) will increase the cost and data flow problems by another order of magnitude.

The reporting of power quality in Australia at present is based on interruption figures and some basic indices covering few PQ disturbances such as unbalance, harmonics, flicker and voltage sags. A proper PQ index would account for the failure modes of modern equipment and gives guidance as to where the utility system needs to be improved.

Research is needed to establish what type of equipment are failing, their failure mechanism, dominant PQ disturbance types, their limiting values, and characterisation. One of the major concerns is how the impact of these disturbances on customers can be best described by representative indices for the development of better PQ data management strategies and reporting methodologies.

1.3 HYPOTHESIS OF THE THESIS

As described above the continuous recording and storage of every voltage waveform at every electricity supply point will add significant expenses and produce enormous quantity of information to be processed. The hypothesis of this thesis is to develop a less comprehensive methodology where the power quality parameters can be identified that will allow different sites to be compared based on their characteristics. Such a methodology will help different sites within a utility and the overall perormance of different utilities to be objectively compared. The development of power quality data management and analysis techniques are described that lead to reporting methodologies thus enabling utilities to better manage their power quality [7, 27, 93]. These methodologies have been demonstrated having limited data available through a PQ survey conducted in Australia over a one year period.

The main research objectives of the work described in this thesis are identified as follows:

1. Development of new power quality disturbance characterisation schemes and indices.
2. Development of PQ reporting methodology to give useful feedback to,
   (a) Consumers, allowing assessment of operability of equipment,
   (b) Regulators for the comparison of different utility performance,
   (c) Utilities for ranking sites with poor PQ to determine the priority for PQ improvements, better directed maintenance and upgrade strategies.

The common objective of this thesis is the development of power quality disturbance characterisation and reporting methodologies for Australian utilities. It is actually the voltage that is being addressed in almost all cases as it is the utility responsibility to maintain the voltage quality, while customers impacting on it by drawing current. The implementation of methodologies and associated guidelines covered in this thesis concentrate on the voltage quality aspects of the power supply, and cover the data management and reporting aspects of all PQ disturbances affecting the deterioration of voltage waveform and their impact on end user equipment.

1.4 ORGANISATION OF THE THESIS

A brief summary of the contributions of each of the remaining chapters of this thesis is described as below:

Chapter 2: In this chapter a literature review on the present situation of PQ monitoring and reporting methodologies throughout the world and their limitations are presented.

Chapter 3: A framework is given in this chapter to identify the important aspects of the PQ data management and reporting. There are three categories of reporting (a) short term, (b) medium term and (c) long term, serving most purposes in PQ data management. This chapter also reviews the existing disturbance characterisation schemes, related indices and their limitations. A new generalised characterisation method is given for discrete disturbances and recommends a single index for each discrete disturbance type.

Chapter 4: A discussion is given in this chapter on the development of a medium term reporting structure which gives useful insights for several different categories of readers; customers, regulators and utilities. A data compression structure has been proposed represented in the form of a triangle termed PQ Analysis Triangle (PQAT). The PQAT has been divided into two major steps; summary statistics for one site, i.e. "time compression" and the summary statistics of the indices obtained over a specified aggregation of sites, i.e. “space compression”. A detailed discussion of “time compression” and “space compression” is given covering all aspects of medium term power quality reporting.

Chapter 5: This chapter presents the long term reporting aspects of power quality monitoring and surveying covering standards and limiting values for PQ disturbances. A novel methodology is given to define discrete disturbance limits based on the 95% of sites measured using long term PQ monitoring data of many countries.

Chapter 6: This chapter gives a comprehensive discussion on the factor analysis of power quality data, i.e. factors contribute to good or bad power quality performance. Multivariable Linear Regression (MVLR) has been identified as a fast and useful approach to find hidden patterns and relationships of long term PQ monitoring data. The techniques developed by means of MVLR are complemented using Data Mining (DM) techniques. A factor analytic model has been developed which reveal the factors that contribute to poor and good power quality performance within different site categories.

A summary and recommendations for further research are given in Chapter 7.

Chapter 2

Literature Review on Power Quality Monitoring and Reporting

2.1 INTRODUCTION

Power quality problems are not necessarily limited to the utility side of the system; indeed, surveys have shown that the majority of problems are localised within customer facilities [28]. Given this, PQ monitoring is an effective customer strategy, but also a way to protect a utility's reputation for quality power and service. This can also be the difference between keeping and losing key customers for bad power quality.

In Australia, the distribution utility practice to date in power quality has concentrated on responding to customer complaints. The whole process is not complete in relation to systematic PQ monitoring and there is no rigorous data on the types of disturbances of most concern, nor on the customers who are most affected [29]. There appears to be little regulation on the tolerance of equipment to PQ disturbances. The rights and responsibilities of customers, utilities, and equipment suppliers are not yet well defined, although some states have their own PQ codes to cover some aspects. In Australia, there is also the National Electricity Rules where the participating Distribution and Transmission Network Service Providers (DNSPs & TNSPs) in the National Electricity Market (NEM) obliged to maintain in relation to steady state voltage, harmonics, flicker and unbalance limits under the Electricity licensing requirements. However, when a power quality problem occurs, it is not clear who should bear the cost of the solution and there is often a loss of goodwill between the parties. In April 2001, Australia's first national power quality benchmark survey was completed by the Integral Energy Power Quality and Reliability Centre (formerly Integral Energy Power Quality Centre) [30]. This pilot survey attempted to benchmark the Australian electricity network. Nine Australian distributors participated in this survey.

This chapter reviews literature on utility based power quality monitoring programmes that have been carried out both nationally and internationally, existing power quality standards and present reporting methodologies and their limitations in an attempt to identify the state-of-art practices in PQ monitoring and reporting methodologies.

2.2 PREVIOUS PQ MONITORING PROGRAMMES

There has been a considerable number of PQ monitoring programmes completed throughout the world. Some of the power quality surveys carried out both nationally and internationally are given below together with a brief description of each of the major survey.

1. EPRI DPQ (Electric Power Research Institute Distribution Power Quality) project: general PQ levels on MV feeders of selected utilities in USA [31]
2. NPL (National Power Laboratory) PQ study: Voltage sags, swells and transients in selected 120 V LV systems in Canada & USA [32]

3. CEA (Canadian Electricity Association) Survey: general PQ levels at main switch boards at distribution level [33]
4. UNIPEDE survey: survey of voltage sags and interruption statistics at selected substations throughout Europe [16].
5. EDF (Electricity De France) Survey: monitoring at every MV substation as part of its Qualimat project to support its Emerald & Premium power options.
6. Swedish power system: voltage sags, harmonics and flicker
7. Northern Taiwan: harmonics
8. European PQ survey campaigns: harmonics, flicker, unbalance and sags
9. Hydro Electric Corporation, Tasmania: voltage sags and harmonics
10. Australian National Power Quality Benchmark Survey: MV and LV PQ disturbances of most interest in Australia covering steady state voltage, unbalance, harmonics and voltage sags.
11. Pan European Power Quality Survey [34]: conducted by Leonardo Power Quality Initiative comprises 62 face - to - face surveys carried out in 8 European countries – voltage sags/swells, short/ long Interruptions, harmonics, surges & transients, flicker, unbalance, earthing, EMC problems and PQ problems.
12. Long Term National Power Quality Survey (LTNPQS) of Australian Utilities: Conducted by Power Quality Australia (A University of Wollongong initiative) its fourth year running with the participation major utilities in Australia – Voltage, Harmonics, Unbalance and Sags.

The information collected during these surveys provide a detailed picture of the expected electrical environment in which end-user appliances are intended to be used.

As described in [30-34] some important details of some of the above surveys are described in Appendix B1. There is also a pilot survey done as part of this Thesis in which the details are given in Appendix A9.

In order to describe PQ surveying and reporting, it is also necessary to review existing and developing standards in power quality monitoring. This will be addressed in the next sub section.

2.3 POWER QUALITY STANDARDS

2.3.1 Introduction

Power quality monitoring and reporting needs to be consistent with existing and developing international practices to allow comparisons with international performance levels. Having recognised the importance of developing standards aiming at ensuring compatibility between the supply networks and customers' electrical equipment connected thereto, IEC has developed a concept defined for Electromagnetic Compatibility (EMC) standardisation for more than a decade ago. Majority of the contents of IEC structure have been widely known to the industry in one form or another. Much of the material contained in the IEC series of standards were adopted from standards and guidelines developed by individual countries. Some of the other organizations who have developed their own standards are CENELEC, UIE, IEEE, ANSI, NEMA. In Australia most of the PQ standards are adopted IEC standards.

2.3.2 IEC Standards on Electromagnetic Compatibility (EMC)

EMC is the ability of equipment or systems to function satisfactorily in their electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment [35].

The IEC 61000 series technical reports and standards are intended to ensure electromagnetic compatibility with signals originating in:

(i) The electricity connection to the mains

(ii) Connections to other equipment by signalling, instrumentation and control lines

(iii) Stray fields due to electrical equipment

To enable the above criterion, following concepts have been established which are illustrated in Fig 2.1.

2.3.2.1 Compatibility Level

This is the reference value of a specified disturbance used for co-ordinating the emission and immunity of equipment connected to a supply network in order to ensure the EMC in the whole system. Compatibility levels are generally based on 95% cumulative probability levels of the entire system considering both space and time variations of disturbances.

2.3.2.2 Planning Level

This is the level of a specified disturbance that is used for planning purposes when determining the impact on the supply system of consumer loads. Planning levels are specified by the utility for all steady state voltages except for LV and are equal to or lower than the compatibility levels. Planning levels depend on network configuration and design and so will vary from one part of the system to another.

2.3.2.3 Emission Limit

This is the maximum permissible level of a given disturbance emitted from a particular device or system.

2.3.2.4 Immunity Limit

Please see print copy for Figure 2.1

Figure 2.1. The compatibility level defined for LV and MV networks [36]

This is the minimum level of a given disturbance, incident in a specified way on a particular device or system, at which no degradation of operation occurs.

2.3.3 IEC Standard/ Technical Report Structure

IEC has defined a category of EMC standards and technical reports that deal with power quality issues. The term electromagnetic compatibility includes concerns for both radiated and conducted interference with end-user equipment. The IEC standards and technical reports are broken down in to six parts [1] as given in Appendix B2.

The majority of the standards concentrate on the emission limits and susceptibility of a particular type or class of equipment or appliance under certain environmental conditions. In addition to the IEC EMC series, the most widely referenced standards or guidelines are EN 50160 (CENELEC) [11], IEEE Standard 1159 [12] and CBEMA/ ITIC [18,20,39,40] voltage tolerance curves. A brief description of relevant standards and guidelines are given in the sections to follow.

2.3.4 EN 50160 (CENELEC) Standard

EN 50160 [11] is a European standard which deals with supply quality requirements for European utilities. EN 50160 [11] was approved by the European Committee for Electrotechnical Standardisation (CENELEC) in 1994. The standard defines specific levels of voltage characteristics that must be met by utilities and methods for evaluating compliance. EN 50160 [11] specifies voltage characteristics at the customer's supply terminals or in public LV and MV electricity distribution systems under normal operating conditions. In other words, EN 50160 confines itself to voltage characteristics at the PCC and does not specify requirements for power quality within the supply system or within customer facilities.

2.3.5 IEEE Standard 1159

IEEE Standard 1159 [12] was developed to provide general guidelines for power quality measurements and to provide standard definitions for different categories of power quality problems. These definitions provide the basis for a common concept in describing the power quality phenomena. Power quality monitoring equipment can use this concept to correctly differentiate different power quality disturbances. After publication of the basic monitoring guidelines, working groups were established for development of more advanced guides for power quality monitoring following which three working groups were established.

The IEEE 1159.1 Working Group developed guidelines for instrumentation requirements associated with different types of power quality disturbances. These requirements address issues such as sampling rate requirements, synchronization, A/D sampling accuracy, and number of cycles to sample.

The IEEE 1159.2 Working Group developed guidelines for characterising different power quality disturbances. This includes definition of important characteristics that may relate to the impacts of the power quality disturbance characteristics (such as minimum magnitude, duration, phase shift, and number of phases for voltage sags). The work of the IEEE 1159.1 and 1159.2 Working Groups has been combined into a single task force and coordinated with the development on an international standard for characterising power quality disturbances with monitoring equipment – IEC-61000-4-30 [13].

The IEEE 1159.3 Working Group defined an interchange format that can be used to exchange power quality monitoring information between different applications. IEEE developed the COMTRADE format for exchanging waveform data between fault recorders and other applications, such as relay testing equipment. A more complete data interchange format is needed for power quality data, which include power quality characterisation of all disturbance types and their statistical concept development.

2.3.6 Voltage Tolerance Curves

Voltage tolerance curves also known as power acceptability curves [37] are plots of voltage deviation versus time duration. They separate the voltage deviation – time duration plane into two regions: “acceptable” and “unacceptable”. Various voltage tolerance curves exist but the most widely publicised is the CBEMA curve [38]. The CBEMA curve has been in existence since 1970s [39]. Its primary intent is to provide a measure of vulnerability of mainframe computers to the disturbances in the electric supply. However its use has been extended to give a measure of power quality for electric drives and solid state loads as well as a host of wide-ranging residential, commercial, and industrial loads [38]. The CBEMA curve [39] was revised in 1996 and renamed for its supporting organisation Information Technology Industry Council (ITIC) [40].

Please see print copy for Figure 2.2

Figure 2.2. CBEMA Curve [18]

The CBEMA curve and ITIC curve differ in the way the acceptable region is presented. CBEMA represents the acceptable region by a curve, whereas ITIC depicts the region by steps. The guiding principle is that if the supply voltage is within the acceptable limits then the sensitive equipment will operate well. The ITIC curve has an expanded acceptable region compared to the CBEMA curve. Both these curves have been accepted as standards and published in the latest version of IEEE Std. 446 [18] and IEEE Std. 1100 [41]. These curves have been used in various PQ studies for discrete disturbance reporting and in the development of PQ indices.

Please see print copy for Figure 2.3

Figure 2.3. ITIC Curve [40]

2.4 POWER QUALITY SURVEYING METHODOLOGIES

Utilities cannot give undertakings to customers without having some idea of the actual disturbances on their systems. This requires monitoring at sufficiently large number of sites to cover the range of circumstances at most sites of the system [42]. Concerned customers might implement their own monitoring programmes to enable them to make cost-effective decisions on the installation of power conditioning equipment.

To allow the results of such PQ monitoring programmes to be analysed effectively and and to maintain consistently between them. There are a number of requirements that need to be satisfied. Few of these important requirements are as follows:

(i) Site selection
(ii) Survey duration
(iii) Measurement methods

2.4.1 Site Selection

The site location and number of monitors is an important question. LV monitoring shows the level seen by domestic customers while MV monitoring emphasises that for large industrial and commercial customers. MV monitoring appears to be the favourite choice of overseas surveys, presumably because one site covers many customers. However, some PQ disturbances that originate in LV system are attenuated at MV [29].

The question of the number and location of PQ monitors is a difficult one. The present incentives for PQ monitoring are not strong enough to encourage a through monitoring program that will handle the needs of all customers. Any attempt to determine the PQ seen by the numerous and widely scattered domestic and rural customers must inevitably be obtained from a sample of sites. This means that the PQ seen by many individual customers will remain unknown, but a measure can be obtained of the overall utility performance provided the monitored sites are selected without bias. In some countries regulators ask for results for a small number of sites, which are chosen randomly and changed regularly [21]. This reduces the cost of instrumentation and should give a detailed view of the system over time. The minimum number of sites to be used can be estimated from factors involved in determining PQ levels. Customer type is one factor, comprising industrial, commercial, residential, rural and remote. There should be a selection of sites chosen to give both average and worst case PQ levels [21]. There is a simple method developed in [43, 47] to determine the PQ monitor placements based on a Voltage Disturbance Figure (VDF). The purpose of the VDF is to theoretically determine the optimal sites for monitoring power quality data within a distribution system when the number of instruments is limited. However this method is applicable to the measurement of continuous or variation types power quality disturbances only.

2.4.2 Survey duration

Monitoring is essential over a year to obtain the full effect of seasonal variations [44], especially with respect of sags due to lightning. In the case of harmonics, it can be less but should cover at least a week and include all significant possibilities of line outages and capacitor bank connections [45]. Ideally, the survey duration should be one to two years [46]. If possible, a minimum survey period of a month should be used for continuous disturbances since there can be combinations of public holidays, abnormal weather, strikes etc which might make a particular week atypical [21]. The discrete disturbances are very dependant on weather conditions and a year is recommended as the minimum period.

2.4.3 Measurement methods

The measurement methods used in the literature reviewed which have spanned over the last two decades or so, have varied depending on the requirement of the PQ monitoring programme. The first consideration to be emphasised by the literature is the type of monitoring equipment used [47]. It is important to calibrate the PQ monitors before being used in the monitoring location.

The IEC Standard IEC 61000-4-30: 2007 [13] brings together recommended practices for measurement of conducted PQ disturbances in 50/60 Hz a.c. power systems. It is this standard that is recommended as a basis for PQ measurements. The standard is meant to be a guide and aims to describe measurement methods that give accurate and repeatable results regardless of the compliant instrument used. The standard itself is a performance specification for instruments, not a design specification, performance requirements being determined by a series of accuracy tests. The effect of transducers being inserted between the power system and the instrument are discussed superficially in an appendix of the above standard.

For each PQ disturbance, two classes of measurement performance are defined, Class A and Class B. The standard states that Class A performance should be used where precise measurements are required e.g. for contractual applications, verifying compliance with standards, resolving disputes, while Class B performance can be used when high accuracy is not required e.g. troubleshooting applications. For the purposes of network surveys and monitoring, Class A instruments should be used so that reference to limiting values from appropriate standards can be made with confidence. For Class A instruments, a basic time interval of 10 cycles is specified for measuring voltage magnitude for continuous disturbances for 50 Hz systems. These 10-cycle values are aggregated over three different time intervals, namely 3 seconds, 10 minutes and 2 hours, using the square root of the mean of the squared input values. There is a concept of “flagging” that the standard introduces for Class A instruments. This aims to avoid a single disturbance event being counted more than once in different PQ disturbances. Flagging is only applied to continuous PQ disturbance values and is triggered by sags, swells and interruptions i.e. continuous PQ disturbance values should not be used for assessment purposes if sags, swells or interruptions occur during their aggregation time interval.

2.5 POWER QUALITY REPORTING METHODOLOGIES

2.5.1 Overview

Irrespective of the sources of power quality disturbances, power quality standards state that utilities are responsible for controlling their power quality levels and ensuring that they do not exceed the limits of acceptability [9,10]. This has been reinforced by the regulators who are beginning to ask the utilities to demonstrate that their PQ levels are acceptable [21]. As a result, utilities have taken initiating to set up permanent power quality monitoring systems at representative sites with communications to central database where they analyse and prepare reports for regulatory reporting. Some regulators are now requiring the annual reporting of some PQ performance parameters.

2.5.2 Present PQ reporting practices

The emphasis has been on the detailed reporting of a few disturbance types which experience over the years suggests that could be capable of causing the observed problems. Current is usually monitored to help assess the source of disturbances. There is no strong need to have very consistent measurement practices with every investigation. In contrast, reporting practices usually involve the measurement of voltage disturbances only. This is for the disturbance types of interest to the utility, i.e. it may be harmonics, sags or any other disturbance for a particular site that may be of giving problems [21]. These power quality reporting practices are different from country to country and some times it is different from organisation to organisation. Some preferred to use graphical reporting formats while others use figures or numbers by means of power quality indices. As examples, some of the selected well known methods of reporting for power quality disturbances which are being used around the world are given below.

2.5.2.1 Graphical reporting formats

Graphical formats have been used by many utilities around the world to provide useful information on network power quality monitoring to report their customers, regulators and in relation to internal maintenance and planning practices. Given below are some examples where power quality reporting in power systems is implemented. Figures 2.4 – 2.7 give some well known graphical interpretations used for voltage sag reporting where as Figures 2.8 and 2.9 would give some of harmonic reporting examples used by the utilities around the world.

Please see print copy for Figure 2.4

Figure 2.4 CBEMA/ITIC magnitude duration scatter plot [1]

Please see print copy for Figure 2.5

Fig. 2.5 Sag and interruption rate by month and magnitude histogram, treated by sampling weights, a PQ survey 24 utilities in USA [50]

Please see print copy for Figure 2.6

Fig. 2.6 Sag and interruptions below 90 and 70% voltage per site per year, treated by sampling weights, a PQ survey 24 utilities in USA [51]

Please see print copy for Figure 2.7

Fig. 2.7 EPRI 3D Histogram for voltage sag magnitude/duration/event count [52]

Please see print copy for Figure 2.8

Figure 2.8 Histograms of CP95 value for voltage THD [48]

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Figure 2.9 Individual harmonics and SATHD values at monitoring sites in USA [49]

2.5.2.2 Power quality indices

Power quality indices aim to quantify certain aspects of service quality of power supply and are being used by utilities for system benchmarking, customer benchmarking services, internal maintenance and operational planning.

There are many power quality indices which have been developed in many countries for power quality reporting and use by many utilities around the world. Some examples include Canadian Electricity Association (CEA) approved quality indices [6,53], CIGRE/ CIRED joint working group C4.07 recommended power quality indices [53], Electricity De France (EDF) certified power quality indices [54], Electric Power Research Institute (EPRI) power quality indices [35,37] , University of Wollongong (UOW) sag index [66].

2.5.2.3 Existing Indices

Harmonics

As described in the Joint Working Group CIGRE C4.07/ CIRED final report [53], obtaining harmonic indices consists of a number of steps: obtaining the spectrum of voltage or current over a given window of time; obtaining a site index from the spectra over a given period; and eventually obtaining a system index from the site indices. Various methods for obtaining the spectrum are being discussed in the technical literature, but the method almost exclusively used in power quality monitoring is the Fast Fourier Transform (FFT).

A number of international standards define the measurement process, including IEC 61000- 4-7 [55], and the recent 61000-4-30 [13].

The method proceeds as follows:

- Obtain the spectrum over a 10-cycle (50 Hz systems) or 12-cycle (60 Hz systems) window. The window shall be synchronized to the actual frequency during the measurement;
- the spectra are combined (RMS) to a spectrum over a 3-second interval (150 cycles for 50 Hz systems and 180 cycles for 60 Hz systems) and the so obtained values are referred to as ‘’very short time’’ indices;
- the 3-second values are combined to a 10-minute value and referred to as ‘’short time’’ indices;
- 3-second and 10-minute values are evaluated over a one-day or a one-week period depending on the index.

The 95%, 99% or maximum values of the distributions are used as site indices.

Table B1-B3 in Appendix B provides a summary comparison of harmonic indices used in standards and guidelines. It shows that in most cases the reference standard to perform harmonic measurements is IEC 61000-4-7 [55].

Practically, the most common index for harmonic voltage is the so-called short time or 10-min value. It is used mainly for voltage characteristics and the level of harmonics to be compared with the objectives is usually the value corresponding to 95% probability of weekly statistics.

Flicker

Publication AS/NZS 61000.3.7:2001 (IEC 61000-3-7:1996) [9] refers to IEC 61000-4-15 [15] (formerly IEC 868) for measurements. The minimum measurement period should be one week. For flicker, indices should be:

1. P_{st} 99% weekly;
2. P_{lt} 99% weekly.

Standard IEC 61000-4-30 [13] also refers to standard IEC 61000-4-15 for flicker measurement (Class A performance). Voltage sags, swells, and interruptions may cause P_{st} and P_{lt} values to be flagged so that they can later be removed from statistics. The minimum assessment period should be one week.

In CENELEC EN 50160 [11], the index to be used is the weekly 95 % P_{lt} value. A number of other regional or national standards and guidelines such as NRS 048-2:2003 [21], Emeraude contract [56], ER P28 [57]. Voltage Characteristics [58] also recommend indices, some of which are similar to the above. Standard NRS-048-2:2003 [21] also applied a weekly P_{lt} for 95% of the time. High P_{st} values that are known to have occurred at the time of a voltage sag should be removed from the data.

The Emeraude contract specifies that the flicker measurements should be carried out according to IEC 61000-4-15 (formerly IEC 868) [15]. No further specifications are given.

Table B4-B5 in Appendix B provides a summary comparison of flicker indices used in various standards and guidelines. It confirms that the most common reference for flicker measurement is basically IEC 61000-4-15. The 95% or 99% weekly values of P_{st} or P_{lt} indices are mostly in use.

Unbalance

For a three phase system, the degree of the inequality should be expressed as the ratios of the negative or zero-sequence components to the positive-sequence component. Only the negative-sequence component is addressed in most cases as it is the quantity of most concern [53].

Only the fundamental components shall be used: all harmonic components should be eliminated e.g. by using DFT (Discrete Fourier Transform) algorithm. Further processing is defined in a similar way as the harmonic indices discussed above: from 10-cycle (50 Hz) and 12-cycle (60 Hz), to 3-second intervals, to 10-minute intervals. 2-hour values (obtained by combining 10-minute values) are also used. The measurement and evaluation procedure is defined in detail in IEC 61000-4-30. In CENELEC EN 50160 the unbalance index is the 95 % 10-min mean rms value of the negative phase sequence component of the supply voltage to assessed over a one week period. Cigre 1992 paper 36-203 [59] is a result of the work done within WG 36.05; it was among the first to propose indices for unbalance as given below.

- At the end of the total observation period (at least a few days including a week-end, preferably one week), the greatest 95% probability daily value of the 3-second index shall be compared;
- One additional criterion was left under consideration, waiting for more field experience: the greatest daily value of the maximum rms value over 10 min periods to be compared.

National standard NRS 048-2:2007 states that for each phase, the highest 10 minute root-mean-square (rms) value which is not exceeded for 95 % of the week is noted. The assessment period shall be a minimum of 7 continuous days.

Table B5-B6 in Appendix B summarises the indices relevant to negative sequence voltage unbalance factor. It can be seen that 10-min values are most commonly in use. Although different equations may be used for calculating the voltage unbalance factor, results should be similar for a given integration time provided they consider negative sequence voltage. Other approximations such as NEMA [60] formula based on the maximum difference between the phase-to-neutral voltages may give poor approximations especially if zero-sequence is not extracted.

More accurate formulae are given in [13] and [14] for calculating voltage unbalance factor using only the magnitude of the phase-to-phase voltages.

Voltage Sags (Dips)

Where it is possible to evaluate system performance against a harmonic, flicker, or unbalance index over a relatively short time period (e.g. a week), voltage sag performance must be evaluated over a longer period of time (at least one year) [53].

Voltage sags with a retained voltage below a threshold (typically 10% of declared voltage, sometimes lower) prescribed in a number of international standards and guidelines are referred to as short interruptions.

- IEC 61000-4-30 [13] provides the first international definition and measurement method for the most common characterisation of voltage sags (i.e. in terms of magnitude and duration). For the measurement of sags, IEC 61000-4-30 states that "the basic measurement of a voltage sag and swell shall be $V_{rms(1/2)}$ on each measurement channel ($V_{rms(1/2)}$ is "the value of the rms voltage measured over one cycle and refreshed each half cycle'' (refer to class A measurements)).

A voltage sag is characterised by a pair of measured data, either retained voltage and duration or depth and duration:

- retained voltage is the lowest $V_{rms(1/2)}$ value measured on any channel during the sag;

- depth is the difference between the reference voltage and the retained voltage. It is generally expressed as a % of the reference voltage;
- duration of a voltage sag is the time difference between the beginning and the end of the voltage sag.

The choice of a sag threshold is essential for determining the duration of the event. This choice of threshold is also important for counting events, as events are only counted as voltage sags when the rms voltage drops below the threshold. Sag threshold can be a percentage of either nominal or declared voltage, or a percentage of the sliding voltage reference, which takes into account the actual steady state voltage prior to the occurrence of a sag. The user shall declare the reference voltage in use. Voltage sag envelopes may not be rectangular. As a consequence, for a given voltage sag, the measured duration is dependent on the selected sag threshold value. The shape of the envelope may be assessed using several sag thresholds set within the range of voltage sag and voltage interruption threshold detection. The latter concept also called ‘’Time Below Specified Voltage Threshold’’ is presented is discussed in detail in [62]. In the latter method, characteristics are no longer determined for each individual event, but the rms voltage versus time curves are directly used to obtain a so-called “voltage-sag co-ordination chart”. The method in [62] can be seen as a generalised version of the method proposed in [61]. Finally, the University of Wollongong (UOW) approach [66] proposes a method giving a better discrimination between sags lying near and far from the CBEMA curve. A series of contour lines is produced by scaling the CBEMA curve and allocating a CBEMA Number (CN) to each one.

A number of other characteristics for voltage sags is mentioned in an annex to IEC 61000-4-30 including phase angle shift, point-on-wave, three-phase unbalance, missing voltage and distortion during the sag. The use of additional characteristics and indices may give additional information on the origin of the event, on the system and on the effect of the dip on equipment. Although several of these terms are used in the power-quality literature there is no consistent set of definitions.

The IEC 61000-2-8 [16] also refers to the IEC 61000-4-30 for measurement, but introduces a number of additional recommendations for calculating voltage-sag indices. Recommended values are 90% and 91% for dip-start threshold and dip-end threshold, respectively, and 10% for the interruption threshold. Sags involving more than one phase should be designated as a single event if they overlap in time.

2.5.2.3 Existing Disturbance Limits

Continuous disturbances limits

Steady state voltage

EN 50160 defines the characteristics of the supply at a customer's terminals under normal operating conditions, given limits for the LV supply voltage as 230 ±10% and states that "under normal operating conditions, excluding voltage interruptions, during each period of one week 95% of the 10 minute rms value of the supply voltage shall be within the range Vn ±10%". EN 50160 therefore permits a variation outside the stated limits for a total of 504 minutes in any one week.

The British Electricity Supply Regulations, in line with European harmonisation, the normal supply voltage in Great Britain was changed from 240 Volt ±6% (i.e. 225.6 Volt to 254.4 Volt) to 230 Volt +10%, -6% (i.e. 216.2 Volt to 253 Volt). The allowable voltage limits are thus wider than allowed before but the upper limit has been lowered slightly. Revisions to above are now covered by the new IEC 60038: 2008 [23] standard.

A new Australian standard was introduced in 2000, i.e. "AS 60038 – Standard Voltages" an adopted version of the IEC 60038: 1983 which is soon to be replaced with new IEC 60038:2008 [23]. However, Australia may choose a separate Power Quality standard for 230/400V standard voltages [80] in the near future. It is intended that the nominal supply voltage would be 230/400, 10% to -6%, but allowing a utilisation voltage drop of 5%, as determined in AS 3000 (Australian Wiring Rules).

Unbalance

The voltage unbalance limits are expressed as a percentage magnitude of the ratio of the negative sequence component to the positive sequence component. According to CENELEC EN 50160 [11] limits for voltage unbalance state "under normal operating conditions, during each period of one week, 95% of the 10 minute mean rms values of the negative sequence component of the supply voltage shall be within the range 0 to 2% of the positive phase sequence component. In some areas unbalances up to 3% occur". Similarly, IEC61000-2-2 [84] and IEC61000-2-12 [14] give the compatibility level for voltage unbalance on LV and MV systems as 2% (3% for special loading conditions e.g. where there is a practice of connecting large single phase loads). Also, a comprehensive discussion on unbalance is given in IEC 61000-3-13:2008 [87] which is available as a published IEC technical report.

Flicker

CENELEC EN 50160 [11] defines and describes the main characteristics of the voltage flicker at the customer's supply terminals in public low voltage and medium voltage electricity distribution systems under normal operating conditions. The standard gives the limits "under normal operating conditions, and in any period of one week the long term flicker severity (P_{lt}) caused by voltage fluctuation should be ≤ 1 for 95% of the time. IEC 61000-3-7 [10] compatibility levels are generally based on the 95% probability levels (See Appendix A.3 for details)

Harmonics

Compatibility levels for voltage harmonics are generally based on the 95% probability levels of an entire system using distributions which represent both time and space variation of disturbances. IEC 61000-3-6 [9] specified limits for both harmonics and interharmonics. However, it does not give any details on flicker arising as a result of interharmonics. AS/NZS 61000.3.6 [9], the adopted version of IEC 61000-3-6 [9] gives limits for each harmonic up to the 40th and total harmonic distortion as given in the Table A4.1 (See Appendix A.4). The planning levels are specified by the utility for all steady state voltages of the system and can be considered as internal quality objectives of the utility. Only indicative values are given in Table A4.2 (See Appendix A.4) as per IEC 61000-3-6 [9] as planning levels may differ from case to case, depending on the network structure and circumstances.

In Australia, there is an application guide, i.e. Standards Australia Power Quality Hand Book, HB 264: 2003 [47] which has given a simplified approach as to how to apply the AS/NZS 61000.3.6 standard for defining harmonic allocation and planning levels for power distribution systems up 132kV [47].

Discrete disturbance limits

Specific objectives for discrete disturbances are not yet available in any international standard. However, there are only two standards available at national level that describe discrete disturbance limits, i.e. South African PQ Standard [21] for voltage sag limits and Chilean PQ Standard [82] for voltage sags and swell limits. Both these standards have been developed based on their long term PQ monitoring data.

South African PQ Standard (ESKOM):

The South African Standard NRS 048-2:2007[21] was primarily developed by utilities, although the process included customer forums hosted by South African National Electricity Regulator (NER) [83]. In addition to the voltage quality requirements, the standard has prescribed utility voltage sag performance limits. In this aspect South Africa uses a two-dimensional scatter plot of the magnitude of voltage depression versus sag duration to present voltage sag data as illustrated in Fig. 2.10.

Please see print copy for Figure 2.10

Figure 2.10 ESKOM voltage sag characterisation chart [21]

Chilean PQ Standard:

The Chilean PQ Standard DS 327: 1997 [82] gives limits for the number of voltage sags and swells per year in different magnitude and duration ranges in connection with the different standard voltages than ESKOM Standard. However the number of sags per year is the same sag count as in the superseded ESKOM Standard as illustrated by Fig. 2.11 and Table 2.1.

Please see print copy for Figure 2.11

Figure 2.11 Chilean standard sag charts [82]

Table 2.1 – Chilean sags/ swells characterisation method [82]

Please see print copy for Table 2.1

2.6 CONCLUSION

This chapter has presented a comprehensive literature review on existing methods of power quality surveying and reporting practices in relation to a number of countries who seem to use IEC/ IEEE approaches or have developed their own approaches. The literature review suggested that there has been considerable amount of work on the characterisation of continuous or variation type disturbances. However, there are no generally acceptable methods of characterisation of discrete or event type disturbances. Furthermore, there is no consistent method of characterising the quality of power supply which will allow different sites within a utility and overall power quality performance of different utilities to be objectively compared. Therefore, the power quality surveying methodologies require extensive research where detail attention is required with regard to data management and reporting. For this, there is a need for a consistent power quality data analysis and reporting structure that can be generalised for all reporting needs.

Next chapter gives a structured approach as a foundation to this problem and the chapters to follow are based on the new framework given. A detailed discussion of power quality disturbance characterisation and indices, new developments and their limitations are also given in the chapters to follow.

Chapter 3

Power Quality (PQ) Data Management and Reporting

3.1 PQ Data Management – A New Structured Approach

As described in the previous chapter, there are many approaches have been given in the literature for how power quality measurements should be processed. However, the PQ data management and reporting is an area that many utilities in Australia and overseas are faced with difficulties, as present reporting practices have many limitations. In this section, a new structure is presented which describes in general terms the data processing stages involved in power quality monitoring and reporting.

The new structure starting with the voltage waveform obtained from the power quality monitor and leading to power quality indices to characterise a particular monitoring site of a utility or an area covering the whole range of sites in a network, is shown in Figure 3.1.

Before discussing the structure of the flow chart in Figure 3.1, some broad concepts need to be made clear. The raw data available is the sampled points of the voltage waveforms from a particular PQ monitor of each site. As the data can originate from monitors having different models of the same manufacturer or from different manufacturers some process is required to convert to a common format.

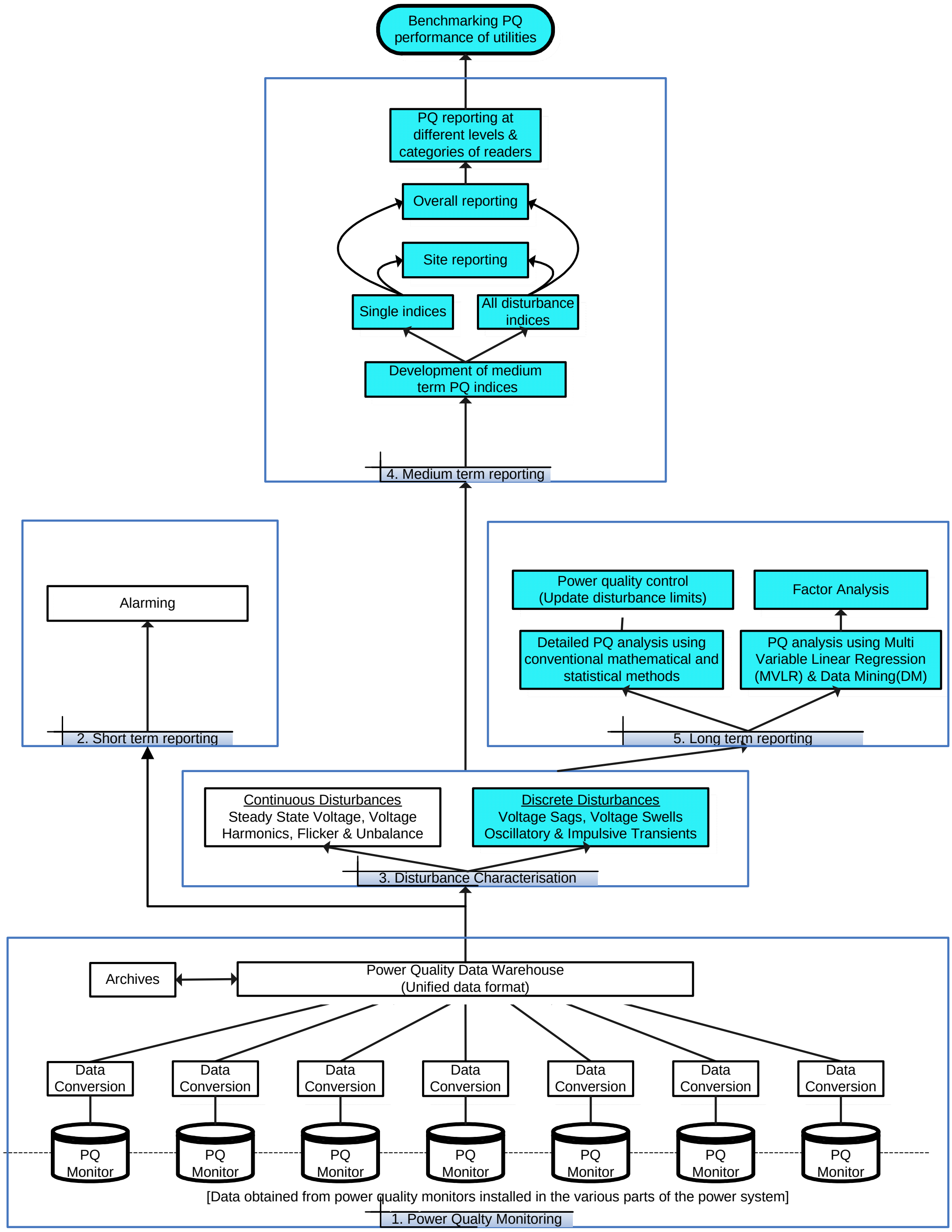


Figure 3.1 PQ data management and reporting structure

The first step in Block 1 (labelled power quality monitoring) of the flowchart is the data conversion. This involves conversion of the data associate with different PQ monitors into a one unified data format and stored in a large data storage facility, i.e. in this case, a power quality data warehouse. The easily accessible stored data contains details such as site number, instrument details, date and time of each disturbance parameter, voltage characteristics and many more.

Three categories can be identified as useful in power quality data management and reporting, i.e. short-term, medium-term and long-term reporting.

Short-term reporting as indicated by Block 2 (labelled short-term reporting), suggests need for immediate alarming to take appropriate corrective action to reinstate the problem site. In most cases it is recommended to perform this within the instrument itself for giving out immediate information to the relevant party for corrective and preventive actions. As shown in the flowchart in Figure 3.1, short-term reporting is performed just after the Block 1, i.e. before proceeding to the Block 3. Noting that short-term reporting is associated with an alarming system incorporated with the instrument, it is therefore not covered in this thesis.

In order to perform medium-term (Block 4) and long-term (Block 5) reporting, there is a need for disturbance characterisation employing the data obtained for the various types of PQ disturbances. This is carried out in Block 3 where disturbances are characterised using the raw data taken from the PQ data warehouse and converting to disturbance indices. Block 3 performs this in two separate ways. Continuous or variation type disturbances are processed separately where parameters corresponding to trends of voltage, unbalance, harmonics and flicker are determined. With discrete or event type disturbances, it produces a date and time stamp and other parameters to characterise each discrete event. In the case of simple rectangular sags, which are balanced across the three phases, depth and duration have been suggested [63]. Transients may be specified by height and effective duration, with perhaps a separate treatment for impulsive and oscillatory types as they affect equipment in different ways. Further work required for characterising discrete type disturbances is covered in Section 3.2 of this thesis.

Medium-term reporting covered in Block 4 is the most general and most regular reporting method in power quality monitoring and data analysis. A power distribution utility may find this objective important, if it has the need to understand its system performance for regulatory reporting, match the system performance in relation to customer needs and compare with other utilities. By understanding the normal power quality performance of a system, a utility can quickly identify the problems and can provide information to its customers to help them match their sensitive equipment characteristics with the realistic power quality characteristics of the power system. The final goal of medium term reporting is to compare utilities for their overall power quality performance for benchmark comparisons. A comprehensive analysis of Block 4 is given in Chapter 4.

Long-term reporting (Block 5) is the highest level of reporting that would lead to many aspects. This includes; update limits and procedures given in PQ standards, understand PQ trends and correlations, predict future PQ problems before they become problems and even forecast power quality. This information is especially important for utilities and regulators when monitoring objectives are intended to address specific power quality problems.

The analysis of long-term power quality data covered in Block 5 has been done in two ways, use of conventional methods and data mining techniques. Detailed insights into long-term reporting are covered in Chapters 5 and 6 of the thesis. This would lead to proper power quality control on equipment maintenance to avoid catastrophic failures, thus preventing major power quality disturbance effects on customer equipment, which ultimately impact on overall PQ performance of the whole power system.

3.2 POWER QUALITY DISTURBANCE CHARACTERISATION

Characterisation of power quality disturbances is aimed at extracting distinctive and pertinent parameters for describing specific waveform characteristics and events. These parameters are useful for power quality reporting, system planning, troubleshooting and system control etc. Particularly, these parameters play an essential role in the equipment sensitivity that aims at improving the immunity or ride-through ability of the loads sensitive to specific types of power quality disturbances [37]. As different types of disturbances require different parameters for description, the waveforms need to be classified before characterization.

There are many different PQ disturbance classification schemes available, for example the one used in IEEE Std 1159: 1995 [see Appendix A.1]. The classification described in this thesis characterise PQ disturbances into “continuous” or variation type and “discrete” or event type disturbances [64] with the disturbances ordered roughly by increasing frequency content in them. Continuous disturbances are present in every cycle to a greater or lesser degree and typically include steady state voltage, unbalance, flicker and harmonics. This disturbance type can be represented by a parameter for every cycle or shown as a trend graph giving the disturbance magnitude as a function of time. The discrete type appears as isolated and independent events. Discrete events can be given as a series of diary entries, where for each date and time-stamped event a captured waveform (rms in case of sags and swells, instantaneous in the case of transients) is given. However, it would be convenient to have one parameter for each disturbance type, that is easy to compare and useful for power quality reporting. The disturbance characterisation scheme given below is aims to give a single parameter for each PQ disturbance type.

3.3 CONTINUOUS DISTURBANCE CHARACTERISATION

Customer equipment do not respond instantaneously to a continuous disturbance over one particular cycle and hence the cycle-by-cycle values would be aggregated into average values for longer periods. IEC standards recognize a number of time scales, which can be used for averaging purposes, of which the very short (3s), short (10 minutes) and long (2hour) are most important [13-16]. The 95% cumulative probability value is commonly used for continuous disturbances. This is the value which is not exceeded 95% of time, in other words it will be exceeded 8.4 hours in a week.

Although values for continuous disturbances can be calculated over each cycle, the majority of standards generally recommend that averaging over each 10-minute interval be carried out. For example the instantaneous flicker sensation level Pf(t) is processed by statistical means to give the short term flicker severity index P_{st} over 10 minutes. It would not be useful to determine steady state voltage, unbalance and harmonics during the period of a sag or any other discrete event, as they are to be represented as unusual operating regimes. For this reason, IEC-61000-4-30 [13] recommends flagging of measurements during voltage sag (dip) events.

3.3.1 Steady state voltage (voltage level)

The utility has some control over the fundamental voltage while the harmonic voltages are the result of loads. It is recommended that the voltage recorded is that for the fundamental value, not the rms value of the total waveform, for each phase. A value should be determined for each 10-minute interval.

In defining an index for steady state voltage (voltage level), the 95% cumulative value would not be applied to voltage level since this will take no account of the separate limits for high and low voltage. This concept is best applied to a parameter which is most acceptable when it is at zero value.

Voltage error is also not appropriate, since positive and negative numbers cannot be combined to give a sensible 95% value. Separate 95% levels for the positive and negative error periods has the difficulty that the 95% period will vary from site to site, depending on whether the voltage is higher or lower than nominal for most of the time. Absolute voltage error would be preferred [76, 77] since its most acceptable value is zero and its 95% value is a good measure of voltage acceptability. Care must be used when the voltage range is unsymmetrical, as with the proposed new LV Australian standard of 230V +10%/-6% [80]. An absolute voltage error based on 230V would not give proper allowance to the larger margin in the overvoltage direction. The absolute error must be taken with respect to the middle of the voltage range, for the above case 234.6V (for new LV voltage standard).

It is recommended that the 95% absolute error be determined for each of the three phases and the maximum of the three is taken.

3.3.2 Unbalance

The IEC definition of voltage unbalance factor (Negative sequence unbalance factor) is the one used as a common practice to define voltage unbalance. As discussed in Chapter 2, Unbalance can also be measured using NEMA definition. However, IEC definition would be preferred in most cases (see Appendix A2 for details).

For index determination purposes, the 95% unbalance factor can be taken with none of the difficulties, which apply to steady state voltage (voltage level). It is to be noted that an assessment is required for sources of error in attempting to meet standards for the measurement and reporting of negative sequence voltage unbalance. A detailed discussion on the sources of errors in unbalance measurements are given in Appendix A8.

3.3.3 Flicker

Australian standards define two factors related to flicker severity; P_{st} and P_{lt} for short term and long term respectively [13] (Refer Appendix A3). Flicker measurement is expensive because the monitor AD converters need good resolution to at least 0.1%, since even small levels of voltage change at 10Hz can cause annoying light flicker.

Since the most common reference for flicker is IEC 61000-4-15 [15] the 95% or 99% weekly values of P_{st} and P_{lt} to be taken as a measure of flicker.

3.3.4 Harmonics

AS/NZS61000.3.6 [9] gives limits for each harmonic up to the 40th and for the total harmonic distortion (THD). Again, there will be a variation between the three phases. For index determination purposes, for each of the 40 harmonic “indicators”, determine the 95% probability level of each 10-minute values of V_{THD} and each harmonic for each phase over a one week. Maximum of phase values is determined for each week and then the maximum of weekly values is taken over the survey period. Measurement and analysis of interharmonics is not well developed and will not be considered in this thesis.

3.4 DISCRETE DISTURBANCE CHARACTERISATION

There is no unified approach for discrete disturbance characterisation found in the literature. Apart from the reporting methods given the previous chapter, some standard characterisation approaches for discrete disturbances are given below. However, a new generalised characterisation method has been developed in Section 3.5 that shows a better way of characterising the discrete disturbances.

A single index needs to be obtained for each disturbance type. One first determines a severity index for each event. For sags, this might be based on a CBEMA number [66]. The severity indices for all sites are summed to give a survey period disturbance index, which is scaled to an agreed period such as one year to give a disturbance index. In principle this approach can be extended to swells and transients.

The results of the above are to determine a single summary index corresponding to each disturbance type for each site. This can be presented as a table of indices for each type, ranked in an appropriate order.

3.4.1 Voltage sags

Balanced rectangular sags can be characterised by the steady state voltage and duration. The maximum voltage depth is taken if the voltage envelope is not rectangular. For unbalanced sags, the phase with the greatest sag depth is used to characterise the disturbance, a process called “phase aggregation” [26].

When there are several sags in quick succession, usually as part of protection operation, these are considered to be part of one customer event. The sag with the greatest depth is taken to be the one used for characterisation. This process is called time aggregation and the aggregation period is usually taken as 1 minute [64]. However, time aggregation is not recommended in IEC 61000-4-30 [13]. The choice of whether to install measuring equipment in line-line or line-neutral depends on the reason for performing sag measurements [81]. Some Australian utilities connect measurement devices to measure line-neutral sags for LV and line-line sags for MV and above. However, there are no rules defined as to how these measurements are performed.

3.4.2 Voltage swells

A voltage swell is described in [37, 40] as an rms voltage rise up to 120% of the nominal voltage, with a duration of up to 1 minute. The swell with the greatest depth can be used as for sags for the characterisation of swells. It is unlikely that several swells will occur in quick succession and time aggregation is not a major issue.

3.4.3 Oscillatory transients

IEC 61000-2-5 [67] classification divides transients into two groups: oscillatory and impulsive. However, there are no standards which completely describe how transients can be measured. Oscillatory transients result from the switching in of power factor correction capacitors and can be characterised by magnitude, oscillatory frequency and decay time.

3.4.4 Impulsive transients

Impulsive transients are mainly due to lightning strikes. Capture of impulsive transient events is difficult because (i) their short duration requires very high speed sampling, (ii) transducer requirements for high frequency transient capture and (iii) their high value (upto 10kV) imposes an enormous dynamic range on the sampling AD converter. Generally monitors with good transient capture ability have a second AD converter just for this purpose and are much expensive. Much work needs to be done on a suitable characterisation method for impulsive transients. One scheme is to use rise time, magnitude and decay time.

3.5 A NEW GENERALISED METHOD OF CHARACTERISATION OF DISCRETE DISTURBANCES

3.5.1 Overview

There is a need for a method based on sound arguments leading to a single meaningful indicator from a disturbance site report, i.e. single site index for each discrete disturbance type. The presently available characterisation schemes do not lead to a single site index for each discrete disturbance type. A new method is proposed in this section to overcome this difficulty that suggests a generalised characterisation approach for all discrete disturbance types based on voltage tolerance curves.

Derivation of all discrete type disturbance indices described here are made on the basis of constant customer complaint contour proportional to the CBEMA or ITIC curve [68]. It is assumed that all events causing identical customer complaint rate can be described by a contour in the voltage – duration plane. Curve fittings to CBEMA curve has been chosen for rms events (sags and swells) as the modern ITIC curve has sudden jumps in this region which are considered to be unlikely to give a smooth contour distribution for sags and swells. However, the modern ITIC curve has been used to characterise oscillatory and impulsive transients.

The method of least squares was applied to the log plot of CBEMA/ ITIC curves to give an analytical expression that could be used for calculation purposes in connection with the curve fittings as shown in Fig 3.2. A brief discussion of all of these indices is given below which is based on the graphical format of discrete disturbances as described in [69].

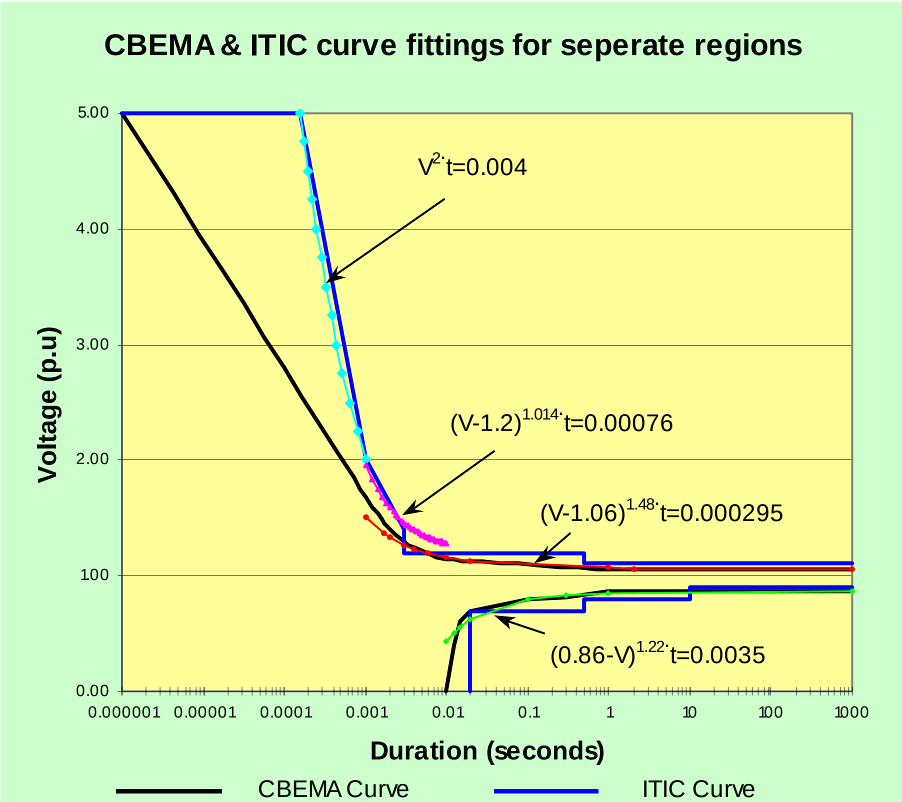


Figure 3.2 CBEMA and ITIC curve fittings for different discrete disturbances

3.5.2 Disturbance Severity Indicator (DSI)

There is a need for a single indicator as a number which gives a relative ranking of discrete disturbances indicating their adverse effects on customer equipment. It can be thought of as a number which gives a measure of the percentage of nominal or specific types of reference customers who are affected.

The DSI is a single indicator to characterise sags, swells and transients which leads to give a single site index for each disturbance type. A description is given below of a standard approach for defining DSIs for all discrete disturbance types.

The following pragmatic assumptions would made to allow an estimation of a contour distribution of each disturbance type:

1) PQ curves used by Reliable Power Meters (RPM) [68, 70] (or CBEMA or ITIC) scaled similarly to the proposal of RPM, represent a locus of constant customer complaint rate (except for the modifications described in 3 and 4 below).

2) The customer complaint rate varies directly in proportion to the RPM index (See Appendix A9 for further details on RPM index).

3) For each disturbance type equipment will begin to fail at their minimum voltage threshold levels (V=0.9 p.u. for sags, V=1.1 p.u. for swells, V=1.2 p.u. for oscillatory transients and V=2.0 p.u. for impulsive transients) and the respective

durations as described in [68].

4) It is assumed that the following V and t values as the maximum thresholds for respective disturbances, Sags; V=0 p.u. t=3s, Swells; V=1.8 p.u., t=3s, Oscillatory Transients; V=2 p.u., t=0.01s, Impulsive Transients; V=5 p.u. t=0.001s and no equipment will survive an event more severe than their maximum threshold.

Based on the curve fittings shown in Fig. 3.2, CBEMA or ITIC voltage ($V_{CBEMA/ITIC}$ or $V_{CBEMA/ITIC}$) can be expressed as,

Voltage sags;

$$\boldsymbol{V_{CBEMA-Sag}(t) = 0.86 - \left(\frac{0.0035}{t}\right)^{(1/1.22)}} \tag{3.1}$$

Voltage swells;

$$\boldsymbol{V_{CBEMA-Swell}(t) = 1.06 + \left(\frac{0.000295}{t}\right)^{(1/1.48)}} \tag{3.2}$$

Oscillatory transients;

$$\boldsymbol{V_{ITIC-Os.Trans.}(t) = 1.2 + \left(\frac{0.00076}{t}\right)^{1/1.014}} \tag{3.3}$$

Following [70], for any point (t, V) on the voltage tolerance plane; we define the CBEMA or ITIC Contour Number (CN) as;

$$CN = \left[\left| \frac{V - 1}{V_{CBEMA/ITIC} - 1} \right| \right] \tag{3.4}$$

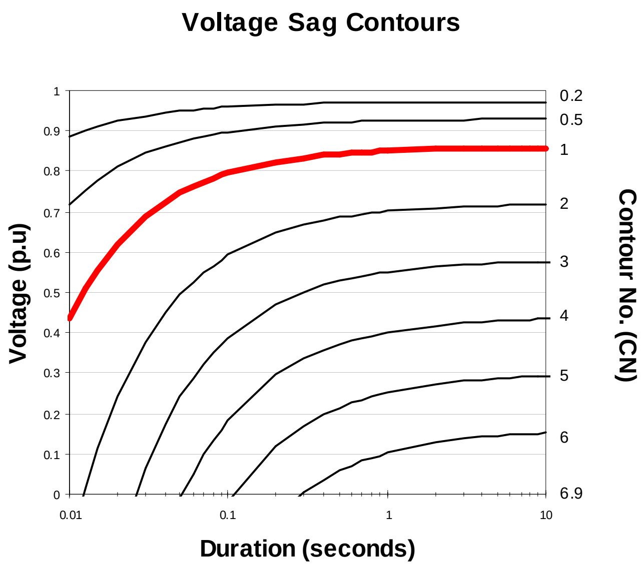


Figure 3.3 Voltage sag contours

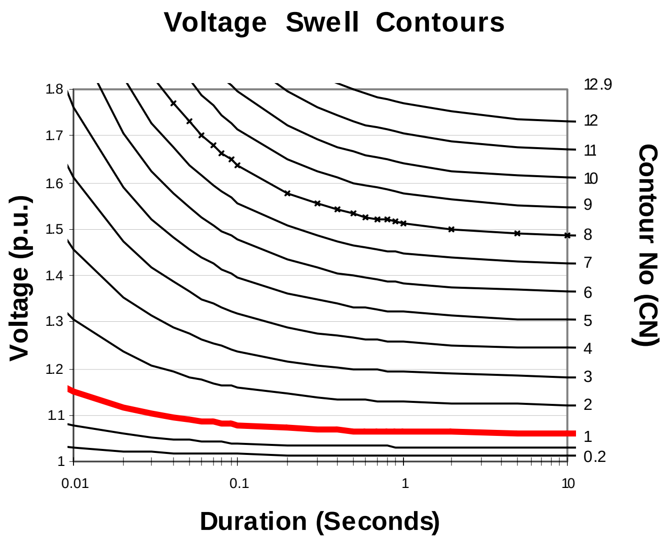


Figure 3.4 Voltage swell contours

Equation (3.4) differs slightly from the method described in [70] as it is preferred to represent voltage in per unit rather than as a percentage. This defines a series of curves which are scaled upwards or downwards as shown in Figures 3.3, 3.4 and 3.5.

These curves have the characteristic that at the worst part of the plane, the CN= 6.9 (V=0 p.u. & t=3s) for sags, CN=12.9 (V=1.8 p.u. & t=3s) for swells and CN=3.6 (V=2 p.u. & t=0.01s) for oscillatory transients.

As described in [71] the contour distribution for impulsive transients (Fig. 3.6) is less complicated and it is given by $V^2 \cdot t / 0.004 = 1$ curve fit (i.e. CN = 1 = $V^2 \cdot t / 0.004$ and below the maximum threshold of 6.2 (V=5 p.u. & t = 0.001s), with an exception to be given in transition region described in the next section. It is assumed that the highest value for CN of each disturbance type corresponds to 100% of customers experiencing problems, and a linear relationship between CN and customer complaint rate. In general, the DSI is taken to be equal to the CN for each disturbance type, but with modifications to allow for assumptions in above 3 and 4 for DSI, together with the transition region.

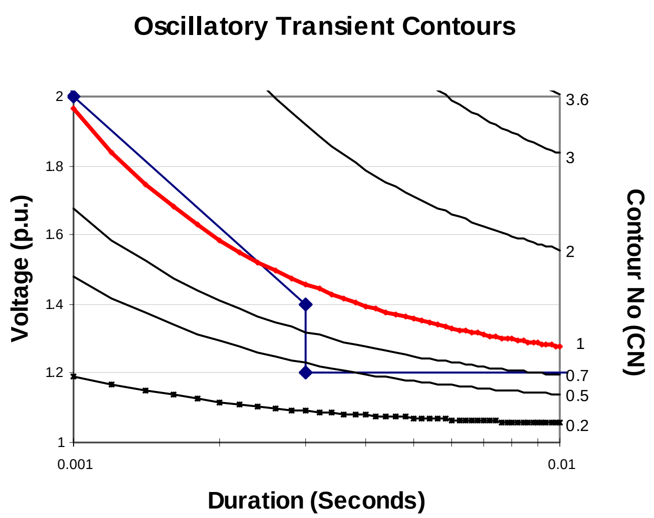


Figure 3.5 Oscillatory transient contours

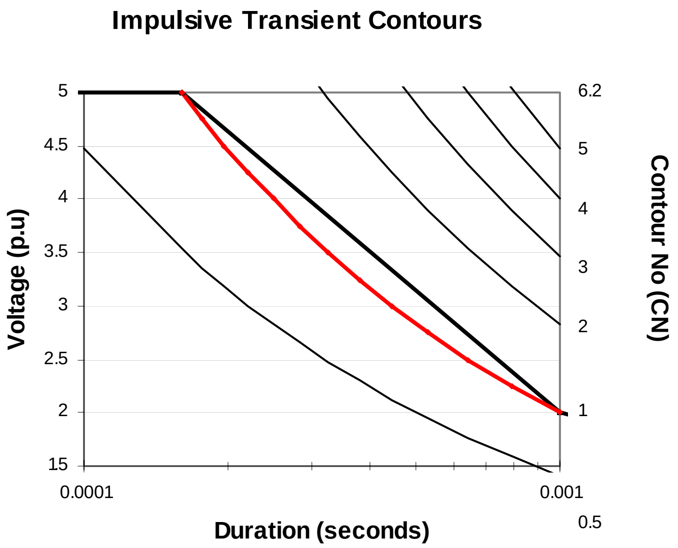


Figure 3.6 Impulsive transient contours

3.5.3 Transition Region

There is a difficulty with PQ monitoring of disturbances that are lying on the border of the set threshold of the PQ monitor [66]. Many such events may or may not be recorded depending on the exact threshold setting of the monitor. This uncertainty can be fixed by adopting a transition region for each disturbance type as is described below.

3.5.3.1 Voltage Sags: In the case of sags, the transition region is defined by assuming maximum threshold for sags is 0 p.u. and of 3 seconds duration as described above. A consideration is given for small sag depths is that; many sag surveys utilise a threshold value of 0.9 p.u. [66]. A difficulty with voltage sags is that a sag on the border of the threshold of long duration could give a CN as high as 0.7.

The transition region reducing the Disturbance Severity Indicator for sags (DSI_{Sag}) from the CBEMA Contour Number to zero linearly in the voltage range 0.8 to 0.9 p.u. by multiplying (5) by the term 10(0.9 - V). Since it is assumed that all equipment has failed at the bottom right hand point of sags in Figure 3.3, where the DSI_{Sag} is limited to the maximum value of 6.9 as described above. The proposed DSI_{Sag} can be written as;

$$DSI_{Sag} = \min\{10(0.9 - V), 1\} \times \min\{CN, 6.9\} \qquad (3.5)$$

3.5.3.2 Voltage Swells: Similar to the case of sags, the transition region for swells is recorded between 1.1 and 1.2 p.u. A similar difficulty arises with swells as with sags that a swell on the border of the threshold of long duration would give a CN as high as 1.95. This can be rectified by multiplying (5) by the term 10(V-1.1). Based on the assumption that all equipment have failed at the top right hand corner point of swells in Fig. 3.4, the DSI_{Swell} is limited to the maximum value of 12.9. The proposed DSI_{Swell} can be written as;

$$DSI_{Swell} = \min\{10(V - 1.1), 1\} \times \min\{CN, 12.9\} \qquad (3.6)$$

3.5.3.3 Oscillatory Transients: Oscillatory transients also can be tackled in the same manner as sags and swells. It is observed that the events which occur at the border of the threshold of short duration would give higher CN values than expected (Fig. 3.5). To be consistent with the sags and swells the value of $DSI_{Os.Trans}$ can be written as;

$$DSI_{Os.Trans.} = \min\{(V-1.2),1\} \times \min\{CN, 3.6\} \tag{3.7}$$

3.5.3.4 Impulsive Transients: The way the transition region described for impulsive transients is different to the method for sags, swells and oscillatory transients. This has been examined in [71] and transition region is defined between 2.0 – 2.3 p.u. and DSI of any impulsive transient event that falls in to this region will be applied with a weighting factor that lies between 0 – 1. As an example let a transient event has V=2.25 p.u. and t = 0.004 seconds where the contour number is $V^2 \cdot t / 0.004$, i.e. $(2.25)^2 \cdot 0.004 / 0.004 = 0.50625$, which is approximately the 0.51 contour. As the event lies in the transition region, it has to be multiplied by the weighting factor $= (2.25-2)/(2.3-3)$ = 0.8333, which gives the $DSI_{\mathrm{Im}.Trans.} = 0.42$.

In general, site index for each discrete disturbance type is calculated as the sum of DSIs over the specified survey period (i.e. generally one year to give an annual site index for each disturbance type).

3.5.4 Illustrative Example

Synthetic data for 4 sites have been constructed by modifying a set of actual data collected over a one-month survey [72] to express the capability of one of the above described indices (i.e. V^2t transient index), for ranking sites on their transient severity as given in the Table 3.1.

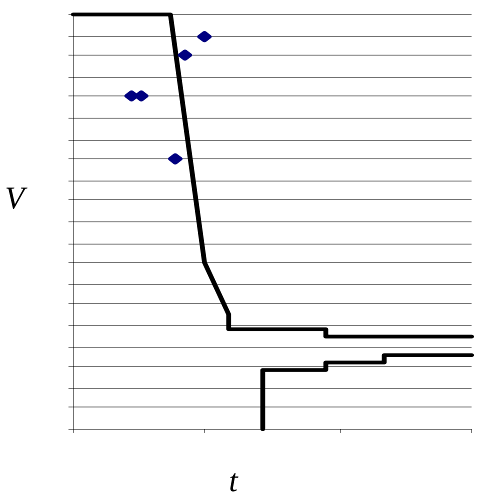
Table3.1 - One month transients survey data of four sites

(Voltage (V) in % and time (t) in seconds)

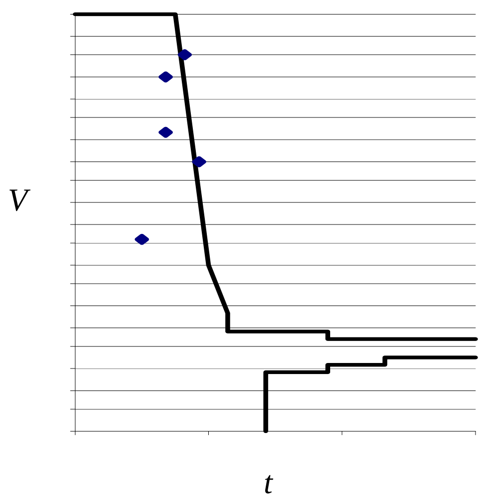
Site 1		**Site 2**		**Site 3**		**Site 4**	
V	**t**	**V**	**t**	**V**	**t**	**V**	**t**
400	.000021	230	.00003	320	.000002	220	.000001
400	.000034	360	.0001	340	.000003	210	.000001
475	.0009	450	.0003	400	.0006	225	.000002
450	.0003	425	.0001	350	.0002	380	.000004
325	.0002	325	.0006	300	.0007	500	.0003

3.5.4.1 Existing Transient Site Characterization Approaches

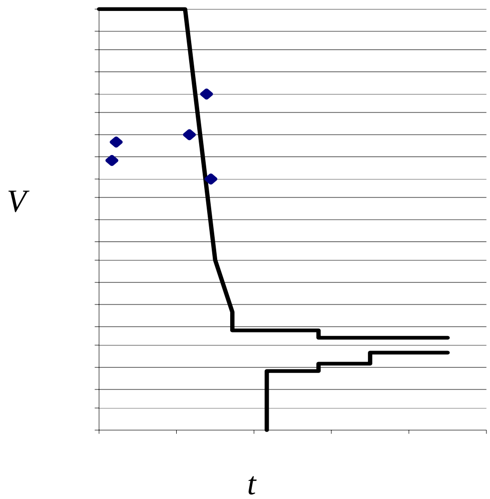
As shown in Figure 3.7, ITIC overlays illustrate one of the site characterization schemes based on event count.



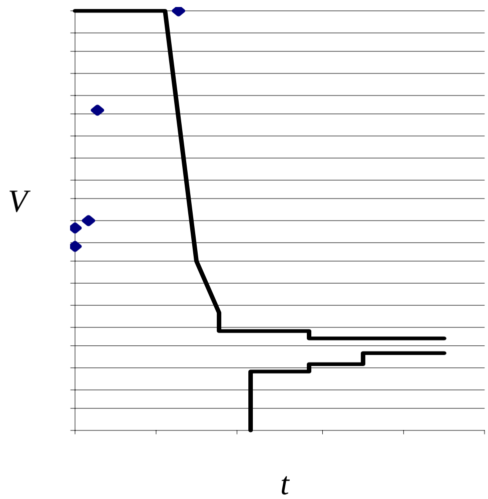
Site 1



Site 2



Site 3



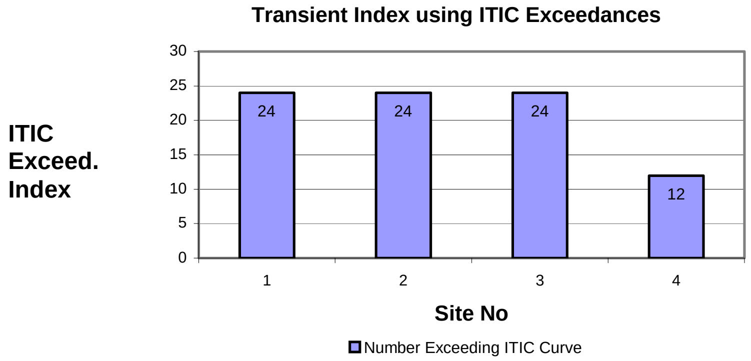
Site 4

Figure 3.7. ITIC overlays of transient data for each site

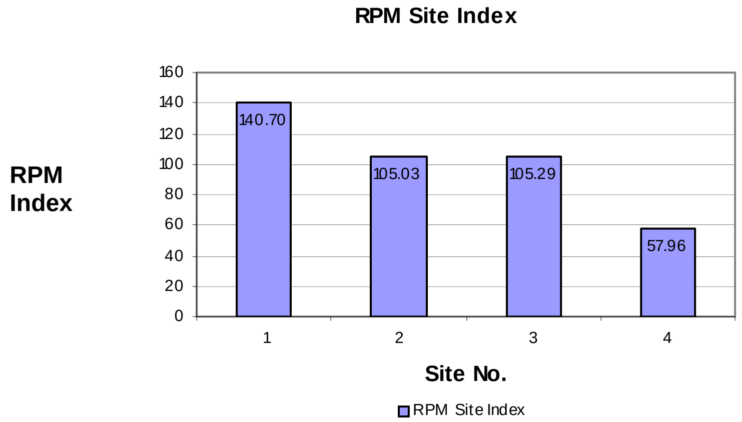
It is seen that the sites 1, 2 and 3 have three transient events within the boundary and two events outside the boundary of ITIC curve whereas site 4 has only one event outside the boundary and all other four events within the boundary. We can only distinguish site 4 from the sites 1, 2 and 3 and no clear differentiation can be found between sites 1, 2 and 3. Therefore, it is clear that one of the existing characterisation schemes using ITIC overlays may not give a clear differentiation of the four sites.

3.5.4.2 Transient Site Index Approaches

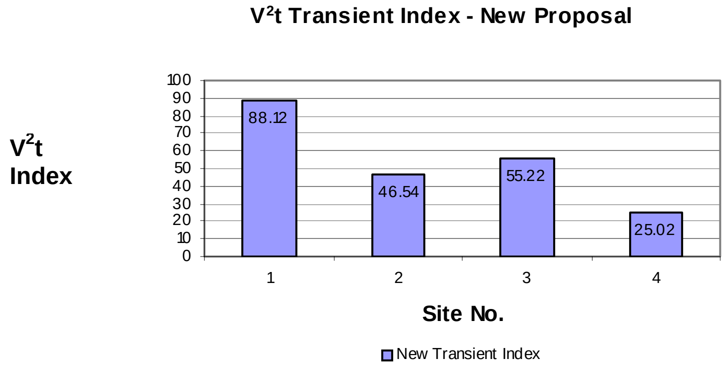
The count of the number of incidents, which exceeds the ITIC curve, is annualised [73] and is shown for four sites by a bar graph in Figure 3.8 (a).



(a)



(b)



(c)

Figure 3.8. A comparison between different transient index characterisations for sites 1- 4. (a)Number exceeding ITIC Curve, (b) RPM site index and (c) V^2t transient index, scaled to one year.

As explained above in relation to ITIC overlays, the sites 1, 2 and 3 have the same

PQ index by this measure where only the site 4 can be ranked against the sites 1, 2 and 3. Therefore, all sites cannot be effectively compared and ranked by this measure. The RPM site index as per the bar graph in Figure 3.8(b) would give a better indication than the ITIC exceedences, but the sites cannot be distinguished effectively.

The Proposed V^2t transient index has been applied to the data and displayed as a bar graph in Figure 3.8(c). This shows the clear distinction between the sites for their transient severity and possible ranking of sites for remedial work.

3.6 CONCLUSION

This chapter described a framework to identify the most important aspects of the PQ data management and reporting. This framework encompasses the whole field of PQ reporting which is the basis of this thesis. The three categories of PQ reporting have been identified as long-term, medium-term and short-term reporting.

As the term suggests the short-term reporting is meant to be short-term alarming where immediate corrective action is required. In most situations this is performed within the PQ monitoring instrument itself, for information dissemination to the relevant party for taking preventative measures.

Medium-term reporting takes care of the most regular reporting in PQ monitoring where utilities need to understand its system performance for regulatory reporting, customer satisfaction and subsequently enables comparison of the system performance with other utilities. An in depth analysis of medium term reporting is given in chapter 4.

Long-term reporting is the highest level of reporting leading to define disturbance limits and procedures given in PQ standards, factors leading to poor or good power quality performance, understand PQ trends and correlations where there are possibilities of forecasting PQ. More detailed analysis of long term reporting are given in Chapters 5 and 6.

This Chapter also comprehensively discussed the disturbance characterisation and determination of a single index for each power quality disturbance type leading to rank sites for particular disturbances. A new generalised characterisation method has been developed for discrete disturbances. This method is based on a Disturbance Severity Indicator (DSI) proportional to the customer complaint rate. Scaled versions of CBEMA and ITIC curve have been used as the working hypothesis. This assumption has been made because a representative set of distribution of customer complaint contours is not available.

The power quality indices developed in this chapter have been applied to representative data of some Australian sites. Analysis of those sites shows a better way of characterising and gives a clearer differentiation of ranking sites for appropriate corrective actions.

Chapter 4

Medium Term Reporting

4.1 INTRODUCTION

This chapter develops a methodology for medium term reporting (refer Section 3.1), i.e. the most general and useful aspect of power quality monitoring and data management. A power distribution utility may find this objective important as it has the need to understand its system performance for many purposes. One purpose is regulatory reporting and the others are customer reporting and utility internal reporting. Customer reporting is there to match the system performance in comparison with the other utilities with the needs of customer expectations. Utility reporting helps prioritise predictive maintenance practices where the appropriate maintenance strategies can be developed based on site performance requirements.

The flow chart given in Figure 4.1 describes medium term reporting which is an extract of the overall reporting structure illustrated by Figure 3.1. By understanding the general power quality performance of a system, a utility can quickly identify the problems and can provide information to its customers to help them match their sensitive equipment behaviour with the power quality characteristics of the power system. Also it can help identify problem sites and prioritise them for appropriate corrective actions. The ultimate goal of the medium term reporting is to compare a utility for its overall power quality performance with other utilities, allowing benchmarking performance across the board.

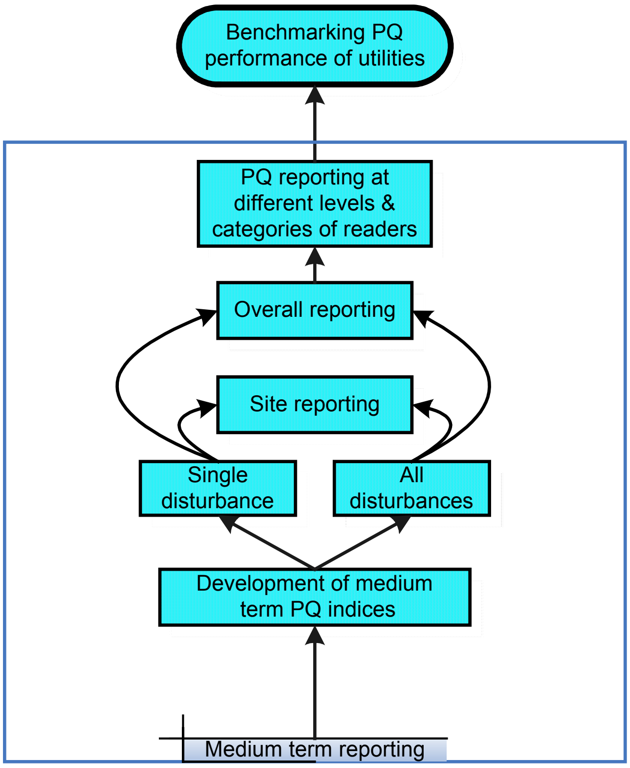


Figure 4.1 Analysis structure for medium term reporting

4.2 MEDIUM TERM REPORTING REQUIREMENTS

4.2.1 Overview

The measurement of power quality for various reporting purposes is not straight forward. There are, for example, different approaches which can be used to measure harmonics and these affect the results, especially when the harmonic levels vary with time. It is important that there be consistency in measurement procedures so that utilities can be compared and best practices be established. Standards are important for specifying consistent procedures for obtaining measurement results such as 95% values of particular harmonics, and/or any other similar measure for all the disturbances.

Another issue requiring standardisation is reporting of a monitoring campaign, particularly where it involves many sites over a period of one year. Summary indices need to be chosen which do not mask important diagnostic details. Additional complications occur when it is desired to make useful comparisons between the monitoring results for several utilities.

Some of the questions that a power quality reporting approach need to be addressed are:

(i) Which sites will need attention as soon as possible?

(ii) What is the likely cause of high disturbance levels?

(iii) Which protection practices are effective in reducing sag activity?

(iv) How does one utility compares with other utility regarding its voltage regulation practices?

(v) What is a suitable limiting value for sags based on a national survey?

(vi) Are there any implications of current or developing standards on the utility practices? As an example, implications of the existing 230V Australian Voltage Standard AS 60038.

The questions such as above can be seen to be classified into two major reporting styles; site reporting and overall reporting. Site reporting gives the detailed behaviour of one site and overall reporting gives a comparison between different sites in one network or comparison between different utilities. However, in practice the division between these reporting approaches is not clear. Nevertheless, this classification has found to be useful in developing the reporting methodology throughout the thesis.

4.2.2 Site Reporting

The aim of site reporting is to give sufficient details about one disturbance at a time for one site that post-mortem investigation and hence a choice of remedial actions can be made. Site reporting is significantly different for continuous and discrete disturbances.

For continuous type disturbances, it is possible to calculate a measure every cycle. Therefore, continuous disturbances can be interpreted as a trend graph that gives the disturbance magnitude as a function of time. However, the time variation of three phases over a long period is difficult to interpret. Therefore, histograms are recommended as being easier to use.

For discrete type disturbances, a scatter graph with a CBEMA/ITIC overlay shows the duration/retained voltage characteristics of each individual event occurring in the monitoring period was shown in Sections 2.5.2 and 3.5.2.

4.2.3 Overall Reporting

Overall reporting aims to give simple site indices for all measurement points, i.e. all sites in the network or a utility, so that the all sites can be prioritised for further investigation. Overall reporting at network level i.e. network reporting [29, 75] needs single site indices that were developed in Chapter 3. Again, the overall reporting can be further extended to compare one utility with others without revealing the site details. However, the overall reporting at utility level, i.e. utility reporting [29, 75], for each disturbance type, a single index can be obtained for the utility by combining the indices for all measured sites.

A utility can be compared with others employing two methods; giving an overall index for one disturbance type or giving an overall index for all PQ disturbances i.e. Unified Power Quality Index (UPQI) for a utility [65,76]. In general, with the overall reporting, the summary indices are used to rank sites, allowing identification of problem sites at the network level. At utility level, reporting gives average performance across many sites and allows benchmarking against other utilities while meeting regulatory requirements.

4.2.4 Data Analysis Triangle

The above proposals result in each reporting style being derived from the data in the previous style. This leads to the data being considered in the form of a triangle with each level being a summary of the information of the level below. Further details of the data structures and their relationships in the triangle are given the next section.

4.3 POWER QUALITY ANALYSIS TRIANGLE (PQAT)

4.3.1 Overview

The Power Quality Analysis Triangle (PQAT) given in Fig. 4.2 has been developed to show the different data types, indices and their relationships arising from utility PQ survey measurements [26, 65]. A brief discussion of the PQAT is given below.

Please see print copy for Figure 4.2

Figure 4.2 Power Quality Analysis Triangle (PQAT) [26]

The base of the triangle is made up of the raw data (Block 1), with an appropriate sample rate; a monitor collecting three phase voltage measurements from a site that may produce 10GB of data or more per week. The lower half of the triangle involves a reduction in the data flow from a site in a series of steps, a process described as ‘time compression’.

The first step is to break up the data into the different disturbance types and characterise each separately (Blocks 2, 3, 4). At Block 6, each disturbance is represented by one index or more indices giving a measure of the disturbance levels over a specified survey period.

Block 7 is the level at which the above indices are compared against the set standard limits to see the severity of the site disturbance levels. At the input to Block 9, each disturbance type is represented by one index, which is a quotient of the measured level and the set limit. These indices are brought together to form one Unified PQ Index for a site (UPQI-S) at Block 9.

The UPQI-S at Block 9 can be incorporated with an intermediate step by defining UPQI-c and UPQI-d to establish an overview of continuous and discrete disturbances separately. Further movement to the top of the triangle involves incorporation of unified PQ indices of larger and larger collections of sites into area and utility indices, a process described as “space compression”. The following sections give further details on time and space compression.

4.3.2 Time compression

At the base of the triangle is Block 1, where the raw data from the sampled points of the voltage at particular site can be found. The disturbance characterisation is the determination of appropriate parameters for each disturbance type. For continuous disturbances, this process is relatively straight-forward, resulting in parameters being calculated for each sampled cycle (Block 2). There is one parameter for each steady state voltage and unbalance, two for flicker (P_{st} and P_{lt}) and many for harmonics (V_2 – V_{40} and V_{THD}).

The procedure for the discrete disturbances is considerably complex as discussed in the previous chapter. Each set of data needs to be compared with a threshold to determine which discrete events are present (Block 3). Block 4 then processes each identified disturbance according to its type and ascribes appropriate parameters. Chapter 3 covered the details of the process on how to determine a single number for each event to give a Disturbance Severity, represented by Block 5. Block 6 calculates a Disturbance Index for each disturbance type to give a measure of levels over the survey period. A site UPQI (UPQI-S) is a single PQ index measuring the overall level of PQ disturbances and is accomplished in Block 9 from the individual disturbance indices. This cannot be simply done on the output of Block 6, as there is more than one number to describe flicker and harmonics. Two intermediate stages shown, as Block 7 and 8 are required to reduce this to one each and this is treated in more detail in a Section 4.3.4.

4.3.3 Space compression

Further data compression is possible to give indices to show the level of PQ over areas of more than one site [74]. It would be useful if this aggregation could be done in a number of stages. A feeder UPQI represents the average PQ along the feeder using the site UPQIs from all monitored sites. Weighting could be applied according to the number of customers or customer kVA, load category, site category and various other factors involved. Feeder UPQIs can be lumped into substation indices, and finally a single index for the utility (UPQI-U). Achieving a single index for a utility is described in Blocks 10 to 13 of PQAT. This index can also be obtained as a single utility index for each disturbance type. Further details on achieving a single utility index for each disturbance type are described in Section 4.4.

4.3.4 Normalisation and consolidation

There is a proposed two-step process involved in the derivation of a single index for each disturbance type where there is more than one indicator per disturbance. The two steps are described as (i) normalisation and (ii) consolidation.

Normalisation, represented by Block 7 in the PQAT, is the process of dividing an index by its maximum acceptable value, i.e. the limit, so that it has the value unity when it is at the limit of acceptability. In the case of the flicker indices P_{st} and P_{lt}, [10] gives limits for 95% cumulative probability (CP) values of 0.9 and 0.7 respectively. For example, if the 95% values of these indices were measured at 0.8 and 0.8, the normalised indices would be 0.89 and 1.14, showing immediately that the P_{lt} value is worse than P_{st}. For LV harmonics the 95% values for V_{THD}, V_2-V_{40}

are normalised by dividing them by numbers ranging from 0.065 to 0.002 as given by the planning levels in [9].

Consolidation combines all the normalised values for one disturbance type into a single index. It is recommended that the maximum value be used – for example, in the above case of flicker, the consolidated flicker index is 1.14. When a similar approach is applied to the 40 harmonic indices, a single “consolidated index” can be determined. This method can be extended in an obvious manner to consolidate the 120 harmonic indices of AS/NZS 61000.3.6 [9] into one index. This method is more comprehensive than that described in [17] where harmonics are represented by an indicator of V_{THD} only.

4.4 UNIFIED POWER QUALITY INDEX (UPQI)

4.4.1 Overview

The disturbance characterisation process in PQAT leads to 48 different annual disturbance indices: voltage (1), unbalance (1), flicker (2), and harmonics (40), voltage sags (1), voltage swells (1), oscillatory transients (1) and impulsive transients (1). The assessment of all these figures over many different sites will be difficult. Normalisation and consolidation (Block 7 & 8 of PQAT) that was described in Section 4.3.4 reduces these 48 continuous disturbance indices (or more depending on the standards used) to four, one for each of steady state voltage, unbalance, flicker and harmonics. However only normalisation is applicable to discrete disturbances (Block 7 of PQAT) as there is only one annual index described for each sags, swells, oscillatory and impulsive transients. Moreover the "normalised" and/or "consolidated" indices have the simple property that their maximum acceptable value is unity. Nevertheless, the assessment and ranking of many sites with each represented by these eight indices will be difficult. Therefore a single number, the Unified power Quality Index (UPQI) for a site (Block 9 of PQAT), is proposed to give a simple measure of its overall power quality and allows ease of site ranking.

There are a couple of intuitive ways of approaching UPQI, involving the average or the maximum of the consolidated indices. There is an intermediate step that can be proposed to give an overall index for each continuous and discrete disturbances i.e. UPQI-c and UPQI-d, which can be later combined to give the same overall UPQI that is scalable [78] in its properties.

4.4.2 Methodology

There is a need to have a clear idea of the purpose of a single PQ index before it can be critically compared with different proposals. It is recommended that the main purpose is to allow the prioritising of sites for power quality improvements. The site which would rank last ought to be the one where customers are having problems with the operation of their equipment. In developing this idea, it is assumed that there is an equal mix of customers having the full range of equipment at each monitored site. It is also assumed that all equipment meet normal equipment emission and immunity requirements. The symbols V, U, F and H are used to represent normalised and consolidated indices for steady state voltage, unbalance, flicker and harmonics whereas symbols Sg, Sw, OT and IT are used to represent the normalised disturbance indices for voltage sags, swells, oscillatory and impulsive transients.

Comparison of some different proposals by assuming the normalised and/or consolidated indices V, U, F and H of continuous type and Sg, Sw, OT and IT of discrete type are given in the Table 4.1, for 3 sites.

Table 4.1 – Example power quality indices

Indices	Sites		
	1	2	3
V	0.6	0.0	0.0
U	0.6	0.0	0.0
F	0.8	1.2	0.0
H	0.8	1.2	1.2
Sg	0.8	0.8	0.4
Sw	0.6	0.0	0.0
OT	0.8	1.2	0.0
IT	0.6	1.2	1.2
$PQI_{Average}$	0.7	0.7	0.35
$PQI_{Maximum}$	0.8	1.2	1.2
$PQI_{Exceedance}$ (UPQI)	0.8	1.8	1.4

One possibility is to use the average of the normalised & consolidated indices, symbolised here by $PQI_{Average}$. This implicity assumes that the effect of power quality is the sum of that of the individual disturbance types, and in particular that excessive disturbances of one type can be mitigated by reducing other types of disturbances.

In Table 4.1 Site 1 and 2 have equal $PQI_{Average}$. At site 1 all disturbances are within the acceptable limits and there should be no difficulty with customer equipment. However, at Site 2, there will be several difficulties such as excessive light flicker, problems with high harmonics affecting capacitors and three phase induction motors, nuisance tripping of Adjustable Speed Drives (ASD) due to oscillatory transients and impulsive transient causing digital equipment errors. Therefore, it is clear that this approach would not give a single index which is useful for ranking the sites.

Another possibility is the use of maximum of the consolidated indices, symbolised here by $PQI_{maximum}$ as used in [77]. This implicitly assumes that the number of customers affected by each disturbance type is identical and independent of the magnitude of other disturbances present. Now, compare the situation at sites 2 and 3 in the Table 4.1, having identical values of $PQI_{Maximum}$. At Site 3, those customers with three phase induction motors will experience additional losses and customers with digital equipment show errors. At Site 2 customers with three phase induction motors and digital equipment will be similarly affected, but in addition there will be customers experiencing light flicker and ASD trips. Therefore Site 2 should be ranked as worse than Site 3. Hence we discount the maximum as a good overall PQ index. However, it can be a good index to check whether regulatory requirements are met as the regulators require which sites are within the limits and which sites are exceeding the limits as specified. Therefore, it could be a good indicator for regulatory reporting.

The proposed alternative index is called the Unified Power Quality Index (UPQI) and is devised to have the following features,

(a) If all consolidated disturbance indices are less than utility, the index should measure the headroom available to the disturbance.

(b) If some disturbance indices are more than unity, the UPQI gives the measure of the combined effect of all the problem indices.

The calculation of the UPQI is conveniently expressed using the concept of

Exceedance, a measure giving how much a disturbance type exceeds the maximum acceptable value. If a PQ index is less than unity, the corresponding Exceedance is zero. If the index is more than unity, the Exceedance is equal to the index minus one. For example, the voltage sags at Site 2 have an Exceedance of 0 while the oscillatory transients at site 2 have an Exceedance of 0.2.

The definition of exceedance based UPQI is as follows,

(a) If all the consolidated disturbance indices are less than unity, UPQI is equal to the maximum of the indices.

(b) If one or more of the indices exceed unity, UPQI equals 1 plus the sum of Exceedances.

One of the convenient properties of the UPQI that follows from its definition is that a value of one represents the limit of acceptability. The two step procedure adopted to combine the indices proposed can be further illustrated as follows,

1. If none or no more than One of V, U, F, H, Sg, Sw, OT, IT > 1

   UPQI = max {V, U, F, H, Sg, Sw, OT, IT}

2. If more than One of V, U, F, H, Sg, Sw, OT, IT >1

   - Define Exceedance (e.g. for V as EV = max {V-1, 0})
   - UPQI = 1+ EV+EU+EF+EH+ESg+ESw+EOT+EIT

The overall index has been calculated and displayed for the three sites in Table 4.1. The UPQI indicates Site 2 as the worst, followed by Site 3, with Site 1 being acceptable as would be felt intuitively. The merit of the UPQI is that it can be applied to hundreds or thousands sites giving a ranking without time consuming human intervention. This would be a very useful method of defining overall power quality index for customer reporting and utility internal maintenance reporting .

The intermediate steps of calculation of UPQI for continuous disturbances (UPQI-c) and UPQI for discrete disturbances (UPQI-d) are as follows,

(UPQI-c):

1. If none or no more than One of V, U, F, H > 1

   (UPQI-c) = max {V, U, F, H, Sg, Sw, OT, IT}

2. If more than One of V, U, F, H >1

   - Define Exceedance

   - (UPQI-c) = 1+ EV+EU+EF+EH

(UPQI-d):

1. If none or no more than One of Sg, Sw, OT, IT > 1

   (UPQI-d) = max { Sg, Sw, OT, IT}

2. If more than One of Sg, Sw, OT, IT >1

   - Define Exceedance

   - (UPQI-d) = 1+ ESg+ESw+EOT+EIT

Table 4.2 shows that the intermediate steps of UPQI-c and UPQI-d also lead to give the same UPQI of the example above.

Table 4.2 – Example for UPQI-c and UPQI-d

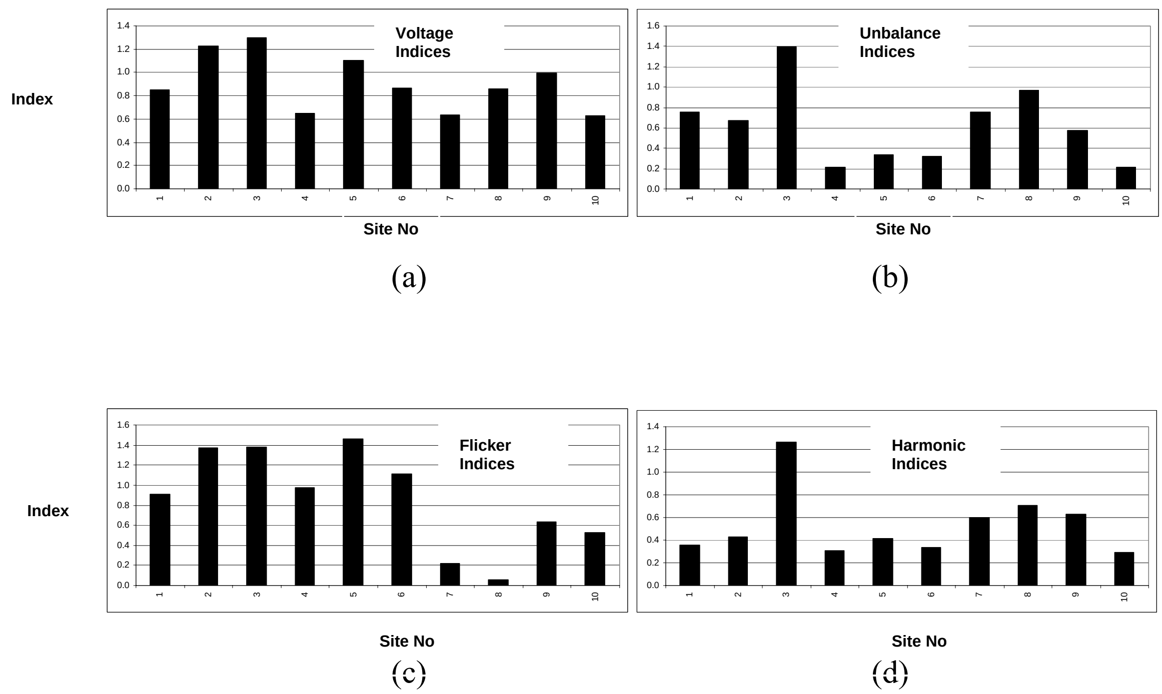
Indices	Sites		
	1	2	3
UPQI-c	0.8	1.4	1.2
UPQI-d	0.8	1.4	1.2
UPQI	0.8	1.8	1.4

4.4.3 Application Example

A set of synthetic data has been constructed for 10 sites by modifying a set of actual data of some Australian sites. However, the impulsive transient data were a modified version of some overseas survey data [79]. The constructed data would have a similar range of variation as actual sites and sufficient to give useful results for the illustration of UPQI.

4.4.3.1 Individual disturbance analysis

Normalised and/or consolidated disturbance indices for all 10 sites for each disturbance type are shown in Figure 4.3.



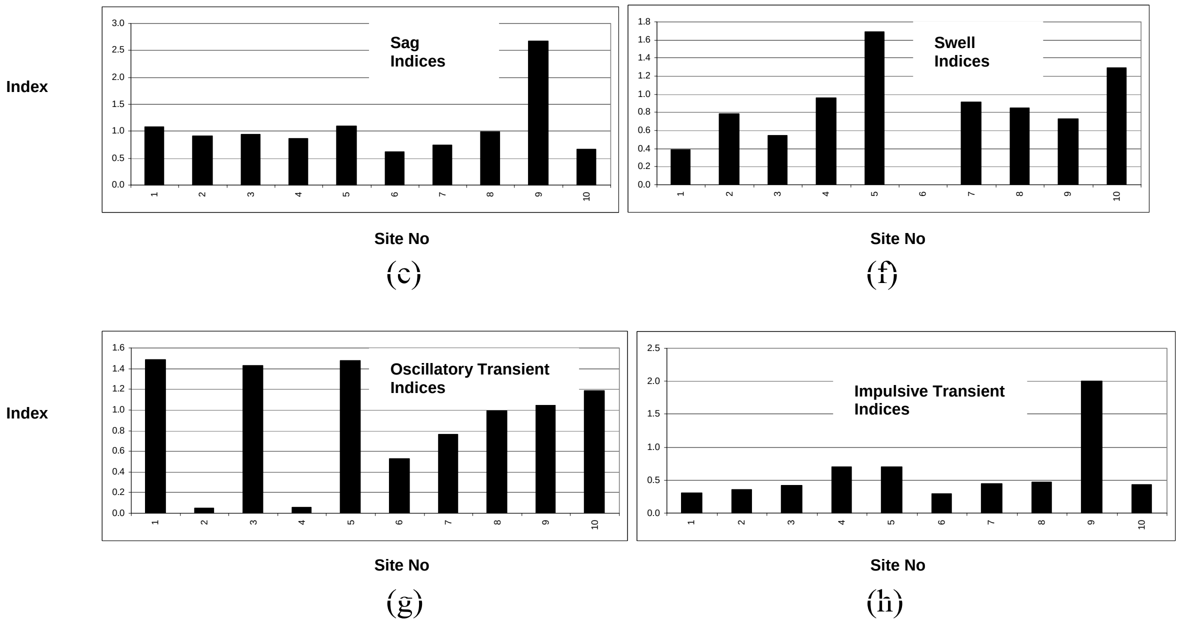


Figure 4.3 Consolidated Indices for Individual Disturbances for all 10 Sites (a) Voltage V, (b) Unbalance U, (c) Flicker F, (d) Harmonics H (e) Sags Sg, (f) Swells Sw, (g) Oscillatory Transients OT, (h) Impulsive Transients IT (Horizontal axis gives site number, vertical axis gives site index)

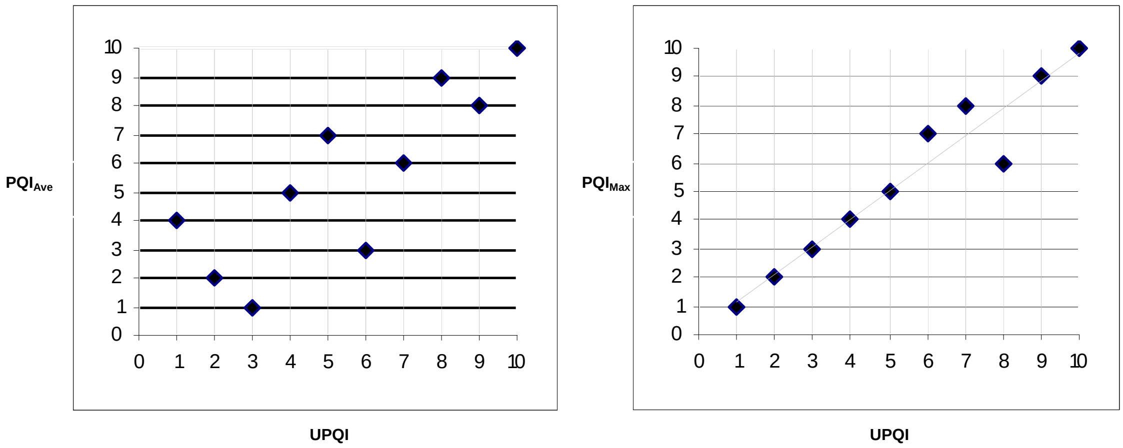
It is seen that the best site for sags is not the best site for harmonics, steady state voltage, flicker, unbalance or transients, and the worst site for transients is not the worst site for sags, harmonics etc. These graphs illustrate that it is not possible to establish a quick impression of the overall level of power quality over the sites by visual inspection.

4.4.3.2 UPQI for the overall PQ condition of site (UPQI-S)

Following [65], the overall PQ index for each site has been determined employing each of the three proposed methods (PQIAverage, PQIMaximum and UPQI). The ranking of the sites has then been determined using each method for all 10 sites.

Table 4.3 – Site ranking based on different algorithms of PQ indices

SiteID	V	U	F	H	Sg	Sw	OT	IT	Ave.	Max	UPQI	Rank Ave.	Rank Max	Rank UPQI
1	0.854	0.756	0.906	0.354	1.076	0.387	1.490	0.308	0.77	1.490	1.566	7	8	6
2	1.229	0.672	1.377	0.431	0.910	0.781	0.047	0.354	0.73	1.377	1.606	5	6	7
3	1.299	1.398	1.379	1.262	0.938	0.543	1.425	0.415	1.08	1.425	2.762	9	7	8
4	0.653	0.216	0.975	0.308	0.861	0.964	0.060	0.708	0.59	0.975	0.975	2	2	2
5	1.104	0.338	1.459	0.415	1.097	1.686	1.479	0.708	1.04	1.686	2.826	8	9	9
6	0.868	0.320	1.115	0.338	0.625	0.000	0.530	0.292	0.51	1.115	1.115	1	4	4
7	0.632	0.759	0.216	0.600	0.736	0.914	0.765	0.446	0.63	0.914	0.914	3	1	1
8	0.861	0.964	0.060	0.708	0.986	0.852	0.992	0.477	0.74	0.992	0.992	6	3	3
9	0.993	0.573	0.635	0.631	2.681	0.730	1.080	2.000	1.17	2.681	3.761	10	10	10
10	0.625	0.213	0.530	0.292	0.667	1.295	1.182	0.431	0.65	1.295	1.477	4	5	5



(a) (b)

Figure 4.4. Comparison of rankings using scatter graph using two approaches (a) PQIAverage vs UPQI, (b) PQIMaximum vs UPQI (Horizontal scale gives rank according to UPQI while the vertical scale gives rank according to the other PQ Index approaches)

Table 4.3 gives a comparison of sites determined by the three methods with rankings given to each site based on all three methods. Figure 4.4 shows a comparison of rankings by means of scatter graphs of ranking by UPQI (horizontal scale) with the ranking by other indices ($PQI_{Average}$, $PQI_{Maximum}$) shown by the vertical scale, based on the results of Table 4.3. It is clear that the $PQI_{Average}$ gives a ranking which is very different from that given by other two PQ indices. The $PQI_{Maximum}$ and UPQI agree for most sites because the two algorithms are equivalent except when a site has two or more disturbances exceeding allowable units. Therefore, $PQI_{Maximum}$ and $PQI_{Exceedance}$ (UPQI) can be considered to be good indices for reporting overall power quality condition of a site.

4.5 BENCHMARKING PQ PERFORMANCE OF UTILITIES

4.5.1 Introduction

Many utilities around the world are adopting the concept of benchmarking power quality. Utilities have realised that they must understand the levels of service quality provided throughout their distribution systems and determine if the levels provided are appropriate. This is certainly becoming more prevalent as many utilities establish contracts with specific customers to provide a specified quality of service. After aquiring the appropriate data, the service provider must determine what levels of quality are appropriate and economically feasible. Increasingly, utilities are making these decisions in conjunction with standards and regulatory bodies. Utilities note that nearly any level of service quality can be achieved through alternative feeders, standby generators, UPS systems, energy storage, etc. However, at some point costs cannot be economically justified and must be balanced with the needs of end users and the value of service to them. Therefore, present system need to be assessed through the PQ monitoring data available. Then it is easy to implement appropriate method of achieving the required level of service quality and prioritise the sites for appropriate actions for the level of service quality to be achieved.

This will give useful insights for identifying suitable area indices (i.e. formation of UPQIs as described in space compression of PQAT for benchmarking power quality performance of utilities. This has been achieved through two different algorithms as described below; (a) benchmarking utilities for single disturbance impact and (b) benchmarking utilities for the impact of overall power quality. This is followed by application examples for each of the method.

4.5.2 Benchmarking Utilities for a single disturbance impact

4.5.2.1 Overview

The basic indicator for single disturbance impact for a utility should be a single parameter for particular disturbance type, aggregated in some way over all the surveyed sites. This parameter would aim to compare one utility with the other, for their overall performance.

As described in [63], most utilities have increased their focus on voltage sags as the sags account for vast majority of recorded equipment trips, therefore voltage sags has been chosen to give an example of benchmarking utilities for single disturbance impact, i.e. a method of formation of a utility sag index to compare utilities for their overall sag performance. However, this concept can be extended to give a utility index for any other single disturbance impact by a slight modification.

4.5.2.2 Voltage sag reporting styles

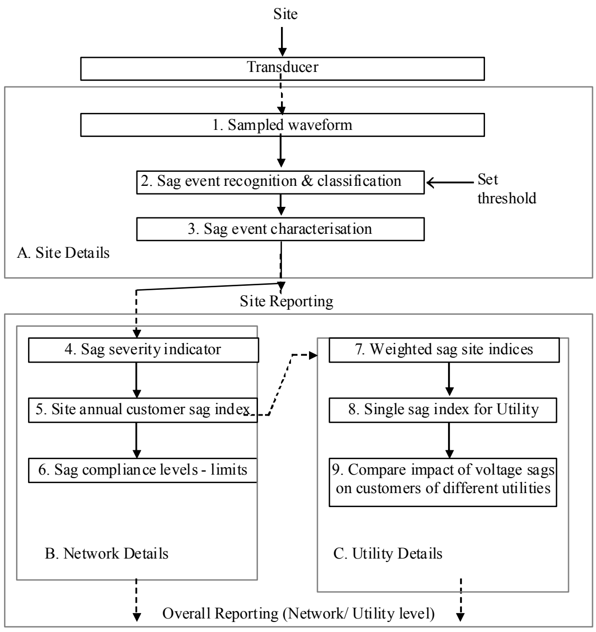


Figure 4.5. Flow chart of voltage sag reporting concepts

In this section a flowchart (Fig. 4.5) is introduced that describes in general terms the voltage sag data processing stages involved in utility surveying, starting with the waveform of the sag event, and then sag event recognition, classification and single sag index determination to characterise the monitored site and the aggregation of site indices to give a utility index.

Following the PQAT described previously, the raw data available is the sampled points of voltage waveforms at a particular site. The first step involves the separation of sag data from other disturbances followed by classification and parameterisation (Blocks 1 & 2). Voltage sag event characterisation is the process of describing a single sag event (output of Block 3). For a three-phase balanced, rectangular sag, it may consist of obtaining the sag voltage and duration. Once the sag events are characterised, a utility needs to prepare information on sag performance levels for several different types of parties, each of which requires a different reporting style. The network planner needs summary information on the worst sites having poor sag performance and the more detailed information on the worst sites to assess what the problem might be. The regulator is not interested in the details of individual sites but requires some type of overall indication of the voltage sag performance of a utility.

Blocks 4, 5 and 6 consist of details which show the summary data for each site so that the compliance levels can be simply checked and problem sites identified. This is achieved by the sag severity indicator (SSI) described in Chapter 3, a single number to characterise the severity of each sag (output of Block 4). All sags with the same sag severity indicator are considered to affect the same fraction of customer equipment at a monitored site. Site annual sag index (Block 5) is a single number to summarise the sag activity at a site over a year obtained by combining together the SSIs of each sag event. Block 6 is the level at which the above sag indices for all sites are compared against the set limits to examine the severity of the site sag levels.

At the input to Block 7 site indices are combined by a simple weighting in proportion to the customer kVA or the customer numbers to give a sag index for the impact of voltage sags on customers (i.e. customer sag index) of a utility (Block 8). The customer sag index for a utility represents an “average site” sag performance to allow overall voltage sag planning effectiveness to be assessed. The customer sag index for a utility will be compared with other utilities (output of Block 9) for benchmarking the impact of voltage sag performance on customers of distribution utilities. A similar flowchart can be formed for all other PQ disturbance types for different purposes (e.g. customer reporting, regulatory reporting and utility reporting etc.). Finally, it leads to the ultimate goal of benchmarking overall PQ performance given to their customers in different utilities.

4.5.2.3 Benchmarking utilities for overall sag performance

Utilities can be compared with regard to voltage sag performance in two ways, both of which are useful for different benchmarking purposes [75].

(i) Benchmarking utilities for the impact of voltage sags on customers

(ii) Benchmarking overall sag performance of a utility

The first approach is that a utility can determine how it performs on its impact of voltage sags on customers relative to another utility, assuming that both have similar types of power systems in terms of load density, external impacts, customers and other related utility practices. The second approach gives a single sag indicator to compare a utility's performance under similar conditions. This task may not be possible until more is understood about which factors contribute to poor or good sag performance. This will be further discussed under Factor Analysis in Chapter 6.

4.5.2.4 Aggregation of Site Sag Indices

Aggregation of site sag indices is the process of combining voltage sag indices across monitored sites of a utility to establish an overall indicator of customer sag levels of that utility. In particular, it can be applied to all sites in a utility to produce a utility index. As we are focusing on customer sag performance index for a utility, our index is weighted by customer load.

Utility Average Customer Sag Index (UACSI) for assessing the impact of voltage sags on customers can be given as,

$$UACSI = \frac{\sum_{s=1}^{n} L_S \cdot (SI_{Site})_s}{L_T} \qquad \text{-----} \quad (4.1)$$

where,

s	-	Site Number
n	-	Total number of sites in the system or utility being assessed
L_s	-	Connected kVA served from site s
L_T	-	Total connected kVA for the system being monitored ($\sum_{s=1}^{n} L_s$)
$(SI_{Site})_s$	-	Annual sag index for site s

4.5.2.5 Application example

The analysis given below has been carried out using data of 9 sites of 3 Australian distributors. The measurements took place over a one year, sufficient to give useful results on the impact of voltage sags on customers of three utilities. The available data was collected from sites having similar mix of industrial, residential and commercial customers for one year.

Site reporting

The field data of nine sites of three Australian distributors monitored over a one year period are analysed and reported to illustrate one of the discussed sag characterisation schemes.

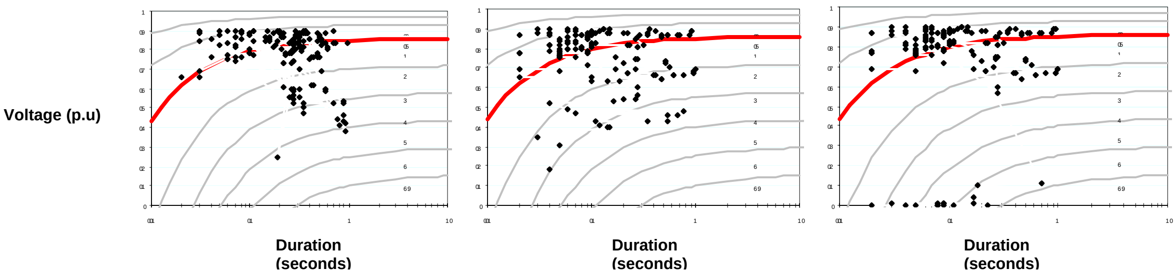


Figure 4.6(a) Distributor 1 (D1) sags overlaid on CBEMA curve

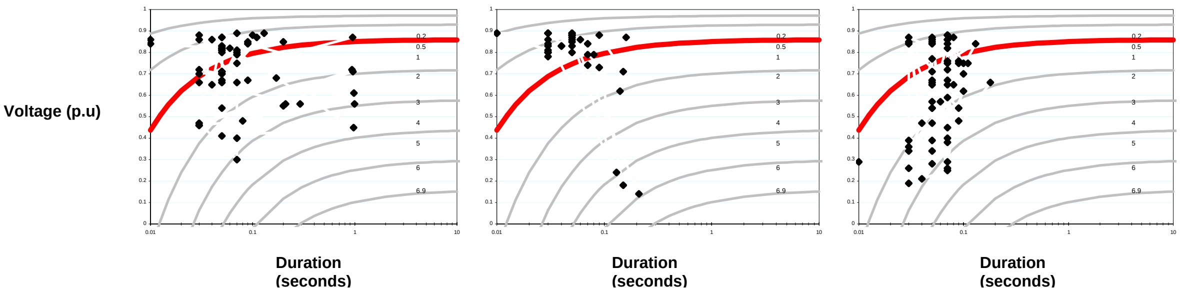


Figure 4.6(b) Distributor 2 (D2) sags overlaid on CBEMA curve

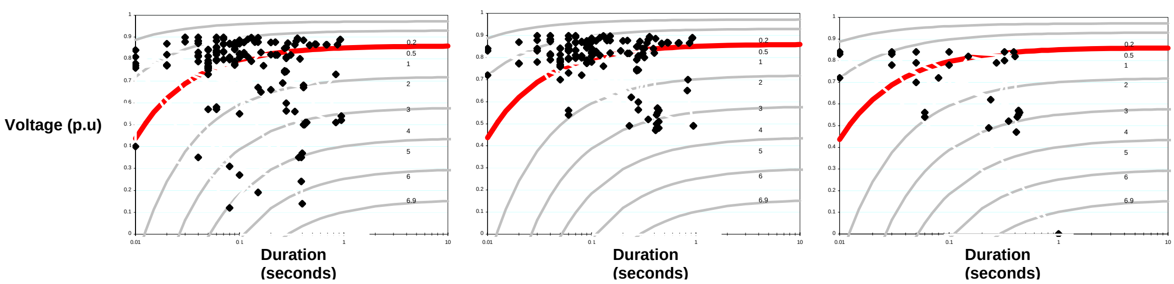


Figure 4.6(c) Distributor 3 (D3) sags overlaid on CBEMA curve

Figures 4.6(a), 4.6(b) and 4.6(c) are shown that site sag data, overlaid with CBEMA Contour Numbers (Bold line or CN=1 giving fitted CBEMA curve) for each of the 3 distributors separately. It is evident that there is no possibility of differentiating sites from site sag report and no clear compliance requirements can be determined.

Overall reporting

Network Level Report:

It is clear from Figure 4.7 that the network report gives a clearer differentiation of sites with network compliance levels and ease for ranking sites for appropriate remedial action. However, there is no possibility of ranking utilities for customer sag performance.

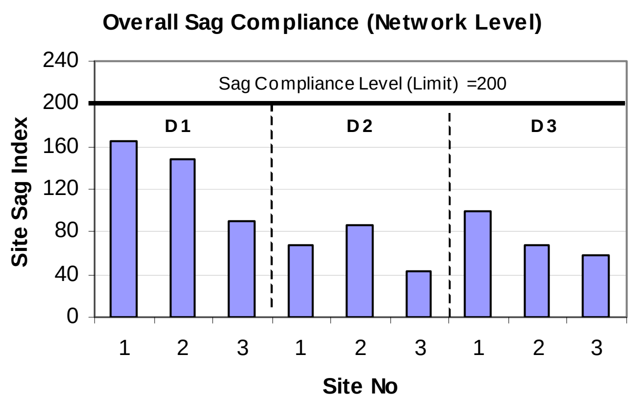


Figure 4.7 Overall reporting (Network Level)

Table 4.4 – Site sag data of three Australian distributors [73]

Please see print copy for Table 4.4

Utility Level Report:

Figure 4.8 shows that the proposed new method gives a comparison of utilities for customer sags. Distributor #1 is considered to be the worst utility for customer sags of both network and utility reporting levels. However, Distributor #2 is better performing than Distributor #3 at Network level, whereas Distributor # 2 out performed Distributor #3 Utility level for overall ranking for the impact of voltage sag performance.

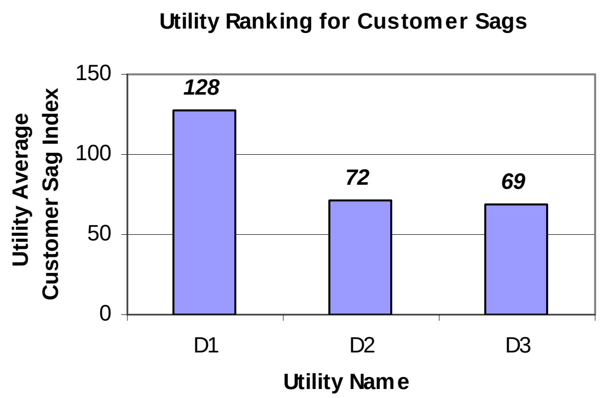


Figure 4.8 Overall reporting (Utility Level)

4.5.3. Benchmarking Utilities for Overall PQ Condition

4.5.3.1 Unified power quality index for a utility (UPQI-U)

Space aggregation described in PQAT is the process of combining site UPQIs across monitored sites to establish a UPQI for an area containing the sites. It can be applied to feeder UPQIs to produce a substation UPQI, or to substation UPQIs to produce a district UPQI. Finally, it can be applied to all sites in a utility to produce a Utility UPQI (UPQI – U).

Following the discussion of aggregation of site sag indices [75] for obtaining a overall sag index for a utility and the process of determining UPQI-S, the proposed UPQI-U can be derived in two ways, both of which have different processes as detailed below:

(i) Derive UPQI-U by taking the average of weighted (UPQI-S)s

i.e. UPQI-U = Av. (UPQI-S)s

(ii) Derive UPQI-U by aggregation of overall utility indices for each disturbance type.

i.e. UPQI-U = f {Av. (V), Av. (U),…...}

The simple example given below can be used to identify the better way of deriving the UPQI-U from (i) and (ii).

Assume two identical sets of sites (S1, S2 & S1`, S2`) of two utilities (Utility A & B) having voltage (V) and unbalance (U) indices as given below,

Utility A

	S1	S2
V	0.5	0.5
U	0.5	0.5
UPQI$_S$	0.5	0.5

Utility B

	S1`	S2`
V	1.0	0.0
U	0.0	1.0
UPQI$_{S`}$	1.0	1.0

Deriving UPQI-U from the methods discussed above would give,

Utility A

(i)		(ii)
Av. V - 0.5		UPQI$_{S1}$- 0.5
Av. U - 0.5		UPQI$_{S2}$- 0.5
(UPQI-U)$_A$ - 0.5	=	(UPQI-U)$_A$ - 0.5

Utility B

(i)		(ii)
Av. V - 0.5		UPQI$_{S1`}$- 1.0
Av. U - 0.5		UPQI$_{S2`}$- 1.0
(UPQI-U)$_B$ - 0.5	$\neq$	(UPQI-U)$_B$ -1.0

This situation can be expressed graphically in the following way with the function $\sqrt[n]{(U^n + V^n)} = 1$.

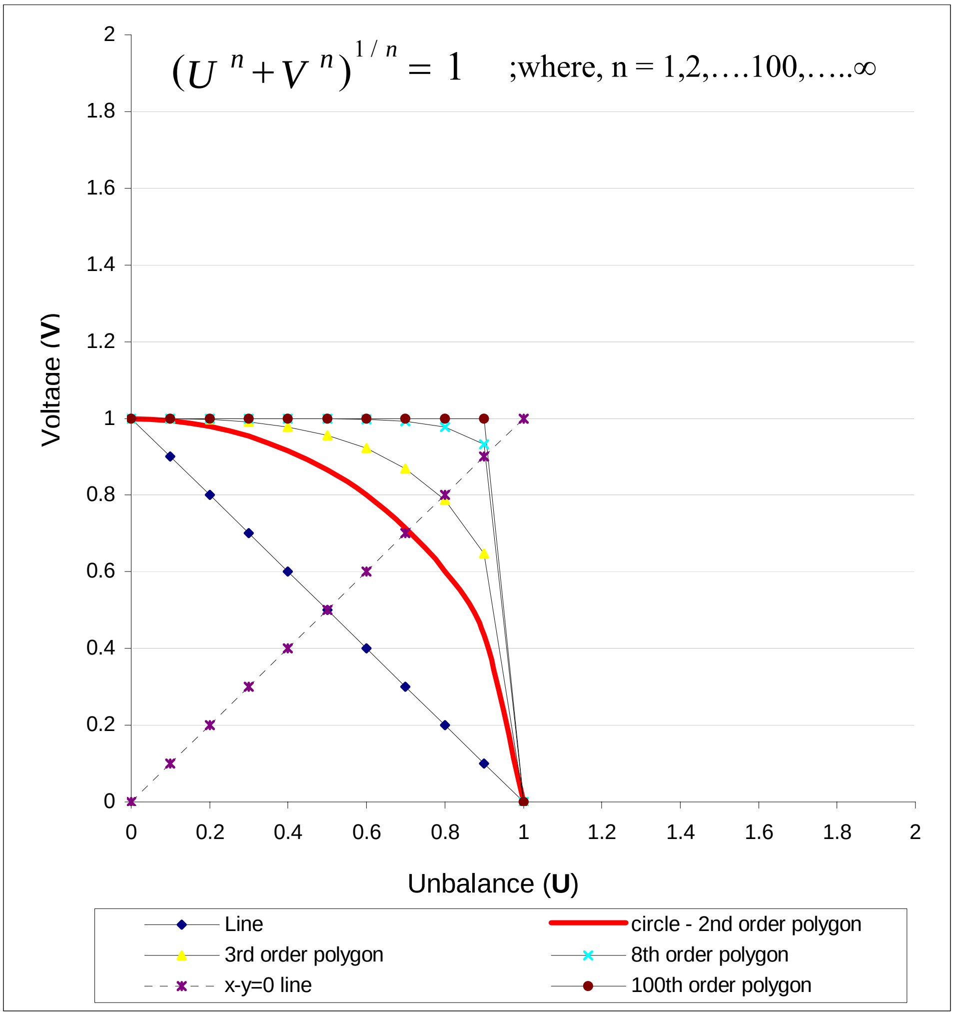


Figure 4.9 Graphical representation of UPQI-U for Voltage & Unbalance

Comparison of the scenarios given by points (0.5, 0.5) with (1, 0) or (0, 1), it is seen that scenario (0.5, 0.5) has an equal standing as (0, 1) or (1, 0). However, the scenario (0.5, 0.5) can be considered better than the scenario (0, 1) or (1, 0), as in the latter case one of the disturbance indices has reached its limit. Hence, (UPQI-U)s for Utility A and B are better represented by method (ii) i.e. (UPQI-U) obtained from average of (UPQI-S)s. Therefore, it is suggested to derive (UPQI-U) from the average of (UPQI-S)s .

The main focus of this index is regulatory reporting which portrays the legalistic point of view on PQ performance. Hence, the derivation of UPQI-U needs to be modified such that is weighted by the number of customers connected. However, the process of deriving UPQI-U can be altered to give customer focussed UPQI-U or Utility internal maintenance focussed UPQI-U by giving the appropriate weighting factors.

Utility average Power Quality Index (UPQI-U) for regulatory reporting by assessing the utility's overall impact of power quality is given by,

$$UPQI-U = \frac{\sum_{S=1}^{n}\{C_S \cdot (UPQI-S)_S\}}{C_T} \qquad \text{----- (4.2)}$$

where,

s - Site Number

n - Total number of sites in the utility being assessed.

Cs - Number of customers connected to site s.

C_T - Total number of customers connected to the system being monitored $(\sum_{S=1}^{n} C_S)$

$(UPQI-S)_S$ - Unified PQ Index for the site *s*.

However, when there are non-identical sites in terms of load density, external impacts, customer load types and other utility practices, the above methodology for deriving UPQI-U needs to be modified with an appropriate weighting factor. This is not possible without knowing more about the factors that contribute to good or bad power quality performance. Factor Analysis described in Chapter 6 and relevant factor analytic models developed would explain some of the major factors that contribute to ranking of Australian utilities. Those factors derived in Chapter 6 have been used to obtain the UPQI-U for the non-identical sites as shown in the illustrative example given in the Section 4.5.3.2.

4.5.3.2 Illustrative example

Again a set of synthetic data of 18 sites has been constructed by modifying a set of actual data of some Australian sites of three distributors (utilities). Similar to the previous example, the impulsive transient data is a modified version of an overseas survey data [79]. The constructed data would have similar range of variation as actual sites and sufficient to give useful results for the illustration of UPQI-U.

Individual disturbance analysis

Normalised and consolidated disturbance indices for all 18 sites for each disturbance type are shown in Fig. 4.10. It is shown that the best site for sags is not the best site for harmonics, steady state voltage, flicker, unbalance or transients, and the worst site for transients is not the worst site for sags, harmonics etc.

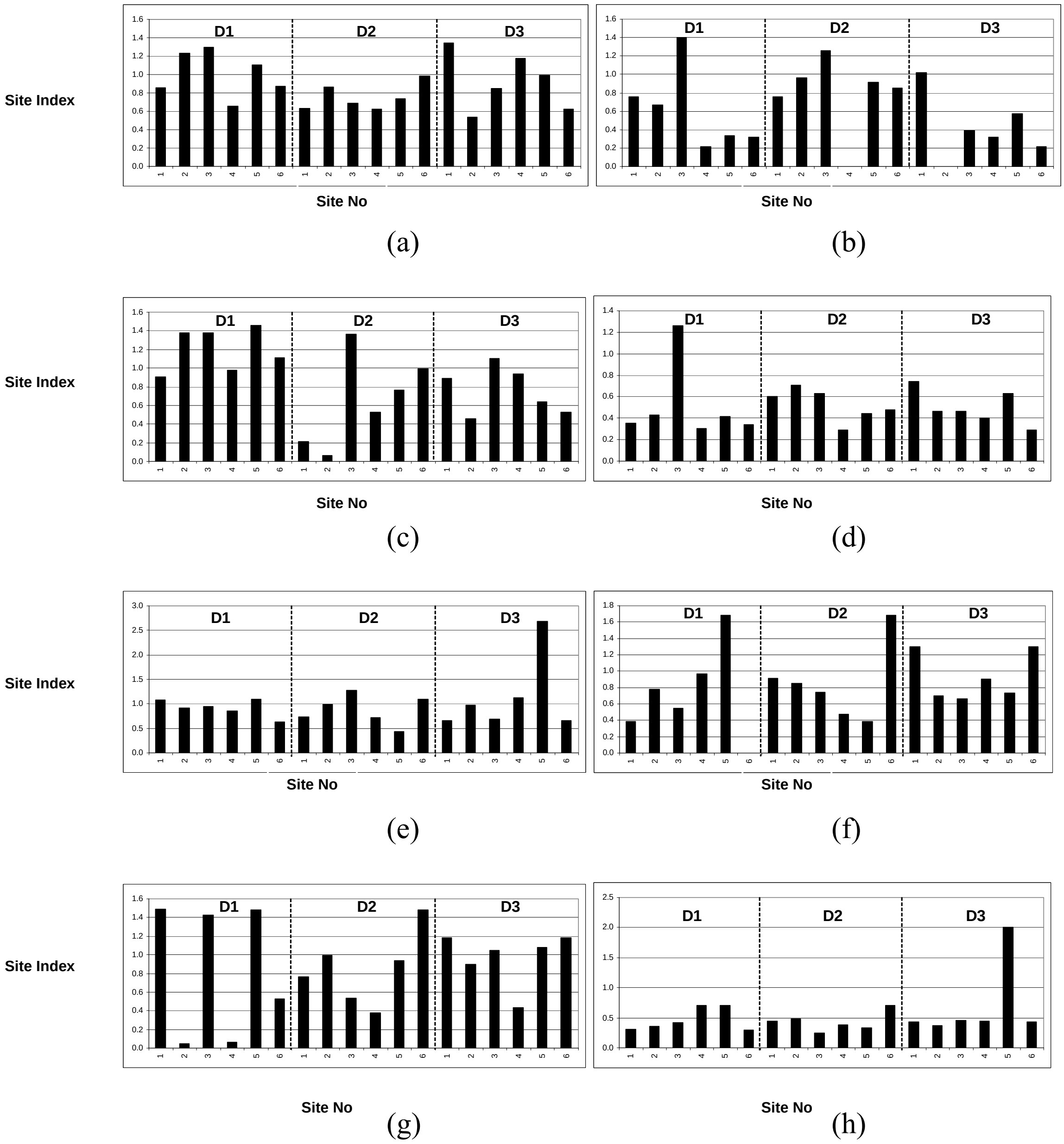


Figure 4.10 Normalised and Consolidated Indices for Individual Disturbances for 18 Sites of 3 Electricity Distributors (a) Voltage V, (b) Unbalance U, (c) Flicker F, (d) Harmonics H (e) Sags Sg, (f) Swells Sw, (g) Oscillatory Transients OT, (h) Impulsive Transients IT (Horizontal axis gives site number for each distribution utility – 6 sites each for Distributor D1, D2 and D3 , vertical axis gives site index)

These graphs illustrate that it is not possible to establish a quick impression of the overall level of power quality over the sites by visual inspection. It can also be seen that different distribution utilities have different patterns of index distributions to a particular disturbance type.

Single indices for overall PQ condition of a site (UPQI-S)

The overall PQ index for each site (UPQI-S) has been determined using the site details of Table 4.5. Figure 4.11 and Figure 4.12 show the comparison of site (UPQI-S)s determined using both ($PQI_{Maximum}$) and ($PQI_{Exceedance}$) for regulatory reporting.

Table 4.5 – Site details of three distribution utilities

Utility Name	Site No	Connected customers	Load Type	Site Type	Overall PQ Index	
					Max	Exced
D1	1	200	Residential	Extreme	1.490	1.566
	2	200	Residential	Extreme	1.377	1.606
	3	300	Commercial	Extreme	1.425	2.762
	4	500	Industrial	Average	0.975	0.975
	5	300	Commercial	Extreme	1.686	2.826
	6	500	Industrial	Extreme	1.115	1.115
D2	1	500	Industrial	Average	0.914	0.914
	2	500	Comercial	Extreme	0.992	0.992
	3	200	Residential	Extreme	1.367	1.367
	4	300	Residential	Average	0.722	0.722
	5	300	Commercial	Average	0.942	0.942
	6	500	Industrial	Average	1.686	1.686
D3	1	200	Residential	Extreme	1.340	1.340
	2	500	Commercial	Average	0.979	0.979
	3	500	Industrial	Average	1.103	1.103
	4	300	Commercial	Extreme	1.174	1.174
	5	500	Industrial	Extreme	2.681	3.761
	6	300	Residential	Average	1.295	1.477

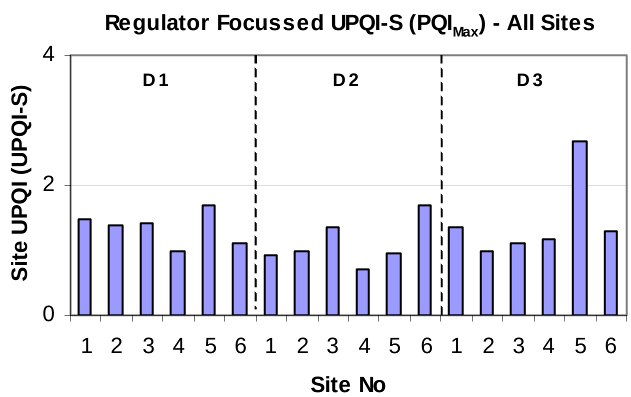


Figure 4.11 Overall reporting (Regulator focussed UPQI-S)

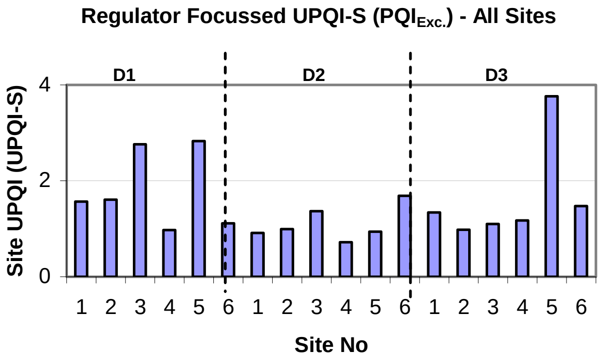


Figure 4.12   Overall reporting (Regulator focussed UPQI-S)

It is clear that the determination of overall PQ index for a utility is not possible by visual inspection as there are more factors involved. This is given in the next sub section. However, the visual inspection report would give a rough idea that the Distributor #2 would be the best utility compared to the other two. This has been confirmed by the both methods of calculations of Site UPQIs i.e. Maximum and Exceedance. However, it is difficult to differentiate D1 and D2 for their overall PQ condition.

Overall PQ Index for a utility (UPQI-U)

Figure 4.13 and Figure 4.14 show that the proposed new Utility index gives a comparison of utilities for their overall power quality condition. Distributor #3 considered to be the worst utility for regulatory reporting derived from both methods of calculation. Also the utility rank further confirms the rough idea taken from the visual inspection report of all sites in the previous sub section is a reasonable guess.

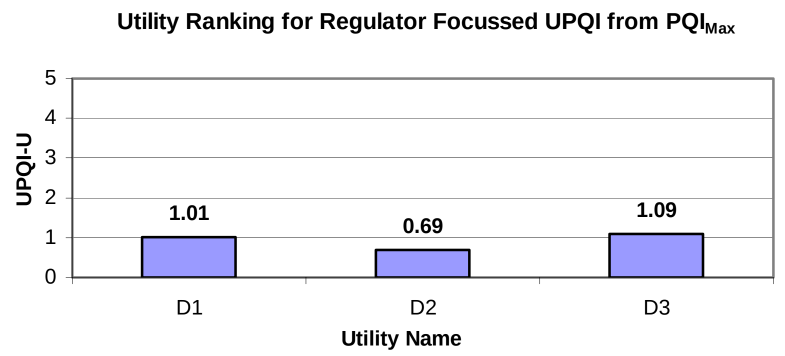


Figure 4.13 Overall reporting (Regulator focussed UPQI-U)

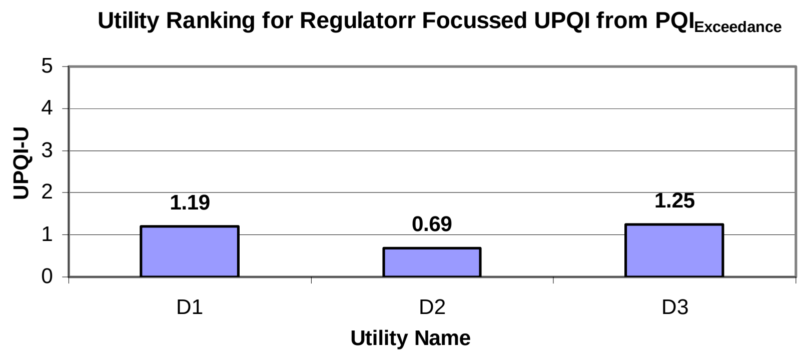


Figure 4.14 Overall reporting (Regulator focussed UPQI-U)

4.6 CONCLUSION

This chapter has given a comprehensive discussion on medium term reporting where the power quality measurement data represented at many different levels ranging from the raw measurement data to highly summarised indices. For this, the information flow has been structured in the form of a triangle termed "Power Quality Analysis Triangle (PQAT)" that has been developed to show the different data formats and their relationships. The major achievement described in this chapter is the development of an overall site PQ index i.e. Unified Power Quality Index (UPQI). This UPQI is used for the determination of a single index representing overall power quality level at a site and a utility. The subsequent aggregation of indices over large areas is an important component. This achievement which may provide useful insights for several different readers, i.e. customers, regulators and utilities.

As discussed above, this chapter developed the determination of a single index representing the overall PQ level at a site and a utility. It includes the determination of the number of customers of a site having PQ related equipment problems. It also takes into account the number of sites of a particular utility having PQ problems. This index has the useful features that it begins to exceed unity when one type of PQ disturbance begins to exceed the maximum acceptable level. For sites of low PQ levels, it gives a measure of the headroom available for the dominant disturbance type. For sites of high PQ levels, it provides a measure of the levels of all excessive disturbances.

The first stage in the determination is to measure all relevant parameters defined in PQ standards in relation to each disturbance type such as 10 minute measurement intervals for continuous disturbances. Statistical values (eg 95% levels) are found over a defined period. Maximum values are found across the three phases. When several weeks of monitoring are involved, values are described for each week and the overall maximum determined.

The next stage is normalisation, so that a particular index has the value of one when it is at the limit of acceptability. Consolidation combines all values describing one disturbance type (eg the short and long term flicker indices). It takes the maximum value to give a single disturbances index for each disturbance type for continuous disturbances. Disturbance Severity Indicator (DSI) as described in Chapter 3 was selected for the aggregation of discrete disturbance impact into a single disturbance index.

The method of aggregation of indices has shown that an overall index can be defined for each PQ disturbance type (i.e. as an example overall sag index for a site or a utility). This method also can determine a single index for overall PQ level of a site or a utility. The methodology developed in this chapter has been applied to representative data of Australian sites to illustrate its ability for benchmarking without the need of a detailed inspection of the detailed characteristics of each site.

Chapter 5

Long Term Reporting

5.1 INTRODUCTION

This chapter describes a methodology for identifying the long term aspects of PQ data which was first introduced in Chapter 3 with regard to Fig. 3.1. For brevity the relevant structure from Fig. 3.1 is extracted and reproduced in Fig. 5.1. This covers the concepts associated with highest level of reporting discussed in this chapter.

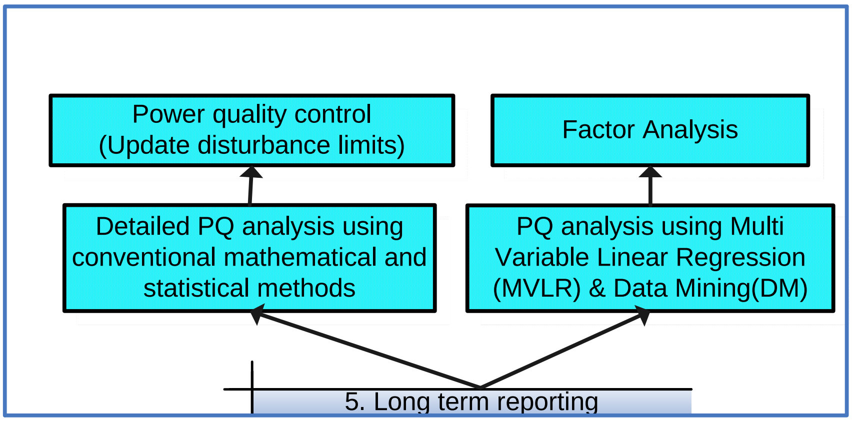


Figure 5.1 Analysis structure for long term reporting

The long term reporting identifies most significant site characteristics over a long period of time using one or more years worth of power quality survey data. When a proper analytical procedures is used, the long term power quality survey data can be helpful for developing new standards and guidelines for power quality limits in relation to different geographical, atmospheric, load and site categories. Further, the long term reporting can be used to understand the hidden patterns, relationships and trends. Two analytical methods are identified in this thesis for long term data analysis and reporting; data analysis using conventional mathematical/statistical methods and data mining techniques. As described in this chapter and Chapter 6, these analysis methods will define particular disturbance limits and some hidden patterns and relationships of power quality data that will be useful for utilities for system planning and developing maintenance strategies.

5.2 LIMITING VALUES FOR PQ DISTURBANCES

5.2.1 Overview

The site indices developed are to be compared with objectives that can be defined in bilateral agreements between a network operator and a customer, set as self-imposed quality objectives by a network operator, or set by a regulator. There are many approaches which have been adopted by international standards to deal with limiting values for continuous disturbances as detailed in Chapter 2. However, there are no specific objectives that can be found in these standards for defining discrete disturbance limits. As an example, European Standard CENELEC EN 50160: 2007 [11] which is considered as the most comprehensive PQ standard, gives only a guide line for number of sags per year. For example it states that "Under normal operating conditions the expected number of voltage sags (dips) in a year may be from up to a few tens to up to one thousand". Further as discussed in Chapter 2, more specific objectives are used in South Africa and Chile. Section 5.2.2 gives a novel methodology for defining limits for all discrete disturbances. These limits are based on single disturbance indices derived from disturbance severity indicators (DSIs), along with the available PQ survey data of large scale power quality surveys that have been carried out around the world.

5.2.2 New proposal for discrete disturbance limits

It is necessary that the discrete disturbance limits are achievable in practice and are consistent with long term PQ survey measurements carried out widely across many utilities. In the case of voltage sags, the period of observation for the number of events needs to be at least one year [53]. The same period can be applied to all other discrete disturbance types due to similar unpredictable behaviour of those events. The discrete event performance at customer supply points and customer requirements may vary from customer to customer.

Based on the work presented in [68] covering the discrete disturbance limits, it is recommended here that the discrete disturbance limits defined as a number of customer events for a given survey category (MV or LV) are met by 95% of the sites measured. The limits described in the section to follow are based on the statistical information of large scale PQ surveys carried out around the world. The combined information of all these surveys would give a good comparison between different countries and regions, which may be helpful in developing global limits for discrete disturbances. Large surveys of this kind have been carried out in US, Canada, Europe and several other countries [17].

5.2.2.2 Voltage Sag Limits

Voltage sag limits are based on survey statistics of UNIPEDE DISDIP survey [16, 84] covering measurement campaigns of nine countries in Europe over a period of three years.

The above survey was carried out over a period of three years. The locations of measurements cover LV bus bars of MV/LV substations or on MV lines to which MV/LV substations are directly connected. This information would give reasonable statistics in defining voltage sag limits. The survey results are available for underground (U/G) and mixed networks where a mixed network is defined to have various proportions of overhead lines and U/G networks. The measurements were taken under normal operating conditions (Table 5.1 & 5.2). It is to be noted that Rural networks were not included in the survey. However, the method can be applied to any network upon the availability of data of various site categories.

Table 5.1 – UNIPEDE DISDIP Survey Voltage Sag Incidence

U/G Networks – 95% Percentile

V \ t	0.01-0.1 s	0.1-0.5 s	0.5 - 1 s	1 - 3 s
70-90%	23	19	3	1
40-70%	5	19	1	0
0-40%	1	8	1	0

Table 5.2 – UNIPEDE DISDIP Survey Voltage Sag Incidence

Mixed Networks – 95% Percentile

V \ t	0.01-0.1 s	0.1-0.5 s	0.5 - 1 s	1 - 3 s
70-90%	61	68	12	6
40-70%	8	38	4	1
0-40%	2	20	4	2

In the current work an important consideration given to defining voltage sag limits is the sensitivity of voltage sags less than 90% in their magnitude and of short duration (less than 3 seconds) as most sag events reported in the UNIPEDE DISDIP survey correspond to this boundary. The sag contour chart is segmented into window format based on UNIPEDE DISDIP survey sag distribution chart and named them as A1, A2,……..C3,C4 windows as shown in Figure 5.2.

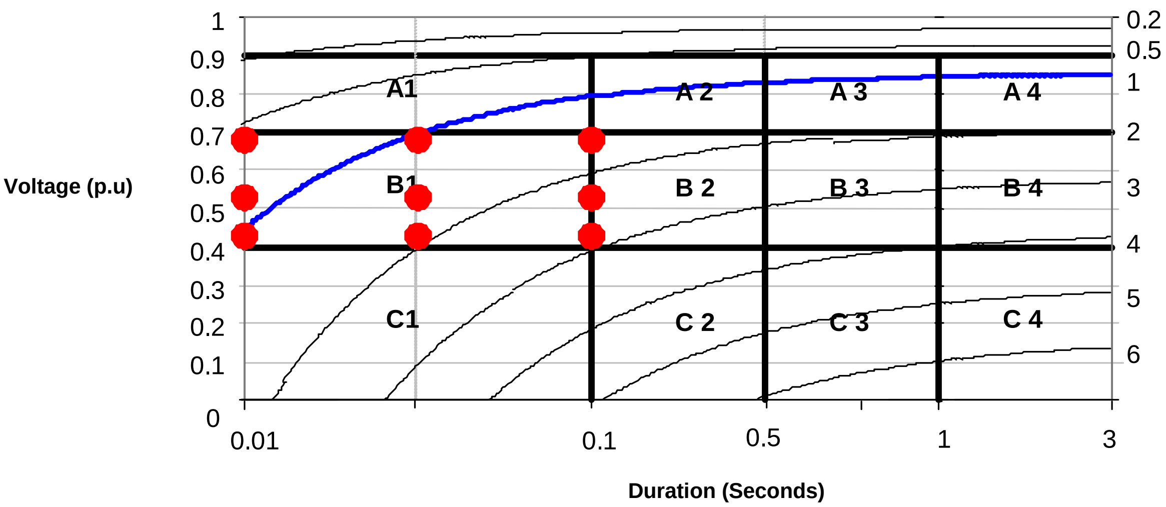


Figure 5.2 UNIPEDE DISDIP survey sag distribution chart with sag contours

Table 5.3 – UNIPEDE DISDIP Survey Distribution Chart in Window Format

(95% CP Statistics of Nine European Countries)

Voltage Sag Window	Average Sag Index	UNIPEDE U/G Networks Sag Count	Window Sag Limit	Single Sag Limit for U/G Networks	UNIPEDE Mixed Networks Sag Count	Window Sag Limit	Single Sag Limit for Mixed Networks
A1	0.68	23	15.71	**100**	61	41.66	**200**
A2	1.15	19	21.85		68	78.20	
A3	1.34	3	4.02		12	16.09	
A4	1.39	1	1.39		6	8.35	
B1	1.53	5	7.67		8	12.26	
B2	2.19	19	41.57		38	83.14	
B3	2.95	1	2.95		4	11.80	
B4	3.05	0	0.00		1	3.05	
C1	2.69	1	2.69		6	16.13	
C2	4.50	8	36.00		17	76.50	
C3	5.15	1	5.15		1	5.15	
C4	5.39	0	0.00		3	16.18	
Sum		**81**	**139.00**		**225**	**368.52**	
Max			**41.57**			**83.14**	

Further, to define limits, illustrated by Fig. 5.2, the UNIPEDE DISDIP survey sag windows as defined by Table 5.1 and 5.2 are mapped onto the voltage-time plane. The DSIs based on CBEMA contours (Chapter 3) can now be assigned to each sag event. The sag events corresponding to each window have to be used to define a sag limit for each window. For this purpose, DSIs developed based on the CBEMA curve are used, as shown in Fig. 5.2. As an example, consider the B1 window where 9 sag events are symmetrically placed, where each sag event corresponds to a particular

DSI. Hence, the average Sag Index for B1 Window = ∑DSI/9 = (0.6+1+1.5+0.8+1.5+2.3+1.1+ 2+3)/9 = 1.533. Then, this average sag index of each window is multiplied by the respective sag count of each survey category, to obtain the sag limit for each window.

Based on the above approach the average sag index developed for each window are given in Table 5.3 in Column 2. Column 3 shows the UNIPEDE DISDIP survey sag counts for U/G networks corresponding to each window and the corresponding limits are shown in Column 4. Columns 6 and 7 correspond to mixed networks. The last two rows of the Table 5.3, the sum and the maximum window limits of successive survey categories are given (e.g. the sum and the maximum of U/G networks are 139.00 and 41.57 respectively).

New Sag Limit: Voltage sag limits of each window are based on the 95% sag statistic of all surveyed sites of nine countries. Therefore, it is evident that a single annual sag index of a site yet to be surveyed should lie between the sum and the maximum of all window limits for each network category. Assuming similar sag variations occur for any site of given category, it is suggested that the proposed single sag limit value for each network category is between the sum and the maximum window limit, i.e. a single sag limit value of between 139.00 and 41.57 for U/G networks and a value of between 368.52 and 83.14 for mixed networks. Geometric mean of those values suggests 80 for U/G networks and 180 for mixed networks. Providing some head room the preferred values are taken as 100 and 200 for U/G and mixed networks respectively. The geometric mean are used to define sag limits as it is a measure of the central tendency or typical value of a set of numbers.

Geometric mean is a useful summary when it is expected that changes in data occur in a relative manner, and also it is useful for summaries of highly skewed data [100]. It is a known fact that any time when there are number of factors contributing to a product, the "average" would be given by the geometric mean where the geometric mean is always less than or equal to the arithmetic mean.

5.2.2.3 Voltage Swell Limits

A similar approach is used to develop swell limits as shown in Fig. 5.3 and Table 5.4 as it is achieved for sags. As with sags, swells are usually associated with system fault conditions, but they are not as common as sags, representing only about 2% to 3% of all power quality problems reported in industry studies [1]. Since there is very little survey data available for swells, the limits given here are based only on EPRI DPQ project data [85] and may not give such confidence as it with sag limits which are based on the survey data for 9 countries. Therefore, it is recommended to review these limits in the future upon the availability of swell data from many countries.

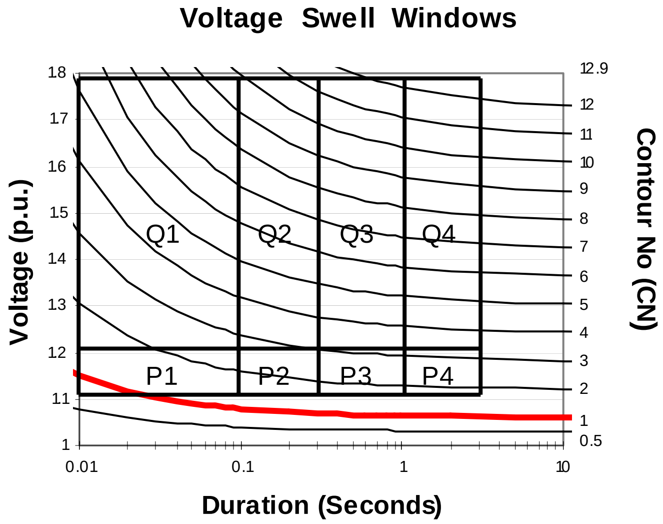


Figure 5.3 Voltage swell windows

Table 5.4 – Voltage swell limits

Swell Window	P1	P2	P3	P4	Q1	Q2	Q3	Q4	Sum
Average window swell index	1.41	2	2.25	2.4	4.76	6.67	7.46	7.86	
EPRI count	114	58	20	12	2	1	0	0	207
Window limit	**161**	116	45	29	9.5	6.7	0	0	**367**
Single Voltage Swell Limit									**250**

5.2.2.4 Oscillatory Transient Limits

A similar procedure as to sags and swells is followed for defining oscillatory transient limits as shown in Fig. 5.4 and Table 5.5. The resultant oscillatory transients due to capacitor voltage overshoot will be in the range of 1.0 p.u. to 2.0 p.u. However, the typical utility capacitor switching transients are in the range 1.3 p.u. to 1.4 p.u., but in some cases those switching transients have been observed near the theoretical maximum [1].

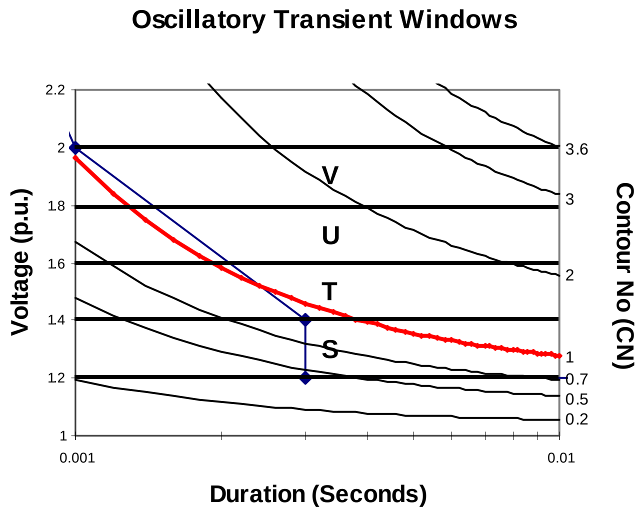


Figure 5.4 Oscillatory transient windows

Table 5.5 – Oscillatory transient limits

Oscillatory Transient Window	S	T	U	V	Sum
Average window Oscillatory Tr. index	0.70	1.16	1.60	2.05	
EPRI osillatory transient count	53.01	15.39	2.11	1.15	71.66
Oscillatory transient limit for each window	**37.11**	17.85	3.37	2.36	**60.69**
Single Oscillatory Transient Limit					**50**

Oscillatory transient limit described here also based on the EPRI DPQ project [85] data as there is very limited other data available. The limits are defined in the same manner as for sag and swell limits and the value lies between sum (60.69) and maximum (37.11) of window counts in Table 5.5. Geometric mean gives a value of 47.48. The preferred value for the single oscillatory transient limit is 50.

5.2.2.5 Impulsive transient limits

The impulsive transients that are mainly due to lightning can also be tackled in the same manner as for sags, swells and oscillatory transients (Fig 5.5). Similar to the swells and oscillatory transients, impulsive transient limits are also based on EPRI DPQ survey data. The values from Table 5.6 suggest that limits be between sum (129.43) and maximum (104.74). The geometric mean of these two values is 116.43 and the preferred value of single impulsive transient limit is taken as 120. The limits described here also needs future revision upon the availability of more survey data from different countries.

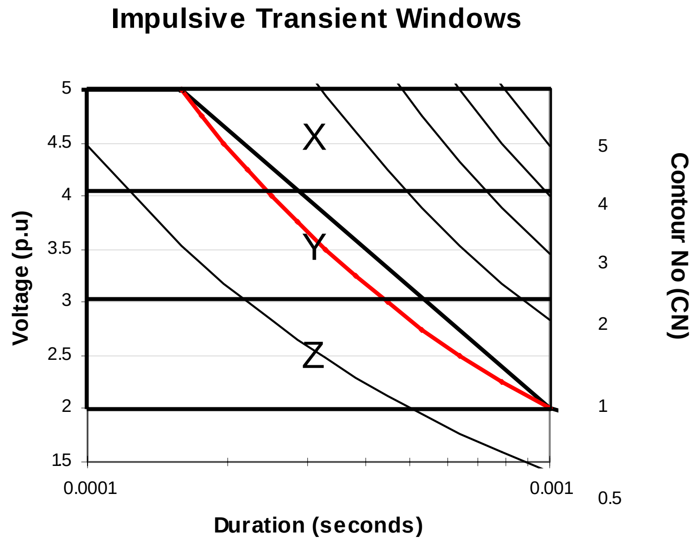


Figure 5.5 Impulsive transient windows

Table 5.6 – Impulsive transient limits

Impulsive Transient Window	X	Y	Z	Sum
Average window impulsive transient index	0.75	1.45	2.38	
EPRI impulsive transient count	139.65	12.35	2.85	154.85
Impulsive transient limit for each window	**104.74**	17.91	6.78	**129.43**
Single Impulsive Transient Limit				**120**

5.2.3 Application example

The voltage sag application example given below is based on the data of four Australian sites where the limits developed in section 5.2.2 are applied. The measurements took place over a period of one year, sufficient to give useful results for voltage sag performance. The available data was collected from two Australian distributors.

5.2.3.1 Analysis of sag data using existing characterisation approaches

The field data of four sites that belong to two Australian distributors were analysed and reported to illustrate some of the existing characterisation schemes. Sag data from four sites is included in Figures 5.6 and 5.7, overlaid with sag Contour Numbers (CN=1 giving the fitted CBEMA curve). It is evident that there is no possibility of differentiating sites as to their acceptable sag limits other than the general acceptance of CBEMA limit exceedances.

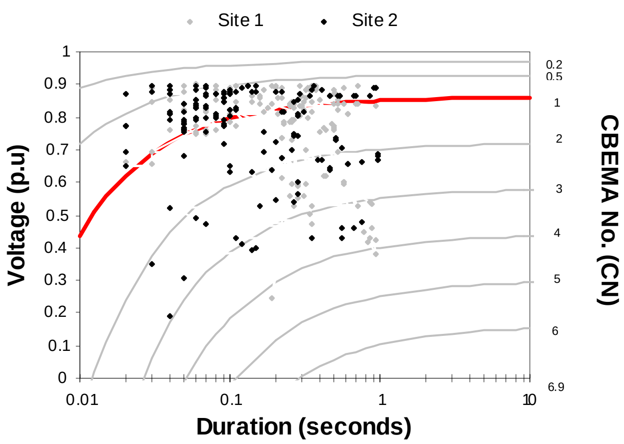


Figure 5.6 Distributor "A" sags overlaid on the CBEMA together with contours

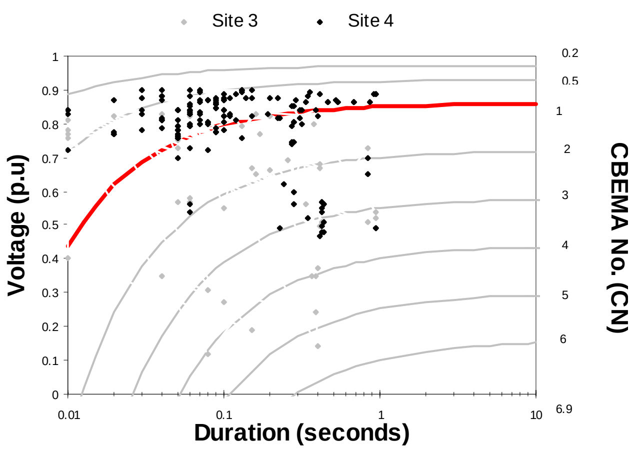


Figure 5.7 Distributor "B" sags overlaid on the CBEMA together with contours

5.2.3.2 Analysis of sag data with sag limits

Sag indices for those 4 sites were calculated as the sum of DSIs based on CBEMA curve as described in Section 3.5 and 5.2. It is clear from Fig. 5.8, that the new method will give a clearer differentiation of sites of their limits of acceptability where the sites can be ranked for their mitigation purposes. Other important feature is that the customers living in the area distributor "A" is more vulnerable to sags than the customers supplied by distributor "B".

Figure 5.8 Single site index with limits for voltage sags

It is clear from the example that the new single limits which has been developed in Section 5.2.2 is much easier to use and is application oriented.

5.3 CONCLUSION

This chapter has given a comprehensive discussion on the determination of a single limit for each discrete disturbance type. An index for voltage sags is proposed involving the addition of a sag severity indicator (SSI) for each sag. The SSI is based on the CBEMA curve, and increases with sag duration but reduces with sag voltage. From examination of typical sag records of 9 European countries, it is proposed that annual sag index limit of 100 (for underground networks) and 200 (for mixed networks) be adopted, based on the performance of the best 95% of sites.

A similar approach is used to develop voltage swell limits and oscillatory & impulsive transient limits on the basis of the disturbance severity indicator (DSI) based on CBEMA or ITIC curve. However, these limits are based on EPRI DPQ project survey data due to limited data available from within Australia or other countries. A single index limit of 250 (swells), 50 (oscillatory transients) and 120 (impulsive transients) be adopted based on the 95% best site performance.

The methodology developed has been applied to representative sag data of Australian sites to illustrate its ability for benchmarking Australian utilities for voltage sag performance. This methodology would be a very useful tool for developing a new standard for Sag, Swell and Transient limits in the future.

Chapter 6

Factor Analysis

6.1 INTRODUCTION

The mass of data gathered for a sample of sites of a large-scale power quality (PQ) survey has the potential to reveal good and bad factors on power quality if an appropriate diagnostic procedure can be determined. Survey results from a particular set of monitored sites can be used to infer the PQ behaviour of other unmonitored sites with similar characteristics in terms of physical behaviour and similar mix of customers. This would be useful for network planners and other power quality engineers. This is only possible if the characteristics that are the most influential in determining PQ levels at a particular site are known.

Factor analysis can be used to enable the factors which contribute to poor or better PQ levels to be identified. Results of such analysis can be used in PQ management, planning and reporting practices in utility environments. If it is known which characteristics are more important in determining the levels of particular PQ disturbances, it could be expected that other sites with similar characteristics would also present similar PQ levels. The Australian National Power Quality Benchmark Survey (ANPQBS) data [94] consists of 70 sites of 11 utilities in Australia has been analysed to provide a model for factor analysis.

This chapter aims to assess the levels of PQ disturbances and factors that influence good or bad PQ levels. ANPQBS Survey data of 70 sites across Australia would be very useful to identify many factors that will influence good or bad PQ levels. The survey data has been analysed using Multivariable Linear Regression (MVLR) and the analysis results were complemented with analysis employing Data Mining (DM) techniques. As described in Sections 6.2 and 6.3, the MVLR and DM are reliable and useful analysis tools for ANPQBS survey data analysis. Microsoft Excel has been used for MVLR analysis whereas “SNOB”[92] and “ACPRO”[93] (i.e. data mining software for unsupervised classification of multivariate data) software were used for data mining analysis.

Based on the factor analytic models developed in this chapter, it can be determined whether any relationship exists between those categorical variables and PQ disturbance levels measured in the survey.

Any variable that is not quantitative is categorical which takes a value that is one of several possible categories. When analysing categorical data, it is typically established using counts or percentages of objects which fall within certain categories. Defining categorical variables in this chapter, i.e. site types and load types, is based on the information obtained from the each utility. Further details on site selection and defining categorical variables which have been used for Multivariable Linear Regression and Data Mining analysis are given in Appendix A5.

6.2 MULTI VARIABLE LINEAR REGRESSION (MVLR)

Multivariable Linear Regression (MVLR) enables fitting a single model for categorical variables such as site type and load type, taking into account the relationships among those power quality data categories for a single disturbance type over many sites. The factor analysis of PQ data [95], can allow uneven representation of different factors, which can be used to establish useful insights on monitored PQ of all sites. In this thesis, the MVLR analysis is carried out using the Microsoft Excel, Solver add in with least squares fit.

The site categories used in MVLR are (see Appendix A5 for an expanded definition):

- Site type (Average, Extreme)
- Load type (Residential, Commercial, Industrial, Rural, Remote)

It is important to determine whether site type or load type is the most important factor determining a PQ problem of interest.

For example, assume that the Voltage Unbalance Factor (VUF) is related to the categorical variables as given by,

$$VUF = K_0 + K_{Site}(Site\ type) + K_{Load}(Load\ type) \qquad (6.1)$$

where, the constants Ksite and Kload are to be determined by means of MVLR. To reduce the number of variables, it is assumed that $K_{Site}(Average)$ and $K_{Load}(Commercial)$ are equal to zero, i.e. they are incorporated into K_0 . Equation (6.1) solved for all constants using a least squared fit in Excel solver. Description of the methods are described in Appendix A6 with examples.

6.2.1 Factor Analysis of Australian Utility Power Quality Data

Based on the methodology described above, Australian National Power Quality Benchmark Survey data have been analysed to describe a factor analysis model representing Australian utility sites. The details of the survey including the types of disturbances monitored based on the site selection described in Appendix A5, are discussed below.

The measured quantities have been divided into two groups: namely, those that were measured by logging and those that were captured as distinct events. The power quality survey was carried out using the following voltage quantities at each site for approximately one week period.

Logged quantities (Continuous disturbances)

1. Steady state voltage
2. Voltage unbalance
3. Voltage harmonics

Normalised indices have been calculated for each site by analysing the survey data for continuous disturbances. Indices for captured quantities (discrete disturbances) have been left out as they were not measured at all sites.

Table 6.1 – Monitored PQ data used for the analysis (Normalised Indices)

Site ID	Site Type	Load Type	Unbalance Index	Voltage Index	Harmonics Index
1	Extreme	Commercial	0.215	0.243	0.134
2	Extreme	Residential	0.420	0.197	0.137
3	Average	Commercial	0.064	0.095	0.130
4	Extreme	Commercial	0.524	0.318	0.267
5	Extreme	Residential	0.354	0.222	0.140
6	Average	Residential	0.127	0.270	0.088
7	Average	Residential	0.210	0.216	0.068
8	Average	Commercial	0.081	0.160	0.065
9	Extreme	Industrial	0.178	0.177	0.082
10	Extreme	Commercial	0.145	0.107	0.072
11	Extreme	Rural	0.632	0.268	0.150
12	Average	Rural	0.485	0.163	0.091
13	Average	Residential	0.263	0.239	0.078
14	Average	Industrial	0.250	0.168	0.098
15	Average	Commercial	0.340	0.273	0.095
16	Extreme	Residential	0.233	0.102	0.098
17	Extreme	Commercial	0.343	0.180	0.095
18	Extreme	Industrial	0.319	0.241	0.101
19	Extreme	Residential	0.383	0.328	0.157
20	Average	Rural	0.090	0.131	0.098
21	Average	Commercial	0.146	0.207	0.098
22	Average	Industrial	0.120	0.287	0.085
23	Average	Residential	0.192	0.182	0.072
24	Extreme	Remote	-	0.153	0.062
25	Extreme	Commercial	0.283	0.209	0.075
26	Extreme	Industrial	0.204	0.280	0.111
27	Extreme	Residential	0.202	0.138	0.091
28	Average	Residential	0.194	0.180	0.101
29	Average	Commercial	0.120	0.212	0.072
30	Average	Industrial	0.090	0.238	0.078
31	Average	Rural	0.217	0.328	0.082
32	Extreme	Remote	-	0.289	0.052
33	Average	Commercial	0.091	0.226	0.117
34	Average	Residential	0.312	0.236	0.098
35	Extreme	Rural	0.546	0.178	0.134

Table 6.1 ...Cont.(Monitored PQ data used for the analysis (Normalised Indices))

Site ID	Site Type	Load Type	Unbalance Index	Voltage Index	Harmonics Index
36	Extreme	Industrial	0.145	0.263	0.065
37	Extreme	Industrial	0.293	0.222	0.075
38	Average	Residential	0.203	0.229	0.088
39	Average	Residential	0.362	0.211	0.150
40	Extreme	Industrial	0.471	0.168	0.134
41	Extreme	Industrial	0.191	0.178	0.098
42	Extreme	Residential	0.228	0.139	0.108
43	Extreme	Commercial	0.082	0.148	0.072
44	Average	Commercial	0.157	0.187	0.049
45	Average	Industrial	0.150	0.273	0.075
46	Average	Residential	0.284	0.155	0.127
47	Average	Rural	0.278	0.313	0.052
48	Extreme	Rural	-	0.195	0.130
49	Average	Industrial	0.126	0.166	0.065
50	Extreme	Commercial	0.298	0.132	0.114
51	Extreme	Residential	0.152	0.209	0.078
52	Average	Rural	0.074	0.207	0.065
53	Extreme	Industrial	0.228	0.355	0.062
54	Average	Commercial	0.044	0.095	0.108
55	Average	Residential	0.188	0.207	0.082
56	Extreme	Remote	-	0.211	0.075
57	Extreme	Residential	0.403	0.297	0.160
58	Average	Industrial	0.050	0.204	0.062
59	Extreme	Industrial	0.209	0.387	0.121
60	Average	Rural	0.078	0.233	0.042
61	Extreme	Commercial	0.089	0.158	0.101
62	Extreme	Remote	-	0.236	0.108
63	Extreme	Commercial	0.274	0.656	1.047
64	Extreme	Rural	0.282	0.302	0.049
65	Extreme	Residential	0.788	0.277	0.114
66	Extreme	Industrial	0.125	0.217	0.091
67	Average	Commercial	0.157	0.082	0.075
68	Average	Industrial	0.374	0.251	0.088
69	Average	Residential	0.252	0.301	0.091
70	Average	Rural	0.259	0.156	0.124

6.2.2 Relationships of Factors on Individual Disturbance Indices

The analysis given below is established separately for each individual disturbances by means of the factors relating to Site and Load types. Site type mainly describes the impedance characteristic of each site where as the Load type is mainly based on how much current flows to the load depending on each load category.

The regression equation by means of MVLR analysis for all the types of disturbance indices is given by,

$$Disturbance\ Index = K_0 + K_{Site\,type}(Av, Ex) + K_{Load\,type}(Rs, Com, Ind, Ru, Rm) \qquad \text{-----} \quad (6.2)$$

In this analysis, Commercial and Average site indices were forced to zero, i.e. they are incorporated into K_0 in MVLR analysis for all the disturbance types described below.

6.2.2.1 Factor Analysis of Voltage Unbalance Indices using MVLR

In Table 6.1, it was noted that there were missing data for unbalance measurements at remote sites. This is due to a fault in the PQ monitors that have been downloading data for those sites. Therefore, the Remote sites were excluded from the unbalance analysis. In general Residential, Rural and Remote sites would show significant voltage unbalance compared to Commercial and Industrial sites. This is mainly because of the presence of single phase unbalanced loads in residential areas and more scattered and isolated unbalanced loads present in rural and remote areas.

Factor analysis for Voltage Unbalance with MVLR is given below.

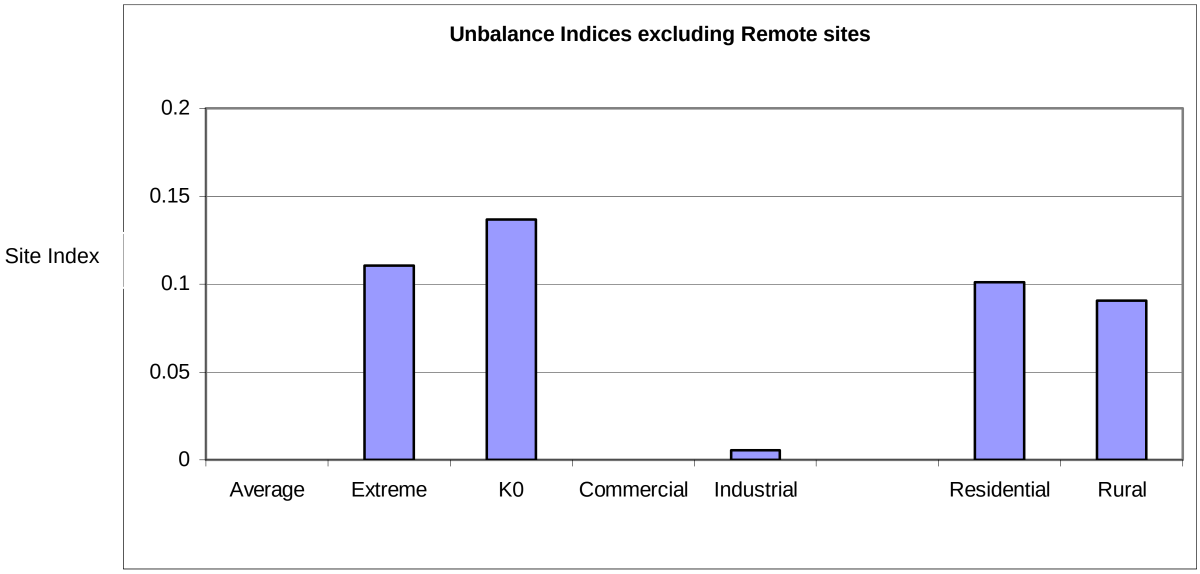


Figure 6.1 MVLR Analysis of Voltage Unbalance

Table 6.2 MVLR Analysis on Voltage Unbalance (Excluding Remote Sites)

Constant	Site Type		Load Type			
K_0	Average	Extreme	Commercial	Industrial	Residential	Rural
0.136	0	0.111	0	0.005	0.101	0.091

In MVLR analysis, K0 of 0.136 is a result of Average and Commercial being forced to zero and is somewhat an arbitrary figure. In this analysis, the absolute values of the numbers are not very critical since they all depend on which of the categorical variables is given a value zero. However, what is of most interest is the range of numbers. It is seen that the Site type category has a variation across the range zero and 0.111 with Average being best and Extreme being worst. Also, it is seen that the Load type category has a variation across the range zero and 0.101 with Commercial being best, with Industrial being similar, and Rural being worst with Residential being similar to that. It is also seen that the range of variation contributed by Site type is very close to that contributed by Load type, so that in conclusion both categories are of the same importance and a significant factor in deciding good or bad unbalance levels.

Calculation of the contribution of Voltage Unbalance Factor (VUF) for site types in relation to Commercial & Industrial load types is given below,

$$\begin{aligned} \text{VUF (Average, Commercial)} &= K_0 + K_S \text{ (Average)} + K_L \text{ (Commercial)} \\ &= 0.136 + 0 + 0 \\ &= 0.136 \end{aligned}$$

Table 6.3 Factors contributing to Voltage Unbalance

Description	VUF Contribution
VUF (Average, Commercial)	0.136
VUF (Average, Industrial)	0.141
VUF(Extreme, Commercial)	0.247
VUF(Extreme, Industrial)	0.252

Calculation in relation to VUF shows that unbalance contributions of industrial & commercial sites are almost similar. Values for average & extreme sites for commercial & industrial are 0.136, 0.141 and 0.247, 0.252 respectively. The extreme sites, i.e. the sites further away from the transformer have higher contribution to the voltage unbalance. Also, Figure 6.1 shows that unbalance contribution by residential and rural load categories is similar. However, the worst unbalances are reported from (Extreme, Residential) sites. Thus, the most significant factor for voltage unbalance is (Extreme, Residential) followed by (Extreme, Rural). The extreme sites show a significant difference with average sites, i.e. a factor of 0.111 difference between the site categories.

It is to be noted that the exclusion of remote sites in MVLR analysis described above have only been considered for Voltage Unbalance. As discussed above, it is because that the Unbalance data for Remote sites were not recorded by PQ monitors of those sites. However, this is not the case for voltage harmonics and steady state voltage analysis which are given in the sections to follow.

6.2.2.2 Factor Analysis of Harmonic Indices using MVLR

Harmonic data of the survey were logged for all 70 sites and no data loss has been reported. Therefore the MVLR analysis on harmonics has included all sites measured in the survey. Also in this analysis, the commercial and average site indices were forced to zero for consistency where those values are incorporated in to K_0.

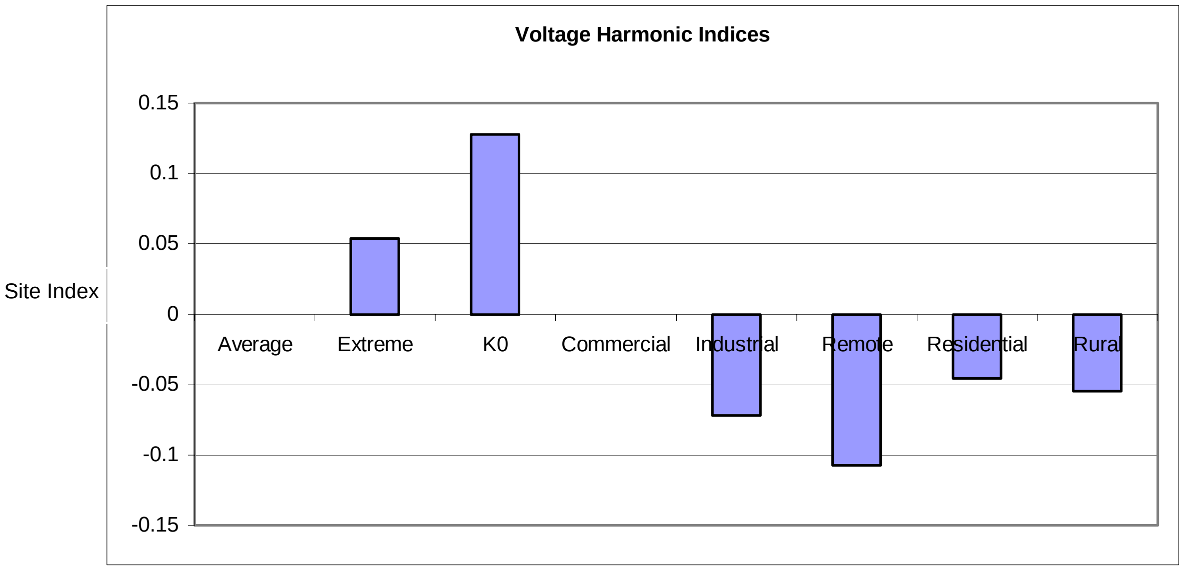


Figure 6.2 MVLR Analysis of Voltage Harmonics

Table 6.4 MVLR Analysis on Voltage Harmonics

Constant	Site Type		Load Type				
K_0	Average	Extreme	Commercial	Industrial	Remote	Residential	Rural
0.128	0	0.054	0	-0.072	-0.107	-0.046	-0.055

Results of MVLR analysis illustrated in Fig 6.2 show that extreme sites have worst harmonic levels in the system; in particular (Extreme, Commercial) are the worst performing sites for harmonics, followed by (Extreme, Residential), (Extreme, Rural), (Extreme, Industrial) and (Extreme, Remote). Similar to the analysis for unbalance, the commercial and industrial sites were compared for voltage harmonic (VHarm) contribution as shown below.

Table 6.5 Factors contributing to Voltage Harmonics

Description	VHarm Contribution
VHarm (Average, Commercial)	0.128
VHarm (Average, Industrial)	0.056
VHarm (Extreme, Commercial)	0.182
VHarm (Extreme, Industrial)	0.110

Analysis shows that the commercial sites are the worst performing for harmonics in relation to load category. This is followed by residential, rural, industrial and remote. Also, the extreme sites, i.e. sites further away from the transformer contribute more harmonics into the system than average sites, i.e. those sites close to the transformer. Therefore, it is noted that both site type and load type are contributing factors for harmonic performance of a utility network where (Extreme, Commercial) sites are the worst performing ones for harmonics.

6.2.2.3 Factor Analysis of Steady State Voltage Indices using MVLR

The MVLR analysis given below is based on the PQ data recorded for 70 sites in relation to the steady state voltage.

Similar to the analysis of voltage unbalance and harmonics in MVLR, the indices for Average and Commercial site were forced to zero for consistency where those indices were incorporated into K_0 (constant). The difference in the voltage analysis compared to unbalance and harmonics has shown a significant variation between K_0 and site and load categories. It is shown in Fig. 6.3 that both Site type and Load type are significant factors for deciding good or bad steady state voltage levels. Therefore, the being close to the transformer or further away from the transformer is one of the deciding factors for steady state voltage.

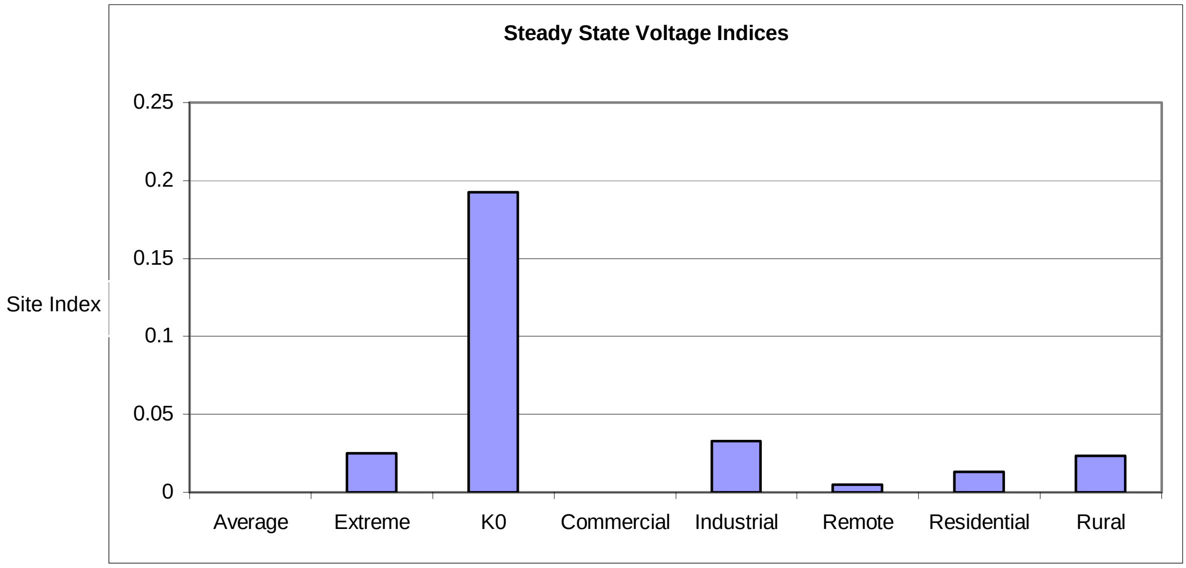


Figure 6.3 MVLR Analysis of Steady State Voltage

Table 6.6 MVLR Analysis on Steady State Voltage

Constant	Site Type		Load Type				
K_0	Average	Extreme	Commercial	Industrial	Remote	Residential	Rural
0.192	0	0.025	0	0.033	0.005	0.013	0.024

Furthermore, for steady state voltage, the factor of being a residential, commercial or industrial customer is also a deciding factor for good or bad voltage levels. As for voltage unbalance and harmonics, the commercial and industrial sites data were compared in relation to steady state voltage (SSV) as given in Table 6.7.

Table 6.7 Factors contributing to Steady State Voltage

Description	SSV Contribution
SSV (Average, Commercial)	0.192
SSV (Average, Industrial)	0.225
SSV (Extreme, Commercial)	0.217
SSV (Extreme, Industrial)	0.250

As expected, the extreme sites are generally worst performing sites for steady state voltage. The MVLR analysis shows that the most contributing factor for voltage is (Extreme, Industrial) sites, followed by (Extreme, Rural), (Extreme, Residential), (Extreme, Remote) and (Extreme, Commercial). However, it is also to be noted that there is no significant difference between extreme and average sites, i.e. 0.025. Therefore, that being an industrial sites is the most contributing factor for steady state voltage followed by rural, residential, remote and commercial sites.

The following section attempts to give the factors contributing to overall PQ indices.

6.2.3 Factor Analytic Models for Overall PQ Indices using MVLR

Factor analysis of overall PQ indices using MVLR was carried out for one of the types of overall indices described in the Chapter 4, i.e. $UPQI_{Average}$ (Unified Power Quality Index). Similar types of analysis as for individual type of disturbances were carried out for this purpose. Since there are missing data for unbalance analysis due to the unavailability of remote site data, it would be useful to have two options for UPQI analysis, i.e. analysis with and without remote site data. This was considered due to the fact that the absence of Remote data may have accounted for significant change in overall indices distribution and the details of the analysis for all sites are given in Appendix A6.

6.2.3.1 Factor Analysis on $UPQI_{Average}$ using MVLR

MVLR analysis as illustrated in Fig. 6.4 shows that both Site type and Load type are contributing factors for deciding $UPQI_{Average}$, where Extreme sites are the most contributing factor. The analysis show that the (Extreme, Rural) sites give the worst performance for overall PQ condition of a site. Thus, the most significant factor for $UPQI_{Average}$ is (Extreme, Rural) sites followed by (Extreme, Residential), (Extreme, Commercial) and (Extreme, Industrial). In general, both site type and load type contribute to the good or bad overall Power Quality levels of a site, where the highest contribution is from (Extreme, Rural) sites and the lowest contribution is from (Average, Industrial) sites (see Table 6.8).

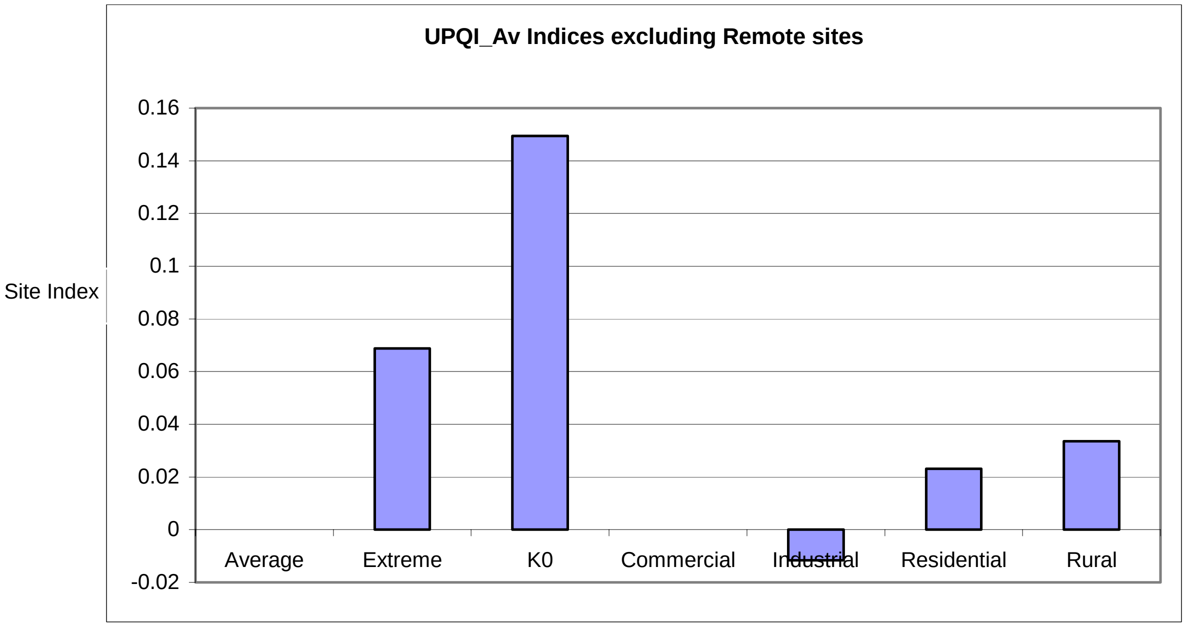


Figure 6.4 MVLR Analysis of $UPQI_{Average}$

Table 6.8 MVLR Analysis on UPQIAverage excluding Remote sites

Constant	Site Type		Load Type			
K_0	Average	Extreme	Commercial	Industrial	Residential	Rural
0.15	0	0.07	0	-0.012	0.023	0.034

Table 6.9 Factors contributing to $UPQI_{Average}$

Description	$UPQI_{Average}$ Contribution
$UPQI_{Av}$ (Extreme, Rural)	0.254
$UPQI_{Av}$ (Extreme, Residential)	0.243
$UPQI_{Av}$ (Extreme, Commercial)	0.220
$UPQI_{Av}$(Extreme, Industrial)	0.208
$UPQI_{Av}$ (Average, Rural)	0.184
$UPQI_{Av}$ (Average, Residential)	0.173
$UPQI_{Av}$ (Average, Commercial)	0.150
$UPQI_{Av}$ (Average, Industrial)	0.138

The next section is dedicated to Factor Analysis of power quality data using data mining, so that the analysis of both methods can be compared for validity of the Factor Analysis models developed in this thesis.

6.3 DATA MINING (DM)

Data mining is a process that uses a variety of data analysis tools to identify hidden patterns and relationships within data. These tools are a mixture of machine learning, statistics and database utilities. Data mining has recently gained popularity among many research fields over classical techniques for the purpose of analysing data [86]. Data mining can provide the answers to various Power Quality problems by converting raw data into useful knowledge [90]. The data mining process differs from classical statistical methods, that is the solutions from statistical methods focus only on model estimation, while data mining techniques focus on both model formation and its performance.

There are two important learning strategies in data mining techniques; Supervised Learning (SL) and Unsupervised Learning (USL). SL provides mapping from attributes to specified classes or concept groupings (i.e. classes are identified and pre-labelled in the data prior to learning). USL generally amounts to discovering a number of patterns, subsets, or segments (clusters) within the data, without any prior knowledge of the target classes or concepts, i.e. learning without any supervision. Since there are no predefined classes within the available Power Quality data, USL is used to identify statistically valid classes within the data itself. Clustering (or segmenting) is an important, if not core, technique in data mining, especially for USL [91-93]. The factor analytic model described below is based on USL techniques and unsupervised clustering with Minimum Message Length (MML) encoding (See

Appendix A7 for more details). The factor analytic model for $UPQI_{Average}$ has been developed using the data mining software "SNOB", i.e. a computer program for unsupervised classification of multivariate data [92]. The results given by the SNOB has been further verified by the use of ACPro, a well known data mining software used for NASA Mars Lander studies in 1998 [93].

6.3.1 Factor Analytic Models for Overall PQ Indices using Data Mining

The same PQ data set of those 70 sites of the 11 Australian utilities has been used for the analysis using data mining to examine whether it would give a similar analysis as obtained by the MVLR method. The two methods have completely different approaches in its method of data analysis to examine whether they similar outcomes or not. MVLR analysis does not take into account the missing data. However, Data Mining can account for the missing data and incorporate the missing values in the analysis while sorting out the data with clustering (segmentation) technique. Each cluster (or segment) has different abundance (significance), i.e. a value which would give a percentage confidence of the model representing each cluster. This is one of the significant advantages in Data Mining where MVLR analysis is not meant to do the analysis of this complexity. However, both analysis methods have their own methods of analysis that will benefit for different purposes.

PQ survey data analysis using SNOB and ACPro provide the following factor analytic models.

6.3.1.1 Factor Analysis on $UPQI_{Average}$ using Data Mining

The PQ data of 70 sites were analysed using SNOB and ACPRO Data Mining packages and given the model for $UPQI_{Average}$ as shown in the Table 6.10.

The model shows that the PQ survey data has been classified into three clusters by the unsupervised classification of multivariate data using the data mining software which uses MML. This is a different approach from the MVLR analysis discussed in Section 6.2. MVLR analysis has one set of parameters whereas Data Mining analysis has three sets of parameters. The three sets of parameters are given as three clusters, i.e. three models which have been identified as having similar patterns of data. Abundance gives the percentage significance of those data in each cluster (segment). The cluster 2 has the most abundance (Highest significance) followed by Cluster 0 and Cluster 1. Thus, the Cluster 2 has been chosen as it has 83.4% confidence in the model for the data having a similar pattern.

Table 6.10 – Factor analytic model for $UPQI_{Average}$

Cluster	**0**					
Abundance	0.137					
SiteType	Extreme	Average				
	0.803	0.152				
LoadType	Commercial	Residential	Industrial	Rural	Remote	Missing
	0.055	0.524	0.119	0.219	0.043	0.040
Cluster	**1**					
Abundance	0.029					
SiteType	Extreme	Average				
	0.714	0.143				
LoadType	Commercial	Residential	Industrial	Rural	Remote	Missing
	0.500	0.100	0.100	0.100	0.100	0.100
Cluster	**2**					
Abundance	0.834					
SiteType	Extreme	Average				
	0.510	0.483				
LoadType	Commercial	Residential	Industrial	Rural	Remote	Missing
	0.253	0.281	0.240	0.158	0.062	0.070

The Data mining analysis given in Table 6.10 is graphically interpreted in Fig 6.5 where it is shown the distribution of factors given in each cluster. The Fig 6.5 graphically shows that the most significance (highest abundance) represented in cluster 2 as the 83.4% data belong to that cluster. Therefore the model given in cluster 2 for the analysis of $UPQI_{Average}$, has a 83.4 confidence in data.

Thus, cluster 2 (segment 2) would give the best model fit for $UPQI_{Average}$, where It could be compared with MVLR analysis given in Section 6.2.

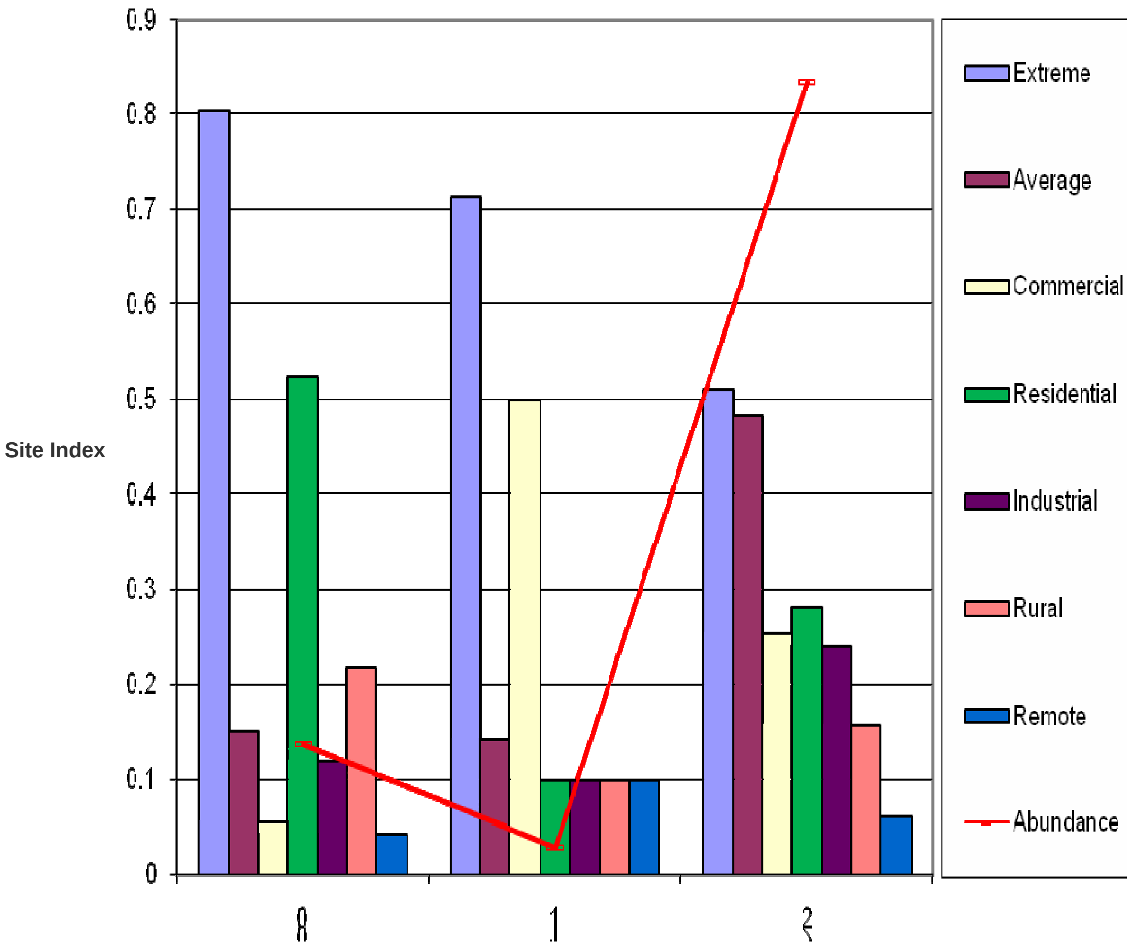


Figure 6.5 Data Mining Analysis of $UPQI_{Average}$ – Cluster Distribution

Table 6.11 (derived from Table 6.10) highlights the Cluster 2 representing highest abundance (Significance). In the model, Site type contributes to 51% extreme and 48.3% average sites whereas Load type contributes to 25.3% commercial, 28.1% residential, 24% industrial, 15.8% rural and 6.2% remote in distribution of indices of 70 Australian sites. However, there is missing data of 7%, which is unexplained. This is the error variable in this model. As it is already known that some data for remote sites are missing due to fault reading of those monitors, the error variable represents the true nature of data in the model.

Table 6.11 Data Mining Model with Most Significance

Cluster No.	Abund. (Signif.)	Site Type		Load Type					
		Average	Extreme	Commercial	Industrial	Remote	Residential	Rural	Missing
0	0.137	0.803	0.152	0.055	0.119	0.043	0.524	0.043	0.04
1	0.029	0.714	0.143	0.1	0.1	0.1	0.1	0.1	0.1
2	0.834	0.510	0.483	0.253	0.24	0.062	0.281	0.158	0.07

6.4 COMPARISON OF RESULTS OF TWO INDEPENDENT METHODS

This subsection of Chapter 6 gives a detailed comparison of the results of two independent methods of analysis for MVLR and Data Mining (section 6.2 and 6.3). The tools used in both methods of analysis are very different. The following discussion entails the suitable method for different purposes in Power Quality data analysis.

Comparing the results, the two methods of analysis needs to be done in a concise manner, because these methods have different ways of analysing the data. MVLR method is primarily a user driven and time consuming exercise where as Data

Mining analysis(USL) is a more automated approach which considers much advanced and modern techniques, such as the multivariate analysis using machine learning with missing data.

One issue is that the factors defined in the survey are relatively important in defining UPQI as to which ones are good and which ones are bad in terms of defining overall PQ condition. Another issue is to consider the noise level (high or low) in the PQ data set in relation to overall PQ condition of a site.

6.4.1 Comparison of Results for $UPQI_{Average}$

The comparison of both MVLR and Data Mining methods for $UPQI_{Average}$ is discussed in this sub section. For MVLR analysis, another set of values has been calculated representing the error variable in the data set, i.e. RMS (root mean square) error. The RMS error has not been taken into account for individual disturbance analysis in MVLR in Section 6.2. This is due to the fact that it is not possible to do an individual disturbance analysis using Data Mining (Unsupervised Learning) and compare them with MVLR.

RMS error is by definition the square root of the residual mean square which helps us to find whether the noise component is high. If the noise component i.e. RMS error is high, it is suggested that there may be other factors that contribute to UPQIAverage. One of those factors may be the type of the Utility or the Region where the sites were located.

MVLR Model (Graphical Representation):

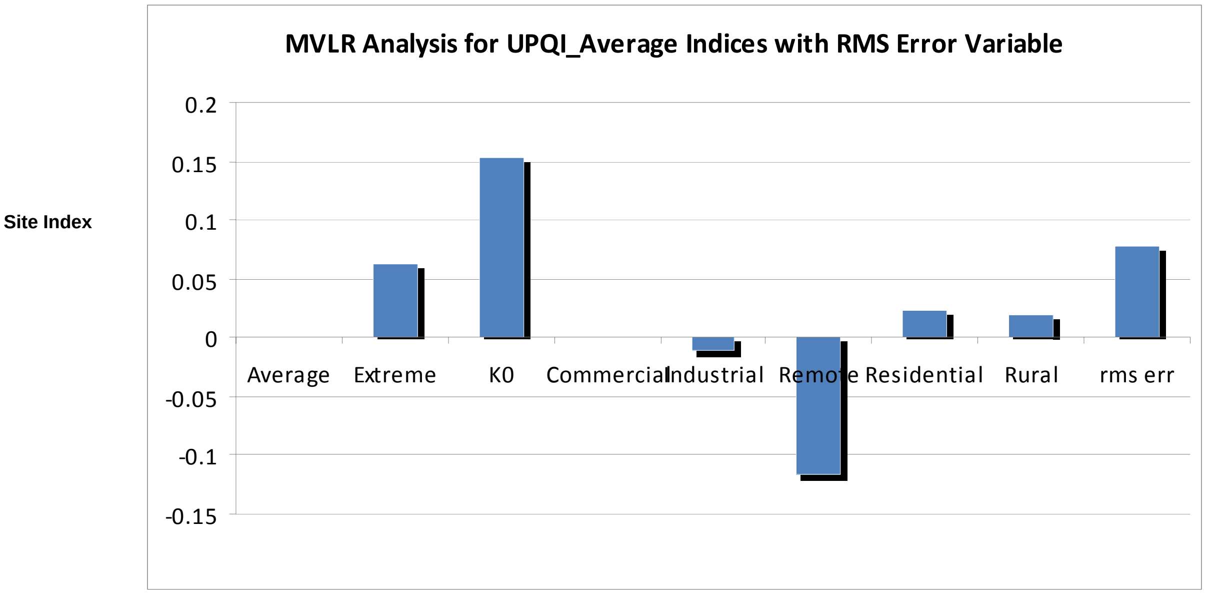


Figure 6.6 MVLR Model for UPQI$_{Average}$ Indices Distribution with RMS error

Data Mining Model (Graphical Representation):

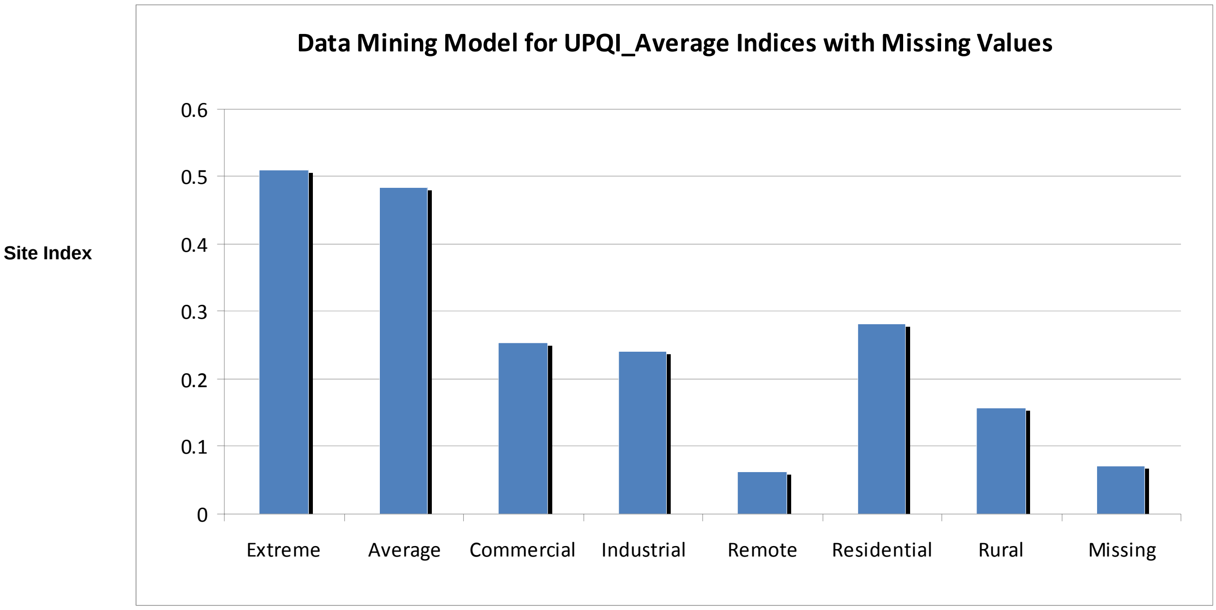


Figure 6.7 Data Mining Model for UPQI$_{Average}$ Indices Distribution

MVLR Model (Tabular Representation):

Table 6.12 MVLR Model for $UPQI_{Average}$ with RMS Error Variable

Constant	Site Type		Load Type					RMS Error
K_0	Average	Extreme	Commercial	Industrial	Remote	Residential	Rural	
0.152	0	0.063	0	-0.011	-0.116	0.023	0.02	0.078

Data Mining Model (Tabular Representation):

Table 6.13 Data Mining Model for $UPQI_{Average}$ with Missing Values

Site Type		Load Type					Missing
Average	Extreme	Commercial	Industrial	Remote	Residential	Rural	
0.483	0.510	0.253	0.24	0.062	0.281	0.158	0.07

The MVLR and Data Mining models as illustrated in Figures 6.6 & 6.7 (graphical representation) and Tables 6.12 & 6.13 (tabular representation) cannot be compared in terms of numerical values because of different algorithms used in both analysis methods. However, both these methods gave similar result; Both Site type and Load type are important factors in defining an overall PQ index where Extreme sites are the most significant factor for deciding PQ levels.

The Data mining model which is based on the Cluster 2 with 83% confidence shows that accuracy of the model is relatively good. In the MVLR and DM analysis, higher error variable suggests that there is a high noise component associated with the analysis. Also the error component in both analysis are very similar i.e. 0.078 and 0.07 for MVLR and DM respectively. This suggests that there may be other important factors for defining an overall PQ index, i.e. $UPQI_{Average}$. These factors may be Utility, Overhead or Underground feeder information or some other factors.

6.5 CONCLUSION

This Chapter discusses the details of factor analysis involved in long term PQ data analysis. Factor analysis has been used to identify hidden patterns and relationships that reveal the factors contributing to poor or good power quality performance in a Utility network. For this analysis, the Australian National Power Quality Benchmark Survey data has been analysed and compared for the dominant factors in long term PQ data. Multi Variable Linear Regression (MVLR) and Data Mining (DM) have been identified as a useful tool for factor analysis of complex power quality data.

It is shown that the factor analysis is a specific analysis technique used to identify hidden patterns and relationships where MVLR and DM techniques (USL) are two methods that can be tried to achieve factor analysis.

In the analysis there are two major factors considered based on the survey data available i.e. Site type and Load type. Site type mainly describes the impedance characteristics whereas Average sites are those sites close to the Transformer and Extreme sites are the ones further away from the transformer. Load type is related to the current disturbances which are present in the load and are identified as Commercial, Industrial, Residential, Rural and Remote load categories.

In the analysis both MVLR and Data Mining indicates that both Load type and Site type are equally important for defining PQ indices where the Extreme sites are the most significant factor for good or bad PQ levels in the network. It is also noted that during the comparison of both analysis methods, the RMS error variable in MVLR and Missing Values in DM analysis suggests that there is a higher noise component associated with the analysis where there may be other factors contributing to the overall PQ index. This indicates that the information obtained from the above analysis suggests that the present classification schemes is not good enough or may not have significance in the analysis. So that, it is suggested that the classification scheme to be improved by adding more new classification details as an improvement for future surveys. New such classifications can be the name of the utility or region where the sites are located, details of overhead and underground feeders etc.

Based on the analysis given above, both analysis methods are relatively important. MVLR analysis is a more time consuming method. However, it leads to specific objectives as required by the user. Data mining analysis, in this case unsupervised learning is a very quick way to perform analysis, but user has a less control over the analysis. In conclusion MVLR analysis is a better method for detailed analysis of PQ data for small number of sites. The number of sites to aim for MVLR analysis can be up to 500. DM analysis could be used for the analysis of PQ data for very large number of sites, i.e. more than 500. However, there is no rigorous statistical method to justify this number of 500. With overall comparison, the MVLR analysis is preferred over the DM (unsupervised learning) for the factor analysis of PQ data as it has a higher control and flexibility driven primarily by the user. However, this may not be the case for DM analysis using supervised learning.

It is important to note that the conclusions of this study are based on a relatively small sample of sites with some missing data. Expanding the number of sites in future surveys may change the results of the analysis significantly. The main aim of this chapter is to develop a methodology for factor analysis in general rather than to obtain specific results from the particular data set available at present.

Chapter 7

Conclusions

7.1 CONCLUSIONS AND RECOMMENDATIONS

The research presented in this thesis has described the development of methodologies and associated guidelines for power quality (PQ) data management and reporting in electrical utility systems in Australia. The implementation of such guidelines is necessary to allow effective management of all PQ disturbances affecting the deterioration of voltage waveform and their impact on end-user equipment.

A comprehensive discussion is given in this thesis, how the PQ data from a typical power quality monitoring system are converted into useful information that would be beneficial to utilities, regulators and customers. The process of analysing unstructured data into useful knowledge has been broadly described using a flow diagram given in Chapter 3.

The technical analysis described in the flow diagram has few key areas to be discussed. It is based on the data classification structure covering three categories of reporting, i.e. short term, medium term and long term reporting.

As the term suggests the short term reporting is meant to be short term alarming where immediate corrective action is required. In most situations this is performed within the PQ monitoring instrument itself, for information dissemination to the relevant party for taking preventative measures.

Medium term reporting overlooking the most regular and important reporting method in PQ monitoring where utilities need to understand its system performance for regulatory reporting, customer satisfaction and match the system performance with other utilities. The main achievement of the thesis is surrounded by the medium term reporting which is the determination of single index representing overall PQ level at a site and a utility. This is achieved by employing two methods; giving an overall index for one disturbance type and giving an overall index for all PQ disturbances. The method of aggregation of indices has shown that overall index can be defined for each PQ disturbance type and a single index for overall PQ level.

Long term reporting is the highest level of reporting leading to update limits and procedures given in PQ standards, understand PQ trends and correlations where there are possibilities of forecasting PQ and find out hidden patterns and relationships in long term PQ data.

In order to perform medium term and long term reporting, there is a need for a method of disturbance characterisation for the data obtained for the various types of PQ disturbances. A broad discussion on disturbance characterisation has been given in Chapter 3. In the initial extraction of PQ survey data there is a need to classify PQ disturbances into “continuous” or variation type (steady state voltage, unbalance, flicker and harmonics) and “discrete” or event type (Voltage sags, swells, oscillatory and impulsive transients) to analyse them separately.

The literature review discussed in Chapter 2 suggests that there has been many studies undertaken on continuous disturbance characterisation and related indices. However, there are no generally acceptable methods of characterisation of discrete disturbances found in any international standard. A generalised method of characterisation is proposed in Chapter 3 for discrete disturbances that are essentially based on a disturbance severity indicator (DSI) proportional to the customer complaint rate. As a representative set of distribution of customer complaint contours are not available directly from any measurements, scaled versions of CBEMA and ITIC curve have been used as the alternative hypothesis.

Chapter 4 describes a data compression structure given for medium term reporting where the power quality monitoring data is considered to be in several layers, with each layer being a summary of the one underneath it. PQ data structured in this manner has been represented in the form of a triangle called the “Power Quality Analysis Triangle (PQAT)”. Hence, if one summary figure suggests a problem, it is easy for the network planner to drill down to the appropriate detail in the next level down. The PQAT plays a major role in power quality data processing and reporting and is considered to be the backbone of the thesis.

The data compression structure in PQAT can be divided into two major steps. Summary statistics for one site over a specified time period, usually a one year, a process called “time compression” and the summary statistics of indices obtained over a specified aggregation of sites i.e. the data for larger and larger areas are brought together, a process called “space compression”. The process within the time compression stages is best explained by making the distinction between continuous and discrete disturbance types. For continuous disturbances, multi-parameter disturbances such as harmonics and flicker give rise to a single parameter via the two-step process of normalisation and consolidation, whereas a single parameter for each discrete disturbance type can be obtained by summing up the DSIs for particular discrete disturbance type at a given site.

When the initial data processing stages described in the PQAT has been completed, the single indices for the different power quality disturbance types can be used to rank sites for appropriate corrective actions. A comprehensive discussion of a determination of a single index representing overall power quality level is given: Single disturbance indices have been further combined into a Unified Power Quality Index (UPQI) for a site (time compressed) and for a utility (space compressed), depending on the specific power quality reporting requirement of a given survey category as detailed in Chapter 4. The reporting methodologies described in PQAT have been applied to representative sites of Australian utilities in Sections 4.4.3, 4.5.2 and 4.5.3, to illustrate its ability to rank sites for PQ improvements and rank utilities for PQ benchmarking.

A novel methodology is given in Chapter 5 to define discrete disturbance limits in relation to long term reporting where there are no generally acceptable limits that are yet to be found in international standards. The limits described are based on statistical information collected from large scale power quality surveys performed around the world. The discrete disturbance limits are defined as a number of customer events, for a given survey category (MV or LV) which are met by 95% of sites measured.

Finally, Chapter 6 discusses factor analysis as a tool to identify hidden patterns and relationships within a large quantity of power quality survey data based on the actual survey data of 11 Australian utilities. A factor analysis model has been developed using Multi Variable Linear Regression (MVLR) and complemented with Data Mining (DM) techniques. For this PQ survey data using Unsupervised Learning (USL) based on clustering techniques using Minimum Message Length (MML) techniques has been used.

It is shown that the factor analysis is a specific analysis technique used to identify hidden patterns and relationships that reveal the factors contributing to poor or good power quality performance of a network based on long term survey data. MVLR and DM techniques (USL) are two methods that can be tried achieve factor analysis. However, the MVLR is recommended to be used for PQ data analysis as it has a higher control and flexibility driven primarily by the user.

7.2 Recommendations for Further Research

Further research is needed for the establishment of automated power quality data management, reporting and analysis systems to be developed. As an initial step, an extensive research is needed on the impulsive transient propagation and behaviour in power systems. Also the use of data mining is recommended for the development of future automated power quality data analysis and reporting technologies. Further research into PQ data analysis using supervised learning (SL) and Unsupervised learning (USL) techniques in data mining are also recommended. The following are more detailed aspects for further work.

1. Disturbance propagation is one aspect of investigation of long term power quality survey data, some of which is already known to the PQ community such as harmonic state estimation in power systems. In general, it is evident that continuous disturbance problems are generated through the LV system. As an example most harmonics are generated and injected to the MV system via LV customers, while most discrete disturbance problems are generated through the MV system. However, there has not been much research done in the area of discrete disturbance propagation and there is a need for further research on impulsive transient propagation in power distribution systems.

Impulsive transients are expected to change shape as they propagate through the power system. Rise times, peak magnitudes, and frequencies are all affected by impedance and the configuration of the power system under investigation. There is no effective way, to predict how transients might look at locations other than where they are recorded. Also, because transient disturbances tend to change shape as they travel, the monitor location relative to the point of origin of transients is more critical than with long-duration voltage disturbances. For this a detailed transient propagation study is necessary.

2. Another area of research is to find any similarity of trends in surveyed sites, for which it is necessary to identify measures of association. Correlation and trend analysis would help utilities to identify problematic power quality disturbance trends

and their relationships to take preventative measures in planning and maintenance of their power networks. The data mining would be a useful tool to identify correlations and trends in PQ monitoring that can be used to predict future PQ trends. This can be further implemented to forecast power quality in future utility systems.

References

[1] Dugan, R.C., McGranaghan, M.F., Santoso, S., Beaty, H.W., *Electrical Power Systems Quality*. 2nd Edition, 2002, New York, McGraw Hill.

[2] Gellings, C., Samotyji, M., *Introduction*. Proc. Second International Conf. On Power Quality, Atlanta, USA, 1992, pp. 9-12.

[3] Rios, S., Castaneda, R., Veas, D., *Harmonic distortion and power factor assessment in city street gas discharge lamps.* IEEE Transactions on Power Delivery, Vol. 11, No.2, April 1996, pp. 1013-1020.

[4] Sabin, D.D., Sundaram, A., *Quality enhances reliability*. IEEE Spectrum, Feb. 1996, Vol. 33, Issue 2, pp. 34-41.

[5] Jurewicz, R.E., *Power quality study – 1990 to 1995.* Proc. IEEE INTELEC, 1990, pp. 443-450.

[6] Hughes, B.M., Chan, J.S., *Canadian national power quality survey*. IEE 14th International Conference on Electricity Distribution, CIRED'99, pp 2.19.1-5.

[7] Gosbell, V., Perera, S., Smith, V., *Improved Quality of Electrical Supply – Final Report.* Internal Publication, Integral Energy Power Quality Centre, University of Wollongong, April 1997.

[8] Meliopoulis, A.P.S., Kennedy, J., Nucci, C.A., Borghetti, A., Contaxis, G., *Power distribution practices in USA and Europe – Impact on power quality*. International Conference on Harmonics and Quality of Power (ICHQP'98), Greece, 1998, pp. 24-29.

[9] AS/NZS 61000.3.6: 2001, *Electromagnetic compatibility (EMC) Part 3.6: Assessment of emission limits for distorting loads in MV and HV power systems*, Australian Standards, 2001.

[10] AS/NZS 61000.3.7:2001, *Electromagnetic compatibility (EMC) Part 3.6: Assessment of emission limits for fluctuating loads in MV and HV power systems*, Australian Standards, 2001.

[11] CENELEC EN 50160: 2007, *Voltage characteristics of electricity supplied by public distribution systems*, European Standard, 2007.

[12] IEEE 1159:1995, *IEEE Recommended practice for monitoring electric power quality*. IEEE Press, New York, 1995.

[13] IEC 61000-4-30 (Ed. 2.0):2007, *Electromagnetic compatibility – Part 4.30: Testing and measurement techniques – Power quality measurement methods.* IEC Standard, 2003.

[14] IEC 61000-2-12:2004, *Electromagnetic compatibility – Part 2.12: Environment – Compatibility levels for low frequency conducted disturbances*

and signalling in public medium voltage power supply systems – Basic EMC publication. IEC Standard, 2004.

[15] IEC 61000-4-15:2003, *Electromagnetic compatibility – Part 4.15: Testing and measurement techniques – Flickermeter-Functional and design specifications*. IEC Standard, 2004.

[16] IEC 61000-2-8:2004, *Electromagnetic compatibility – Part 2.8: Environment – Voltage dips and short interruptions on public electric supply systems with statistical measurement results.* IEC Draft Technical Report – Edition 1.0, 2002.

[17] IEEE P1564:2003, *Voltage sag indices – Draft 5*. Working Group document for project group 1564, IEEE Press, New York, 2003.

[18] IEEE Std 446:1996, *IEEE Recommended practice for powering and grounding sensitive electronic equipment.* IEEE Press, New York, 1996.

[19] IEEE Std 1346:1998, *IEEE Recommended practice for evaluating electric power system compatibility with electronics process equipment.* IEEE Press, New York, 1998.

[20] IEEE Std 493: 1997, *IEEE Recommended practice for the design of reliable industrial and commercial power systems*. IEEE Press, New York. 1997.

[21] NRS-048-2 Rev.2: 2007, *Electricity Supply – Quality of Supply – Part 2: Minimum Standard, South African Power Quality Standards (ESKOM).* SABS Standards, 2003.

[22] AS/NZS 4376:1996, *Flicker meter – Functional and design specifications.* AS/NZS 4377: 1996, *Flicker meter – Evaluation of flicker severity.* Australian Standards, 1996.

[23] IEC 60038(Ed.7.0):2008 (Draft), *IEC Standard Voltages.* IEC Draft Technical Report – Edition 7.0, 2008.

[24] Sweeting, D.K., *How the 230 Volt standard affects you.* Special paper on Australian Voltage Standard, Sweeting consulting Pty. Ltd., St. Ives, NSW, Australia, 2000.

[25] IEC 61000-4-34 (Ed. 1.0): 2001, *Electromagnetic compatibility – Part 4-34: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current more than 16 A per phase.* IEC Standards, 2005.

[26] Gosbell, V.J., Perera, B.S.P., Herath, H.M.S.C., *New framework for utility power quality data analysis*. Proc. Australasian Universities Power Engineering Conference, AUPEC'01, Perth, Australia, September 2001, pp. 577-582.

[27] Gosbell, V.J., Burnett, I.S., Perera, S., Mertins, A., *Power quality survey and monitoring methodologies for the Australian electricity distribution industry.* Internal Publication (SPIRT grant application), Integral Energy Power Quality Centre, University of Wollongong, 2000.

[28] Kennedy, B., *Power quality primer*. 2000, New York, McGraw-Hill,.

[29] Gosbell, V.J., Robinson, D.R., Barr, R.B., Smith, V.W., *How should power quality be reported?*, Electrical Energy Society of Australia (EESA) annual conference (EESA'02), Canberra, 2002.

[30] Gosbell, V.J. et al, *Integral Energy Power Quality Centre – Newsletter No.5/ No.8*, University of Wollongong, Australia, 2001/2002.

[31] Sabin, D.D., Grebe, T.E., Sundaram, A., *RMS Voltage variation statistical analysis for a survey of distribution system power quality performance.* IEEE PES Winter Meeting, Vol.2, 1999, pp. 1235-1240.

[32] Dorr, D.S., *Point of utilization power quality study results.* IEEE Transactions on Industry Applications, Vol. 31, No.4, Jul/Aug 1995, pp. 658-666.

[33] Koval, D.O., Leonard, J.J., *Rural power profiles*. IEEE Transactions on Industry Applications, Vol. 30, No.2, March/April 1994, pp. 469-475.

[34] Targosz, R., Manson, J., *Pan European LPQI Power QualitySurvey.* Proc. 19th IEE International Conference on Electricity Distribution, Vienna, Italy, May 2007, Paper No. 0263.

[35] Arrillaga, J., Watson, N.R., Chen, S., *Power Systems Quality Assessment*. 2000, John Wiley & Sons.

[36] Euroelectic: Network of Experts for Standardisation, *Power quality in European supply networks – 1st Edition.* Union of the Electric Industry, Euro electric, February 2002.

[37] Kyei, J., Ayyanyar, R., Heydt, G.T., Thallam, R.S., Tang, J., *The design of power acceptability curves.* IEEE Transactions on Power Delivery, Vol. 17, No.3, July 2002, pp. 823-833.

[38] Heydt, G.T., Jewell, W.T., *Pitfalls of electric power quality indices.* IEEE Transactions on Power Delivery, Vol. 13, No.2, April 1998, pp. 570-578.

[39] Key, T., *Diagnosing power quality - related computer problems.* IEEE Transactions on Industry Applications, Vol. 15, No.4, July/August 1979, pp. 381-393.

[40] Heydt, G.T., Karady, G.G., Cummings, B., Tang, J., *Improved application of power acceptability curves and their application to certain three-phase loads.*

Journal of Electrical Machines and Power Systems, Vol. 27, 1999, pp. 737-751.

[41] IEEE Std. 1100:1999, *IEEE Recommended practice for powering and grounding sensitive electronic equipment.* IEEE Press, New York, 1999.

[42] Dorr, D.S., Hughes, M.B., Gruzs, T.M., Jurewicz, R.E., McClaine, J.L., *Interpreting recent power quality surveys to define the electrical environment.* IEEE Transactions on Industry Applications, Vol. 33, No. 6, November/December 1997, pp1480-1487.

[43] Gosbell, V., Robinson, R., *A study of continuous PQ disturbance levels in MV/LV distribution systems.* Proc. 17th IEE International Conference on Electricity Distribution, Barcelona, Spain, May 2003, pp. 2.60-1 – 2.60-5.

[44] Hughes, B.M., Chan, J.S., Koval, D.O., *Distribution customer power quality experience.* IEEE Transactions on Industry Applications, Vol. 29, No.6, Nov/Dec 1993, pp. 1204-1211.

[45] Gosbell, V.J., Mannix, D., Robinson, D., Perera, S., *Harmonic survey of a MV distribution system.* Proc. Australasian Universities Power Engineering Conference, AUPEC'01, Perth, Australia, September 2001.

[46] Bollen, M.H.J., *Voltage sags: Effects, mitigation and prediction.* Power Engineering Journal, Vol. 10, No.3, June 1996, pp. 129 – 135.

[47] Standards Australia Power Quality Handbook HB 264: 2003, An application guide to AS/NZS 61000.3.6 and AS/NZS 61000.3.7 for Distribution Systems up to 132kV, 2003 (Revision of HB 264: 2009 to be published).

[48] Sabin, D.D., Grebe, T.E., Brooks, D.L., Sundaram, A., *Rules based algorithm for detecting transient overvoltages due to capacitor switching and statistical analysis of capacitor switching in distribution systems.* Proc. IEEE Transmission and Distribution conference, Vol. 2, 1999, pp. 630 – 635.

[49] Sabin, D.D., Brooks, D.L., Sundaram, A., *Indices for assessing harmonic distortion from power quality measurements: Definitions and benchmark data.* IEEE Transactions on Power Delivery, Vol. 14, No.2, April 1999, pp. 489-495.

[50] Melhorn, C.J., Davis, T.D., Beam, G.E., *Voltage sags: Their impact on the utility and industrial customers.* IEEE Transactions on Industry Applications, Vol. 34, No.3, May/June 1998, pp. 549-558.

[51] Bollen, M.H.J., Sabin, D.D., *International coordination for voltage sag indices.* IEEE PES General Meeting, June 2005, pp. 437-442.

[52] Dabbs, W.W., Sabin, D.D., Grebe, T.E., Mehta, H., *Probing power quality data.* IEEE Computer Applications in Power, Vol. 7, No. 2, 1994, pp. 8 – 14.

[53] Joint Working Group (JWG) CIGRE C4. 07/ Cired (Formerly CIGRE WG 36.07), *Power quality indices and objectives - Final Working Group Report.* Cigre Publication, March 2004.

[54] Euroelectic: Network of Experts for Standardisation, *Power quality in European supply networks – 2nd Edition.* Union of the Electric Industry, Euroelectric, November 2003.

[55] IEC 61000-4-7: 2002, *General guide on harmonics measurements and instrumentation for power supply systems and equipment connected thereto.* IEC Standard, 2002.

[56] *EDF Emeraude Contract*: Electricite de France.

[57] Electricity Association Engineering Recommendation P28: *Planning limits for voltage fluctuations caused by Industrial, Commercial and Domestic Equipment in the UK.* September 1989.

[58] HQ Voltage characteristics: *Characteristics and target values of the voltage supplied by Hydro-Quebec transmission system*, July 1999. And for the distribution system: *Characteristics and target valued of the voltage supplied by Hydro-Quebec MV and LV systems*, 2002. www.hydro-qubec.com.

[59] Robert, A., Marquet, J. (on behalf of CIGRE WG 36.05), *Assessing voltage quality in relation to harmonics, flicker and unbalance.* CIGRE `92 paper 36-203, 1992.

[60] Bollen, M.H.J., *Definitions of unbalance*, IEEE Power Engineering Letters, November 2002.

[61] Brooks, D.L., Gunther, E.W., Sundaram, A., *Recommendations for tabulating RMS variation disturbances with specific reference to utility power contracts.* Cigre 36.05/ Cired 2 CC02 voltage Quality Joint working Group Paper, 2002.

[62] Conrad, L.E., Bollen, M.H.J., *Voltage sag co-ordination for reliable plant operation.* IEEE Transactions on Industry Applications, Vol. 33, No. 6, November/December 1997, pp. 1459-1464.

[63] Bollen, M.H.J., *Understanding Power Quality Problems: Voltage Sags and Interruptions*. IEEE Pres Series on Power Engineering, IEEE Press, 2000, New York.

[64] Bollen, M.H.J., *Comparing voltage dip survey results.* IEEE PES Winter Meeting, New York, January 2002, pp. 1130-1134.

[65] Gosbell, V.J., Perera, S., Herath, H.M.S.C., *Unified Power Quality Index (UPQI) for continuous disturbances.* 10th IEEE International Conference on

Harmonics and Quality of Power (ICHQP'02), Rio de Janeiro, Brazil, October 2002, Vol. 1, pp. 316 – 321.

[66] Gosbell, V.J., Robinson, D., Perera, S., *The analysis of utility sag data.* Proc. Of International Power Quality Conference (IPQC'02), Singapore, October 2002.

[67] IEC/TR2 61000-2-5, *Electromagnetic compatibility – Part 2: Environment – Section 5: Classification of electromagnetic environments.* IEC Standards, 2002.

[68] Herath, H.M.S.C., Gosbell, V.J., Perera, S., *Power quality (PQ) survey reporting: Discrete disturbance limits.* IEEE Transactions on Power Delivery, Vol. 20, N0. 2, April 2005, pp. 851-858.

[69] IEEE Document archives: IEEE P1564_99_01, *Combined ITIC-EUE guidelines, categories and indices curve.* URL: http://grouper.ieee.org.

[70] Fleming, M., *Predicting power quality.* Power Transmission and Distribution, 2000, p.42.

[71] Herath, C., Gosbell, V., Perera, S., Robinson, D., *A transient index for reporting power quality surveys.* Proc. 17th IEE International Conference on Electricity Distribution, Barcelona, Spain, May 2003, pp. 2.61-1 – 2.61-5.

[72] Koval, D.O., Xu, W., Salmon, J., *Power quality characteristics of rural electric secondary power systems.* IEEE Transactions on Industry Applications, Vol. 35, No. 2, March/April 1999, pp. 332-337.

[73] Herath, C., Gosbell, V., Perera, S., *MV Distribution voltage sag limits for network reporting.* Proc. Australasian Universities Power Engineering Conference, AUPEC'01, Christchurch, New Zealand, September, 2003.

[74] Gosbell, V.J., Baitch, A., Bollen, M.H.J., *The reporting of distribution power quality surveys.* CIGRE/ IEEE PES International Symposium on Quality and Security of Power Supply, Montreal, Canada, October 2003, pp. 48-53.

[75] Herath, H.M.S.C., Gosbell, V.J., Perera, S., *Benchmarking utilities for the impact of voltage sags on customers.* 11th IEEE International Conference of Harmonics and Quality of Power (ICHQP`04), Lake Placid, New York, USA, 12-15 September 2004, p. 425-429.

[76] Herath, H.M.S.C., Gosbell, V.J., Stirling, D., Perera, S., *Power quality (PQ) survey reporting: Unified power quality index (UPQI).* IEEE Transactions on Power Delivery, Manuscript is under preparation for submission.

[77] Mamo, X., Javerzac, J.L., *Power quality indicators.* Proc. IEEE Porto Powertech `01, Vol.1, September, 2001, pp 200-203.

[78] Brooks, D.L., Dugan, R.C., Waclawiak, M., Sundaram, A., *Indices for assessing utility distribution system RMS variation performance.* IEEE Transactions on Power Delivery, Vol.13, No.1, January 1998, pp.254-258.

[79] Koval, D.O., Xu, X., Salmon, J., *Power quality characteristics of rural electric secondary power systems.* IEEE Transactions on Industry Applications, Vol. 35, No.3, April 1999, pp.332-337.

[80] ENA (Energy Networks Association) – Reliability & Power Quality Committee Working Group (RPQC-WG4) Report, Proposed draft Australian/ New Zealand Standard. *Steady state voltage limits in public electricity systems,* AS/NZS 61000.3.X:2008.

[81] Didden, M., De jaeger, E., D'haeseleer, W., Belmans, R., *How to connect a voltage sag-measuring device: phase to phase or phase to neutral?,* IEEE transactions on Power Delivery, Vol. 20, No.2, April 2005, pp. 1171-1181.

[82] DS 327: 1997, *Chilean Power Quality Standard*. Chile, 1997.

[83] Robert, K., Balgobind, P., Johnson, P., Sigwebela, I., McCurrach, R., Bhana, D., Wilson, J., *Power quality management in a regulated environment: The South African experience.* CIGRE C4 Session 2004, Paris, France, 2004, pp.C4-110

[84] IEC 61000-2-2: 2002, *Electromagnetic compatibility – Part 2.2: Environment – Compatibility levels for low frequency conducted disturbances and signalling in public medium voltage power supply systems – Basic EMC publication.* IEC Standards, 2001.

[85] Dorr, D.S., *Point of utilisation of power quality study results.* IEEE Transactions on Industry Applications, Vol. 31, No.4, July 1995, pp.658-666.

[86] Groth, R., *Data mining: building competitive advantage*. 2000, USA, Prentice Hall.

[87] IEC 61000-3-13 (Ed. 1.0): 2008 (Draft Technical Report), *Electromagnetic compatibility – Part 3-2: IEC Standard for Voltage Unbalance.* IEC Standards, 2008.

[88] Santoso, S., Lamoree, J.D., *Power quality data analysis: From raw data to knowledge using knowledge discovery approach*. IEEE PES summer meeting, July 2000, Vol. 1, pp. 172-177.

[89] Oliver, J.J., Hand, D.J., *Introduction to Minimum Encoding Inferenc,* [TR 4-94], Department of Statistics, Open Univ., 1998.

[90] Asheibi, A., Stirling, D., Sutanto, D., *Analysing Harmonic Monitoring Data Using Supervised and Unsupervised Learning.* IEEE Transactions on Power Delivery, Submitted. Manuscript is under review. 2008.

[91] Han, J., Kembler, M., *Data mining: concepts and techniques*. 2001, San Francisco, Morgan Kaufmann Publishers.

[92] Wallace, C., Dowe, D., *Intrinsic classification by MML – the SNOB program*. Proc. 7th Australian joint conference on Artificial Intelligence, World Scientific Publishing Co., Armidale, Australia, 1994.

[93] Oliver, J., Roush, T., Gazis, P., Buntine, W., Baxter, R., *Analysing rock samples for MARS landing*. Journal of American Association of Artificial Intelligence, 1998.

[94] Gosbell, V.J., Perera, S., Smith, V.W., *Australian National Power Quality Benchmark survey (ANPQBS) Report.* Integral Energy Power Quality Centre, University of Wollongong, 2001.

[95] Herath, H.M.S.C., Gosbell, V.J., Perera, S., Stirling, D., *Power Quality Survey Factor Analysis using Multivariable Linear Regression (MVLR).* 13th IEEE International Conference of Harmonics and Quality of Power (ICHQP`08), Wollongong, NSW, Australia, September/October 2008, Paper 1145.

[96] Robinson, D.A., Gosbell, V.J., Perera, B.S.P., Herath, H.M.S.C., *SPIRT PQ Monitoring Methodologies – Report II: Survey Results Analysis.* Integral

Energy Power Quality Centre, University of Wollongong, Australia, May 2002.

[97] Gosbell, V.J., Herath, H.M.S.C., Perera, B.S.P., Robinson, D.A., *Sources of error in unbalance measurements.* Proc. Australasian Universities Power Engineering Conference, AUPEC'02, Melbourne, Australia, September 2002.

[98] Manilla, H., *Data mining: Machine learning, statistics, and data bases*. Proc. 8th International conference of scientific and statistical data base systems, 1996.

[99] IEC 61000-3-2 (Ed. 3.0): 2005, *Electromagnetic compatibility – Part 3-2: Limits - Limits for harmonic current emissions (equipment input current <= 16 A per phase).* IEC Standards, 2005.

[100] Spencer, P., *Applications of the Geometric Mean (electronic-publication)* . 2001, University of Toronto, Mathematics Network, Canada.

Appendix A

A1. TABLE1. IEEE 1159:1995 CLASSIFICATION OF PQ DISTURBANCES [12]

Please see print copy for Appendix A1

A2. DEFINITIONS OF VOLTAGE UNBALANCE

IEC definition [59]:

The IEC definition of voltage unbalance factor (VUF), i.e. negative sequence unbalance factor is,

$$VUF = \frac{V_n}{V_p} \tag{A2.1}$$

Where,

$\boldsymbol{V_n}$ - negative sequence voltage ; $\boldsymbol{V_p}$ - positive sequence voltage.

This can be determined using the three line to line voltages as follows:

$$\beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2} \quad VUF = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \tag{A2.2}$$

If line to line voltages are measured, above equation can be used. When line to neutral voltages are measured should not use in IEC equations whereas it has to be formulated in to line to line voltages.

NEMA definition [60]:

$$VUF = \frac{Maximum\ \ deviation\ \ from\ Mean\ of\ \{V_{ab}, V_{bc}, V_{ca}\}}{Mean\ \ of\ \{V_{ab}, V_{bc}, V_{ca}\}} \tag{A2.3}$$

The NEMA definition works only with magnitudes with no consideration given to phase angles.

A3. VOLTAGE FLICKER

Definitions [59]

Australian standards define two factors related to flicker severity; Pst and Plt for short term and long term respectively as below.

$$P_{st} = \sqrt[3]{\frac{\sum t_f}{10\,\text{min}}} \qquad \text{(A3.1)}$$

$$P_{lt} = \sqrt[3]{\frac{\sum t_f}{120\,\text{min}}} \qquad \text{(A3.2)}$$

where, t_f – Memory time.

Compatibility and planning levels [10]

Table A3.1 – Compatibility levels for P_{st} and P_{lt} in LV / MV power systems

	Compatibility Level
Pst	1.0
Plt	0.8

In relation to the flicker planning levels, only indicative values are given in IEC 61000-3-7 [10] as shown in Table A3.2, because planning levels may differ from case to case, depending on network structure and circumstances.

Table A3.2 – Indicative Planning levels for P_{st} and P_{lt} in MV, HV, EHV systems

	Planning Levels	
	MV	HV and EHV
Pst	0.9	0.8
Plt	0.7	0.6

A4. VOLTAGE HARMONICS

Definitions [59]

Australian standards require individual harmonics up to the 40th and the THD to be determined every very short interval [AS/NZS 61000.3.6:2001], i.e. the waveform is resolved into a fundamental V_1 and harmonics V_2, V_3,…..V_{40}.

Harmonic voltage (V_H): $$V_H = \sqrt{(V_2^2 + V_3^2 + ... + V_{40}^2)}$$

Voltage Total Harmonic Distortion (V_{THD}): $$V_{THD} = \frac{V_H}{V_N}(\%)$$

where, V_N nominal voltage

Compatibility and planning levels [9]

IEC 61000-3-6 gives limits for each harmonic up to the 40th and total harmonic distortion as given in Table A4.2.

Table A4.1 – Compatibility levels for harmonic voltages (in % of the nominal voltage) in LV and MV power systems

Odd harmonics non multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Order h	Harmonic voltage %	Order h	Harmonic voltage %	Order h	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,3	6	0,5
13	3	21	0,2	8	0,5
17	2	> 21	0,2	10	0,5
19	1,5			12	0,2
23	1,5			> 12	0,2
25	1,5				
> 25	0,2 + 1,3*25/h				
NOTE – Total Harmonic Distortion (THD): 8%.					

Only indicative values are given in Table A4.2 as per IEC 61000-3-6 because planning levels may differ from case to case, depending on the network structure and circumstances.

Table A4.2 – Indicative values of planning levels for harmonic voltage (in % of the nominal voltage) in MV, HV and EHV power systems

Odd harmonics non multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Order h	Harmonic voltage %		Order h	Harmonic voltage %		Order h	Harmonic voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1,6	1,5
7	4	2	9	1,2	1	4	1	1
11	3	1,5	15	0,3	0,3	6	0,5	0,5
13	2,5	1,5	21	0,2	0,2	8	0,4	0,4
17	1,6	1	> 21	0,2	0,2	10	0,4	0,4
19	1,2	1				12	0,2	0,2
23	1,2	0,7				> 12	0,2	0,2
25	1,2	0,7						
> 25	0,2 + 0,5*25/h	0,2 + 0,5*25/h						
NOTE – Total Harmonic Distortion (THD): 6,5% in MV networks, 3% in HV networks								

A5. FACTOR ANALYSIS – DISCUSSION ON THE AVAILABLE SURVEY DATA

The Australian National Power Quality Benchmark Survey (ANPQBS) data of 70 sites across Australia [94] would be very useful to identify many factors that will influence good or bad PQ levels, if appropriate diagnostic procedures were implemented. So that, the survey site selection and defining categorical variables were key issues in this context. The details of site selection and defining categorical variables are given below that was primarily suggested by the Australian Utilities.

A5.1 Site Selection

Sites selection of the ANPQBS has been carried out in the following manner [93]. The locations at 240/415 V were selected within each participating utility's network. The sites were spread across geographic areas and bulk supply points, and across load categories, i.e. sites that were predominantly residential, commercial, industrial, rural, or remote, depending on the individual network. One set of site locations was selected in locations likely to show power quality problems. The remaining set of site locations were selected from more normal parts of the network. Selection of suitable locations was made in close consultation with each participating utility. Common site selection criteria were applied in all cases. During the selection process, the following were considered.

(i) Fault history of the network

(ii) Operating diagrams/maps showing feeder lengths and circuit arrangements

(iii) Information on loads have a major impact on network

(iv) Relevant previous survey data

(v) Major planned system alterations over the period of the survey.

A5.2 Defining Categorical Variables

Defining categorical variables, (i.e. **Site** and **Load** categories) were based on the information obtained from each utility. Once the load category is defined as **Residential**, **Commercial**, **Industrial**, **Rural** and/or **Remote**, site categories were identified as follows. The poor sites i.e. **Extreme** sites were usually selected at the end of the 240/415V distributor, and the **Average** sites were usually located at the beginning of the feeder or a distributor close to the 11kV/ 415V Substation . The following guidelines were followed for selection of sites with particular power quality problems:

(i) Steady state voltage and unbalance – residential area on outskirts of town

(ii) Sags – industrial area that lightning prone or an area subject to motor starting

(iii) Harmonics – commercial area (say shopping area) outside of city centre

(iv) Transients – area badly affected by capacitor switching and lightning

The sites chosen were preferably on mixed distributors (residential, commercial, industrial) even though one load type may have dominated. Another preference was to nominate sites with the possibility of being subject to the dominance of each load category.

A6 MULTIVARIABLE LINER REGRESSION (MVLR)

A6.1 MVLR analysis examples (theoretical)

Suppose, each site is categorised by,

- Site type (Suburban, CBD)
- Load type (Commercial, Industrial)

Also, suppose there is a need to determine whether site type or load type is the most important factor determining voltage unbalance.

Assume, Voltage unbalance factor (VUF),

$$VUF = K_0 + K_{Site}\ (\text{Site types}) + K_{Load}\ (\text{Load types})$$

Where, each term is a constant to be determined by means of multi variable linear regression (MVLR).

To reduce variables, it is assumed that K_{Site} (Suburban) and K_{Load} (Commercial) are zero, i.e. they are incorporated into K_0. It is solved for all constants using a least squared fit in Excel solver. The two examples given below would give a better representation of the above methodology.

Example 1:

This example gives as to how the constants (VUF's) are incorporated into K_0 when they are forced to zero.

(i) VUF's with no constant (K_0) introduced,

	Site type		**Load type**	
	Suburban	CBD	Commercial	Industrial
VUF	0.2	0.3	0.2	0.1

Based n the above,

(a) Suburban commercial sites will have VUF of 0.4 (i.e. 0.2 + 0.2).
(b) CBD commercial will have VUF, 0.5 (i.e. 0.3+0.2).
(c) Suburban industrial will have VUF, 0.3 (i.e.0.2 + 0.1).
(d) CBD industrial will have VUF, 0.4 (i.e. 0.3+0.1)

(ii) VUF's with constant (K_0),

In this section the constant (K_0), will introduce by forcing some indices to zero such that the configuration of above data will have no effect as below,

		Site type		Load type	
	K_0	Suburban	CBD	Commercial	Industrial
VUF	0.4	0	0.1	0	-0.1

After introducing the constant above indices structure given in (i) will calculate as below,

(e) Suburban commercial sites will have VUF of 0.4 (i.e. 0.4 + 0 +0).
(f) CBD commercial will have VUF, 0.5 (i.e. 0.4 + 0.1 + 0).
(g) Suburban industrial will have VUF, 0.3 (i.e.0.4 + 0 - 0.1).
(h) CBD industrial will have VUF, 0.4 (i.e. 0.4 + 0.1 –0.1)

Example 2:

This example gives an analysis of unbalance based on the regression equation that has been constructed using set of unbalance data of large quantity of sites for a situation similar to the Example 1.

The analysis of 100 sites shows that the unbalance can be approximated well by the following regression equation.

VUF = 0.5 + [0.3 (Suburban) + 0.1 (CBD)] + [0.1(Commercial) + 0.2 (Industrial)]

Based on the above equation in relation to the unbalance, some details of those sites can be described as given below,

(i) VUF in relation to commercial loads of suburban sites are described as,
0.5+0.3+0.1 = 0.9

(j) Most important factor determining unbalance is suburban (contributes to range of 0.3)

(k) Lowest levels of unbalance are found in commercial loads of CBD sites.

A6.2 MVLR analysis examples (applications)

MVLR analysis on voltage unbalance for all sites

Analysis of survey data for all sites (in relation to section 6.2.2 in Chapter 6), including the remote sites are given below.

Table A6.1 MVLR Analysis on Voltage Unbalance (Including Remote Sites)

Constant	Site Type		Load Type				
K_0	Average	Extreme	Commercial	Industrial	Remote	Residential	Rural
0.136	0	0.111	0	0.005	-0.2473	0.101	0.091

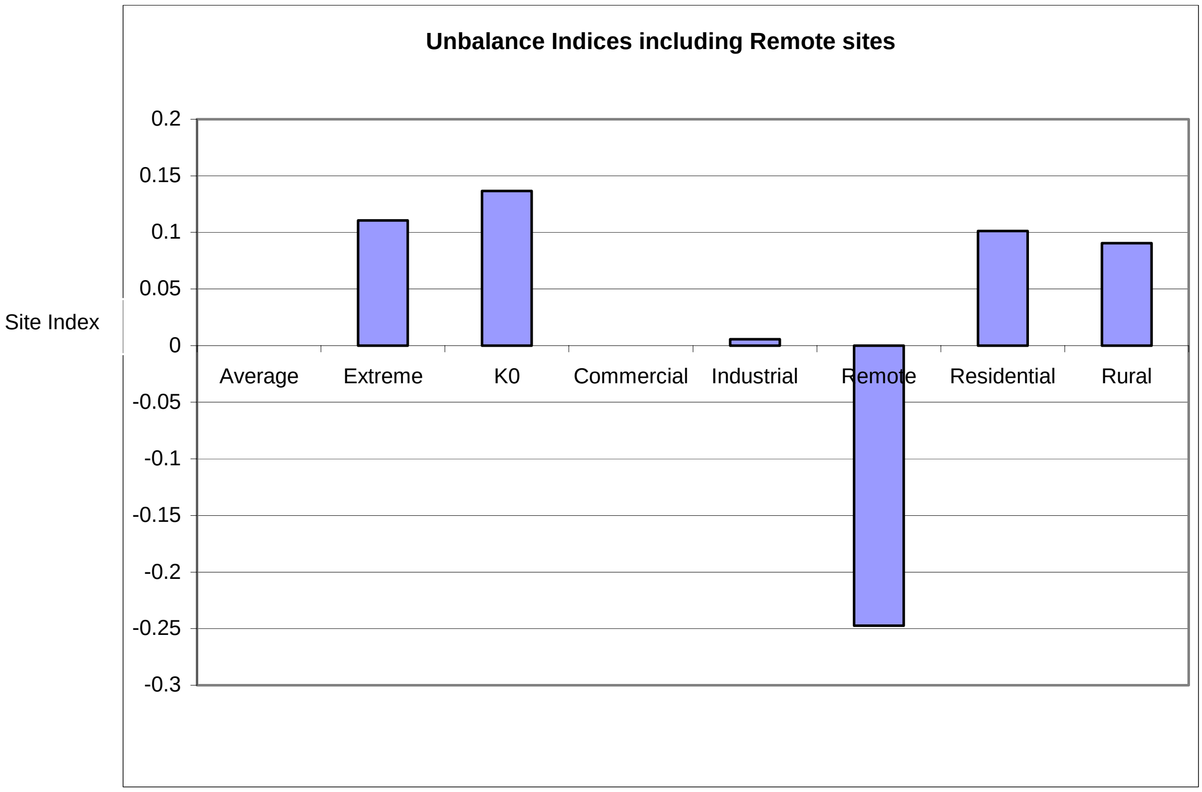


Figure A6.1 MVLR Analysis of Voltage Unbalance – Option2

As shown in the Chapter 6, Table 6.1, the Unbalance data for Remote sites were not recorded. This is due to a fault in the PQ monitors that have been downloading data for those sites. However, Voltage and Harmonic data were recorded for those sites, where the normalised Indices were calculated accordingly (Table A6.1 and Figure A6.1 given in this Appendix A6). The unbalance data were not recorded for Remote sites and the analysis considered the contribution of the "Remote" factor is zero. However, there are other contributions – e.g. K0 and Site Type. It also, shows the validity of MVLR model even though the impact of Remote sites would significantly change the Indices structure.

MVLR analysis on $UPQI_{Average}$ for all sites

The change in the model made by adding Remote sites (Load type) in to the MVLR analysis as given below.

Table A6.2 MVLR Analysis on $UPQI_{Average}$ including Remote Sites

Constant	Site Type		Load Type				
K_0	Average	Extreme	Commercial	Industrial	Remote	Residential	Rural
0.152	0	0.063	0	-0.011	-0.116	0.023	0.02

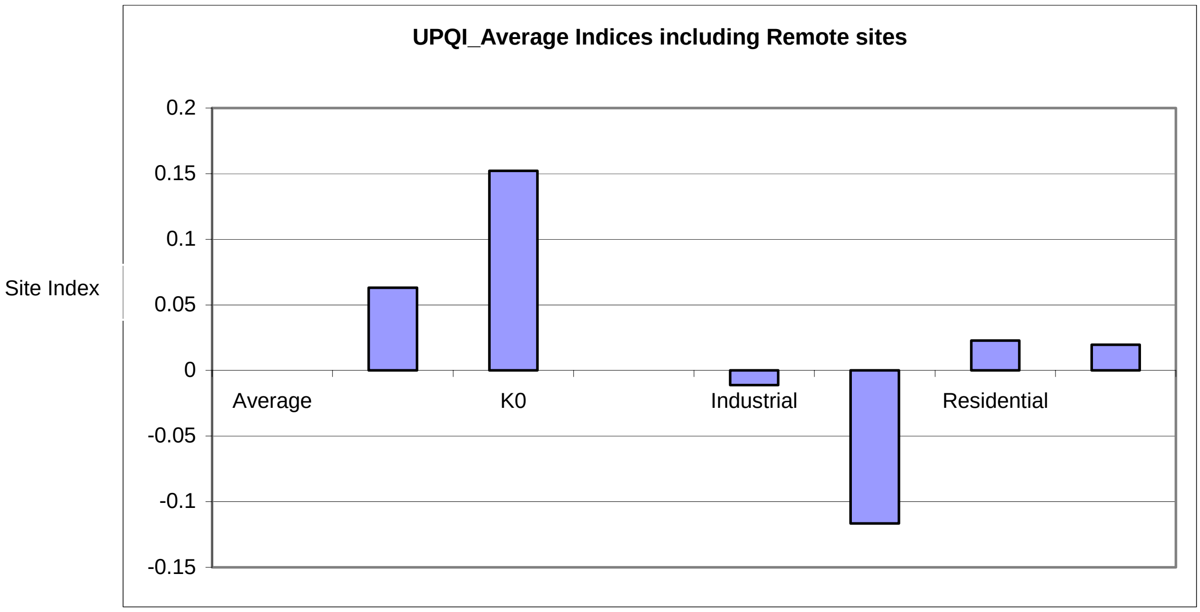


Figure A6.2 MVLR Analysis of $UPQI_{Average}$ – Option 2

Fig. A6.2 shows that Remote sites accounted for a significant shift in the model for load type where the model shows remote sites accounted for better overall PQ in relation to load categories. However, Extreme sites are accounted for worst overall PQ, (i.e. the significance of site factor remain unchanged). (Average,Remote) sites are the best performing sites for UPQI Average based on the available data (It is known that Unbalance data of Remote sites were missing in the analysis, therefore, this may not give the actual performance for UPQI Average of all sites). So that based on the available data, (Average, Rural) and (Average, Residential) would give the better PQ level for deciding overall PQ condition of a site.

A7. UNSUPERVISED CLUSTERING USING MML [94]

There are two important learning strategies in data mining techniques; Supervised Learning (SL) and Unsupervised Learning (USL) as described in section 6.3 of Chapter 6. The factor analytic model described below is based on USL techniques and unsupervised clustering with Minimum Message Length (MML) encoding [89-91]. Unsupervised clustering is based on the premise that there are several underlying classes that are hidden or embedded within a data set. The objective of these processes is to identify a n optimal model representation of these intrinsic classes, by separating the data into multiple subgroups or clusters. The selection of data into candidate subgroups is typically subject to some form of objective function such as a probabilistic model distribution. For any arbitrary data set several possible models or segmentations might exist, each with a plausible assortment of formulated clusters. An evaluation procedure, a technique based on Minimum Message Length (MML), or Minimum Description Length (MDL) encoding criterion, is used to evaluate each successive set of segmentations in order to identify the best model. This methodology is also well known as mixture modelling. In this technique, the measured data is considered as an encoded message. The Minimum Message Length inductive interference, as the name implies, is based on evaluating models according to their ability to compress a message containing the data. Compression methods obtain high compression by forming good models of the data to be encoded.

The encoded message consists of two parts. The first part describes the model and the second part describes the data values using that model. The model parameters and the data values are first encoded using a probability density function (PDF) over the range of the data and assuming a constant accuracy of measurements (AOM) within this range. The total encoded message length (two parts) for different models is then calculated and the best model is the one that results in the shortest total message length. The MML expression for a data set with a normal distribution having a mean (μ) and a standard deviation (σ) is given as [89],

$$Message\ Length = \log_2 \frac{range_{\mu}}{AOPV_{\mu}} + \log_2 \frac{range_{\sigma}}{AOPV_{\sigma}} + N \log_2 \frac{\bar{s}\sqrt{2\pi}}{\varepsilon} + N \frac{s^2 + \frac{\bar{s}^2}{N}}{2\bar{s}^2} \log_2(e) \quad \text{--------- (A7.1)}$$

The first two terms in the equation (A7.1) are the model part and the last two terms are the data part.

Where,

N : number of data samples

$range_{\mu}$: ranges of possible μ values

$range_{\sigma}$: ranges of possible σ values

ε : accuracy of measurement

$AOPV_{\mu}$: accuracy of the parameter value of μ

$$AOPV_{\mu} = \bar{s}\sqrt{\frac{12}{N}} \quad \text{---------(A7.2)}$$

$AOPV_{\sigma}$: accuracy of the parameter value of σ

$$AOPV_{\sigma} = \bar{s}\sqrt{\frac{6}{N-1}} \quad \text{---------(A7.3)}$$

s : sample standard deviation

$$s = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{--------(A7.4)}$$

$\bar{s}$: sample standard deviation

$$\bar{s} = \sqrt{\frac{1}{(N-1)}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad \text{--------(A7.5)}$$

where, $\bar{x}$: sample mean

This methodology is also known as mixture modelling or intrinsic classification. Mixture models typically perform better than those based on prior distance measures, such as a nearest neighbour algorithm.

A8. SOURCES OF ERRORS IN UNBALANCE MEASUREMENTS

This Appendix presents the details of the measurement errors that can be experienced in utility PQ monitoring where the particular attention is given to the voltage unbalance. This would help to determine optimised monitoring and methodologies for effective data analysis and PQ reporting. As described in [97] the errors of unbalance measurements will be discussed in two parts, (i) instantaneous unbalance and (ii) time varying unbalance.

A8.1 Instantaneous unbalance

A8.1.1 Errors due to use of line-neutral voltages

There are two methods that can be used in a power quality monitor for calculation of voltage unbalance factor (VUF) strictly in accordance with standards. NEMA definition has not been detailed here [see Appendix A2].

(i) The measurement of fundamental line-line voltage for each cycle using equation (A2.2).

(ii) Measurement of fundamental line-neutral voltages and fundamental phase angles and the use of symmetrical components to calculate VUF using equation (A2.1).

Some instruments are only able to measure line-neutral voltages when used directly connected to a LV measurement point. It has been investigated that if it is possible to obtain reliable measurements of VUF when only the magnitudes of line-neutral voltages are available. There are two plausible approaches that can be applied to the readings in order to make a VUF calculation possible

(i) assume the zero sequence component is negligible and use the line-neutral voltages directly into (A2.2)

(ii) assume the relative phase angles to be insignificantly disturbed from 120°, determine line-line voltages and substitute into (A2.2).

Use of line-neutral voltages in equation (A2.2)

If no zero sequence voltages are present, the direct application of line-neutral voltages in formula (A2.2) would give the correct unbalance factor. We have investigated the effect of zero sequence by studying several scenarios by means of a spreadsheet. Some results are given in Table A8.1 for fixed line-line voltages of 410, 415 and 420V, giving a negative sequence unbalance of 1.4%. We set-up a zero sequence component of 1% and with varying phase relative to the Vab line-line voltage.

Table A8.1 – Calculated unbalance versus zero sequence phase angle

Zero sequence phase angle	Calculated unbalance (%)
0^0	1.25
60^0	0.39
120^0	1.24
180^0	2.17
240^0	2.39
300^0	2.10

It can be seen that the calculated unbalance varies from 0.4 to 2.4%, that is between the sum and the difference of the negative and zero sequence unbalance factors. We have made many other studies with similar results, and the observation is thought to be very general.

Use of line-neutral voltages with the assumption of 120^0 relative phase angles

As a preliminary investigation of the importance of phase angle deviations on VUF, phase angles have been determined to give unbalance factors of 1% and 2% with constant voltage magnitudes as shown in Table A8.2. It is seen that small variation of phase angle causes higher VUF variations in relation to constant unbalance. For example a change of 2° can result in 2% unbalance and the assumption of 120° relative phase shift between line-neutral voltages may give an erroneous VUF value.

Table A8.2 – Phase angle deviation

Line-neutral Voltage	Phase angle deviation		
	Constant Magnitude	Phase angle φ_1	Phase angle φ_2
V_{an}	240	0	0
V_{bn}	240	-119	-118
V_{cn}	240	+119	+118
VUF %		1%	2%

A mathematical study has been done for the use of line-line voltages calculated from line-neutral voltages with the assumption of 120° relative phase angles for the case of no zero sequence voltage. When the negative sequence unbalance is small (a few percent) it is possible to show that the unbalance computed is half of the correct value.

When zero sequence voltage is present, spreadsheet scenarios suggest that the calculated value varies from the half the difference to half the sum of the negative and zero sequence unbalance factors, depending on the relative phase angle of zero sequence. This is clearly an extension of the result from the preceding Subsection (Use of line-neutral voltages in equation A2.2).

It is concluded that there is no reliable method of determining negative sequence unbalance from line-neutral voltages unless it is known that the zero sequence is relatively small. If this is the case line-line voltages should be substituted in to equation (A2.2).

Although the above conclusion holds for the calculation of instantaneous VUF, it can be shown that line-neutral voltages can be used for the measurement of average VUF over time periods such as 10 minutes.

A8.1.2 Errors due to harmonic distortion

Measured data from PQ monitoring campaigns where there are low cost monitors used may have recorded the rms voltages with harmonics included. Harmonics can be balanced or unbalanced over the three phases. Detailed discussion on the VUF calculated for both situations is given with examples.

Unbalanced fundamental with balanced harmonics

In Table A8.3, two cases have been selected giving both small and large values of

VUF with balanced harmonic distortion on all three phases. It is seen that small VUF remain unchanged while large VUF will decrease on higher harmonic conditions. However, these changes are so small as to be negligible.

Table A8.3 – VUF with balanced harmonics

Line Voltage	V_{THD}					
	0%		2%		8%	
V_{ab}	415	415	415.08	415.08	416.33	416.33
V_{bc}	416	410	416.08	410.08	417.32	411.34
V_{ca}	414	424	414.08	424.08	415.33	425.30
V U F %	0.28	1.97	0.28	1.97	0.28	1.96

Unbalanced fundamental with unbalanced harmonics

Table A8.4 shows that the VUF calculated with both a small and large voltage total harmonic distortion (V_{THD}) conditions respectively in relation to the unbalanced harmonics.

Table A8.4 – VUF with unbalanced harmonics

Line Voltage	V_{THD}					
	0%， 0%， 0%		0%， 2%， 2%		0%， 8%， 8%	
V_{ab}	415	415	415	415	415	415
V_{bc}	416	410	416.08	410.08	417.32	411.34
V_{ca}	414	424	414.08	424.08	415.33	425.30
VUF %	0.28	1.97	0.28	1.97	0.14-0.47	1.76-2.13

In Table A8.4, the same voltages were selected as the previous example to give a good comparison on unbalanced harmonic distortion among three phases. The effect is given as a range of values since it depends on how the unbalance in the harmonics aligns with that in the fundamental voltage. The effect is negligible at medium levels of harmonics, but can approach ±0.2% at values near the harmonic limit. The overall effect of harmonics on unbalance calculations can be seen to be negligible at normal harmonic levels.

A8.2 Time varying unbalance

A8.2.1 Errors due to incorrect averaging

IEC 61000-4-30 [13] recommends monitoring and reporting using 10-minute interval in relation to unbalance. The measurement aggregation algorithm is performed using the square root of the mean of the squared input values, in other words the rms average.

Let’s consider the distinction between two possible methods of measuring VUF in a time-varying situation: (i) calculation from voltages averaged over 0.2 sec followed by averaging the VUF over 10 minutes (“Average of the Unbalance”) or (ii) calculation directly from 10-minute rms average line-line voltage values (“Unbalance of the Average”). The first method follows [13] while the second might be used by cheaper instruments or for off-line calculation when only 10 minute average values of voltage are available.

The two methods will give different values for VUF under time-varying conditions. It is possible to have a situation where the three phase voltages vary differently and have identical 10 minute average values. In this situation the “Unbalance of the

Average" will be zero while the "Average of the Unbalance" is non-zero. Since any unbalance in average voltages must be reflected in the instantaneous voltages, it can be generalized and state that method (ii) will always give a VUF that is smaller than method (i).

Each method has its own use. The Average of the Unbalance gives a measure of the effect on induction motor loads as it is required for the setting of acceptable limits by [13]. The "Unbalance of the Average" gives a measure of the unbalance which stays constant over 10 minute period which is most likely due to unbalanced connection of loads and the intrinsic unbalance in the power system. It is attempted to gain insights into how much the Average of the Unbalance can exceed the Unbalance of the Average. Figure A8.5 shows field measurements that were taken from the Arbiter Systems Inc. GPS synchronized advanced power quality analyser connected to a 415V three-phase line. This instrument gives voltage readings every second.

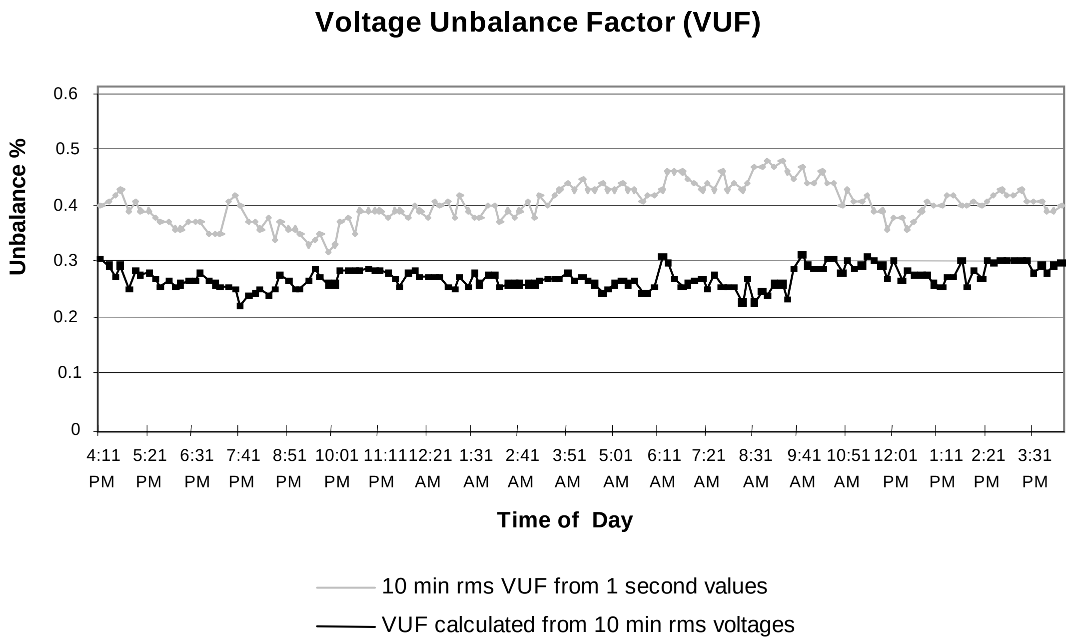


Figure A8.1 - VUF calculated by different algorithms.

Figure 8A.5 shows the Average of the Unbalance (grey) with unbalance calculated from 1 second voltage readings and then averaged over 10 minutes, and also the Unbalance of the Average (black) calculated from the 10 minute voltage readings. It is observed that the Average of the Unbalance always higher than the Unbalance of the Average by about 50%. It needs to be investigated if this ratio holds across a wide variety of sites. [13] actually specifies the Average of the Unbalance using 0.2 second readings rather than the 1 second readings that we were able to achieve. It could be possible that the unbalance readings required by [13] are even larger than the grey curve shown. A provisional recommendation following this study is that where Unbalance of the Average readings are available, the Average of the Unbalance readings are estimated to be 50% larger.

A8.2.2 Errors due to use of line-neutral voltages

Laboratory measurements were taken using two Gridsense PM30 POWERmonics (former CHK) which were connected to the same point in a laboratory supply to measure line-line and line-neutral voltages over a 10 minute intervals. Figure 8A.6 shows the comparison of VUF calculated from both average rms line-line and line-neutral voltages with the assumptions of (i) negligible zero sequence and (ii) negligible deviation of relative phase angles from 120^0. Figure 8A.6 shows that the calculation from the use of line-neutral values directly in (A2.2) gives almost exactly twice the value as for the use of line-line values inferred from the assumption of 120° relative phase angles. It is shown that the first approach gives a trend which is reasonably close to that of the correct use of line-line values. The agreement is sufficiently close that one could consider the use of line-neutral values to estimate the 95% values of unbalance. This suggests that the zero sequence magnitudes and phase angles vary quickly and randomly over the 10 minute interval so that their average effect on the unbalance calculation is very small.

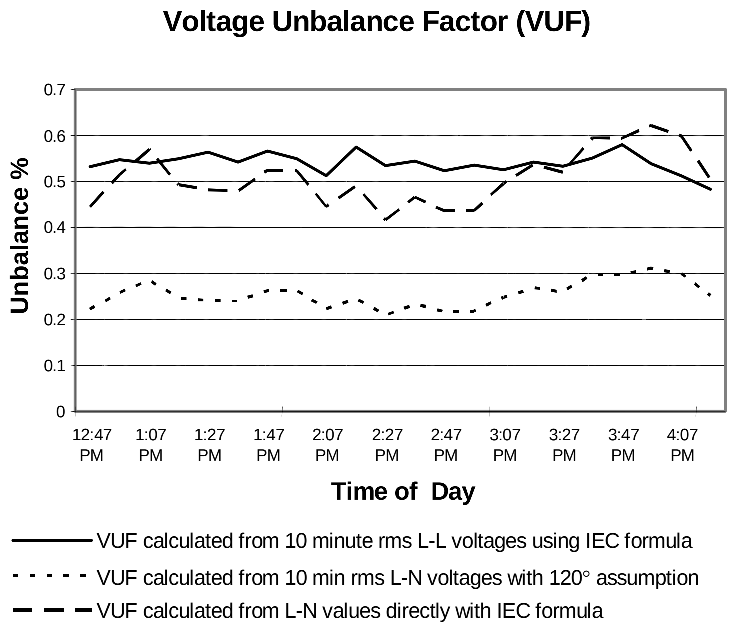


Figure A8.2 - VUF calculated by different algorithms.

It appears that, where only 10 minute line-neutral voltage values are available, the "Unbalance of the Average" can be estimated closely by substitution of these values directly into (A2.2), even when there is zero sequence present. It would be useful to explore this hypothesis with a wide variety of other LV sites.

A9. RPM INDEX

Reliable Power Meters (RPM) have developed [70] a technique for determining an index using CBEMA curve overlays (Fig. A9.1) which is known as the Power Quality Index (PQI) that is used to cover both overvoltage and undervoltage events.

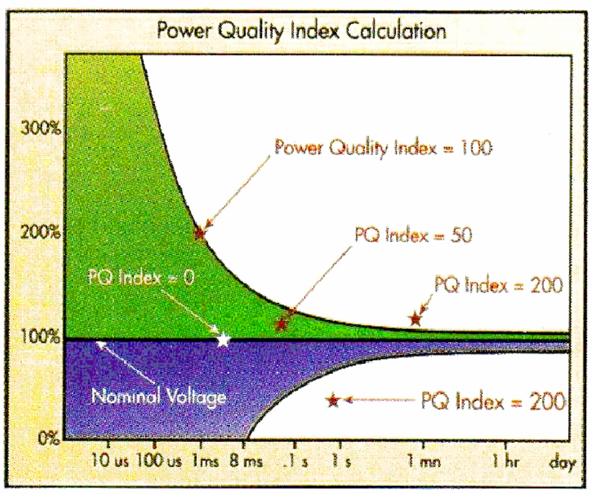


Figure A9.1 – RPM power quality index.

Suppose a voltage event has co-ordinates (T,V). Define the corresponding CBEMA voltage $V_{CBEMA}(T)$ as a voltage on the CBEMA curve corresponding to duration T. The RPM PQI for an overvoltage or undervoltage event is given by,

$$PQ\ Index = \left| \frac{V - 100\%}{V_{CBENMA}(T) - 100\%} \right| \cdot 100\% \qquad \text{--------} \quad \text{(A9.1)}$$

The RPM PQ Index corresponds to an event severity index. The deficiencies of RPM index have been addressed in the Chapter 3 of the Thesis.

Appendix B

B1. Details of Major Power Quality Surveys

B1.1 EPRI DPQ Project

EPRI DPQ Project [32] is a survey entitled "An Assessment of Distribution Power Quality." The goal was to perform the most thorough study to describe power quality levels on primary distribution systems in the United States. The collection of data took place from June 1993 to September 1995. Approximately 50 GB of PQ data were gathered during this time period, including both steady-state measurements and triggered events. The feeders monitored represented a diverse sampling of US distribution systems, with voltage ratings from 4.16 to 34.5 kV and lengths from 1 to 80 km. The feeders represented a wide geographic sampling that covers rural, suburban, and urban load densities and included residential, commercial, and industrial load types. One-third of the monitors were located at substations just down line from the feeder circuit breaker, while the remaining monitors were randomly placed along three-phase sections of the feeder primary. The feeder selection process identified a population of monitoring locations which would be an unbiased representation of the types of distribution feeders present across United States.

B1.2 NPL survey

In 1990, the NPL initiated a five year-survey [32] of single phase normal mode electrical disturbances. The objective of the survey was to provide a large, well-defined database of recorded disturbances that profile power quality at typical points of power usage. Single-phase line-to-neutral data was collected at the standard wall receptacle. The disturbances found at this point of utilisation are often coupled into computers and other electronic appliances. Data was collected from 130 sites within United States and Canada.

The sites included a broad range of building locations, building types, and population areas. Included were locations where participants felt they had power quality problems and, also, those where no problems were perceived. The monitored locations were geographically dispersed throughout the United States and Canada.

B1.3 CEA survey

In 1991, the CEA began a three-year survey of power quality [33]. The objectives of the survey were to determine the general levels of PQ in Canada. The results would serve as a baseline against which future surveys could be compared to determine trends. Twenty-two utilities throughout Canada were participated in the survey, with a total of 550 sites monitored for 25 days each.

Residential, commercial, and industrial sites were monitored at their 120 V or 347 V service entrance panels. Monitoring was done at the service entrance panel because it was considered to offer a blended average of the power quality throughout the customer's premises. The CEA decided that monitoring further into the premises could have made the results unduly influenced by electrical loads on an individual branch circuit, while monitoring at the distribution feeder would not have shown disturbances originating within the customer's own premises. Only line-to neutral voltages were monitored. Steady-state and triggered events were captured.

B1.4 Australian National Power Quality Benchmark Survey

Integral Energy PQRC (then PQC) has been conducting a national power quality voltage survey over a month period involving 9 electricity distributors spread over the all states except Western Australia [31]. The survey was completed on 30th April 2001. It has been chosen 8 sites at 240/ 415 V with in each network representing a range of extreme and average power quality, the sites being chosen to reflect a range of load types, namely, commercial, industrial, residential, rural and remote. This has been examined the level of PQ at each site for 6 disturbance types (voltage, unbalance, harmonics, sags/interruptions and transients) and compare them with standards where they existed. Also examined the variation between distributor types Average and Extreme and among load types commercial, industrial, residential, rural and remote and recommended if there was a case for using different standards in some situations, especially for rural sites.

B1.5 Long Term National Power Quality Survey (LTNPQS) in Australia

Long Term National Power Quality Survey (LTNPQS) of Australian utilities is in its fifth year running which involve in understanding a more critical aspects and long term behaviour in the Australian power system. 11 Australian Distributors covering all states in Australia are participating in the LTNPQS [30], initiated by Energy Networks Association (formerly ESAA (Electricity Supply Association of Australia) which is the peak governing body for Electricity & Gas networks in Australia. It measures voltage sags, steady state voltage, harmonics and voltage unbalance. The utilities participate in the survey, with the objective being a critical first step in the development of comprehensive data base to review national benchmark PQ standards that will guide the Australian Electricity Distribution industry into the future.

B1.6 Pan European LPQI Power Quality Survey

Pan European Leonardo Power Quality Initiative (LPQI) PQ survey comprises 62 face to face surveys carried out in eight European countries [34], which has allowed for an extrapolation of the overall wastage caused by poor PQ in EU-25 countries. This study has investigated industrial sectors that account for 70% of the non-residential consumption of electricity and 38% of the EU-25's turn over (€ trillion). The main purpose of this survey was to estimate costs of wastage generated by inadequate power quality for those sectors within EU-25. All those costs were specified on an annual basis, either reported as such pro-rated where frequency was less than p.a. The main conclusion is that PQ costs in Europe are responsible for serious reduction in industrial performance with an economic impact of € 150 billion.

B2. IEC STANDARDS/TECHNICAL REPORTS STRUCTURE

B2.1 Part 1: General

These standards deal with general considerations such as introduction, fundamental principles, rationale, definitions, and terminologies. They can also describe the application and interpretation of fundamental definitions and terms. Their designation number is IEC 61000-1-x.

B2.2 Part 2: Environment

These standards define characteristics of the environment where equipment will be applied, the classification of such environment, and its compatibility levels. Their designation number is IEC 61000-2-x.

B2.3 Part 3: Limits

These standards define the permissible levels of emissions that can be generated by equipment connected to the environment. They set numerical emission limits and also immunity limits. Their designation number is IEC 61000-3-x

B2.4 Part 4: Testing and measurement techniques

These standards provide detailed guidelines for measurement equipment and test procedures to ensure compliance with the other parts of the standards. Their designation number is IEC 61000-4-x.

B2.5 Part 5: Installation and mitigation guide lines

These standards provide guidelines in application of equipment such as earthing and cabling of electrical and electronic systems for ensuring electromagnetic compatibility among electrical and electronic apparatus or systems. They also describe protection concepts for civil facilities against the high-altitude electromagnetic pulse (HEMP) due to high altitude nuclear explosions they are designated with IEC-61000-5-x.

B2.6 Part 6: Miscellaneous

These standards are generic standards defining immunity and emission levels required for equipment in general categories or for specific types of equipment. Their designation number is IEC 61000-6-x.

B3. SUMMARY OF COMPARISON OF EXISTING HARMONIC INDICES (CIGRE C4.07)

Table B1

HARMONIC VOLTAGE INDICES		International standard or guidelines		Regional or national standards and guidelines						
Standard / Document		IEC 61000-3-6: 1996 [1]	IEC 61000-4-30:2003 [4]	EN50160:1999 [5]	ANSI/IEEE 519:1992 [7]	NRS048-2:2003 [6]	EDF Emeraude contract [8]	ER G5/4: [9]	H.-Q. Voltage Characteristics [10]
Status		Technical report type 3	International Standard	European standard	ANSI Std. Recommended practice	National standard	Power quality contract	National Standard	Voluntary
Where it applies		International	International	19 European countries	Some countries mostly in America	Southern African countries	France	UK Countries	Québec, CA
Purpose		Indicative planning levels for emission limits.	Power quality measurement methods	Supply Voltage characteristics for public networks	Recommended practice for emission limits and systems design values	Minimum standard used by the regulator	Supply voltage characteristics	Planning levels for controlling emissions.	Supply voltage characteristics
Indices / assessment	Very short time (3-s)	$U_{h,vs}$ 95% daily	$U_{h,vs}$ (X% as agreed)		No definite indices				
	Short time (10-min)	$U_{h,sh}$ Max. weekly	$U_{h,sh}$ (X% as agreed)	$U_{h,sh}$ + THD 95% weekly		$U_{h,sh}$ + THD 95% weekly	$U_{h,sh}$ + THD Max		$U_{h,sh}$ +THD 95% weekly
	Other	$U_{h,vs}$ ^ Max. weekly[2]			95% (P519A)			$U_{h,1\text{-}min}$ +THD 95% weekly	
Period for statistical assessment		One week minimum	At least one week or more as agreed	One week	Undefined	One week min.	At least one week or more	One week	One week
Measurement method		IEC 61000-4-7	IEC 61000-4-7	IEC 61000-4-7	No specific measurement method	Specific measurement method	IEC 61000-4-7	Specific measurement method	IEC 61000-4-7
Remarks		Covers MV to EHV (^ Factor 1,5 -2 allowed).	Indices proposed as guidelines for contractual applications in informative annex A6	Applies to LV and MV.	Covers LV to EHV. Currently under revision.	Covers LV-MV HV-EHV.	Covers LV-MV HV-EHV.	Applies to LV-MV and to HV-EHV	Applies to LV-MV and to HV-EHV

B4. SUMMARY OF COMPARISON OF HARMONIC VOLTAGE OBJECTIVES BETWEEN DIFFERENT STANDARDS AND GUIDELINES (CIGRE C4.07)

Table B2

HARMONIC VOLTAGE OBJECTIVES			International standards or guidelines		Regional or national standards or guidelines					
Standard / Document			IEC 61000-2-12: 2003 [11]	IEC 61000-3-6: 1996 [1]	CENELEC EN50160:1999 [5]	ANSI/IEEE 519:1992 [7]	NRS048-2:2003 [6]	EDF Emeraude contract – A. 2 [8]	ER G5/4:2001 [9]	H.-Q. Voltage characteristics [10]
Purpose			Defines compatibility levels for MV public networks	Indicative Planning levels for controlling emissions	Supply voltage characteristics for public networks	Recommended practice for emissions and system design values	Minimum standard used by the regulator	Supply voltage characteristics	Planning levels for the connection of non-linear equipment to public network	Information on supply voltage characteristics
Objectives MV	Voltage level		1 to 35 kV	1 to 35 kV	1 to 35 kV	120V to 69kV	1 to 44 kV	1 to 50kV	6.6 to 20 kV	0,75 to 34,5 kV
	Order		h ≤ 50	Typically h ≤ 40	h ≤ 25	All order	h ≤ 40	h ≤ 25	h ≤ 50	h ≤ 25 +THD
	Levels	Odd	(e.g.: 6% at h=5) See Table 3	(e.g.: 5% at h=5) See Table 3	(e.g.: 6% at h=5) See Table 3	3% all order	(e.g.: 6% at h=5) See Table 3	(e.g.: 6% at h=5) See Table 3	(e.g.: 3% at h=5) See Table 3	(e.g.: 6% at h=5) See Table 3
		Even				3% all order				
		THD	8%	6,5%	8%	5%	8%	8%	4%	8%
Objectives HV-EHV	Voltage level		Not applicable	>35 kV	Not applicable	>69 to 161 kV / >161 kV	> 44 to ≤400 kV	>50 kV	20 to 400 kV	≥44 to ≤315 kV
	Order			Typically h ≤ 40		All order	h ≤ 40	h ≤ 25	h ≤ 50	h ≤ 50 +THD
	Levels	Odd		(e.g.: 2% at h=5) See Table 3		1,5% / 1%	(e.g.: 2% at h=5) See Table 3	(e.g.: 2% at h=5) See Table 3	(e.g.: 2% at h=5) See Table 3	(e.g.: 2% at h=5) See Table 3
		Even				1,5% / 1%				
		THD		3%		2,5% / 1,5%	3%	3%	3%	3%
Remarks			Higher levels (THD up to 11%) are specified for very short time effects.	Covers MV to EHV.	Applies to LV and MV only	Standard currently under revision	Objectives for harmonics at HV are informative	Objectives for harmonics are informative		Covers LV-MV and HV-EHV

B5. SUMMARY OF COMPARISON OF INDIVIDUAL HARMONIC VOLTAGE BETWEEN DIFFERENT STANDARDS AND GUIDELINES (CIGRE C4.07)

Table B3

MV – Harmonic Voltages (% of fundamental or declared voltage)							HV-EHV – Harmonic Voltages (% of fundamental or declared voltage)							
Order h	Comp. levels (IEC 61000-2-12) [11]	Voltage Char. (EN 50160 + Emeraude cont.) [5][8]	Voltage Charact. (NRS 048-2:2003) [6]	Planning levels (IEC 61000-3-6)[1]	Planning levels (ER G5/4)[9]	Voltage Limits. (IEEE 519:92)[7]	Order h	Planning levels (IEC 61000-3-6 NRS 048-2) [6]	Em-eraude contract [8]	Planning levels ER G5/4)[9]		Voltage Limits. IEEE 519:92 [7]		Voltage charact. (H.-Q) [10]
										> 20< 145 kV	275 – 400 kV	>69-161 kV	>161 kV	
2	2	2	2	1,6	1,5	3	2	1,5	1,5	1	1	1,5	1	1,5
3	5	5	5	4	3	3	3	2	2	2	1,5	1,5	1	2
4	1	1	1	1	1	3	4	1	1	0,8	0,8	1,5	1	1
5	6	6	6	5	3	3	5	2	2	2	2	1,5	1	2
6	0,5	0,5	0,5	0,5	0,5	3	6	0,5	0,5	0,5	0,5	1,5	1	0,5
7	5	5	5	4	3	3	7	2	2	2	1,5	1,5	1	2
8	0,5	0,5	0,5	0,4	0,4	3	8	0,4	0,5	0,4	0,4	1,5	1	0,4
9	1,5	1,5	1,5	1,2	1,2	3	9	1	1	1	0,5	1,5	1	1
10	0,5	0,5	0,5	0,4	0,4	3	10	0,4	0,5	0,4	0,4	1,5	1	0,4
11	3,5	3,5	3,5	3	2	3	11	1,5	1,5	1,5	1	1,5	1	1,5
12	0,46	0,5	0,46	0,2	0,2	3	12	0,2	0,5	0,2	0,2	1,5	1	0,3
13	3	3	3	2,5	2	3	13	1,5	1,5	1,5	1	1,5	1	1,5
14	0,43	0,5	0,43	0,2	0,2	3	14	0,2	0,5	0,2	0,2	1,5	1	0,3
15	0,4	0,5	0,4	0,3	0,3	3	15	0,3	0,5	0,3	0,3	1,5	1	0,75
16	0,41	0,5	0,41	0,2	0,2	3	16	0,2	0,5	0,2	0,2	1,5	1	0,3
17	2	2	2	1,6	1,6	3	17	1	1	1	0,5	1,5	1	1
18	0,39	0,5	0,39	0,2	0,2	3	18	0,2	0,5	0,2	0,2	1,5	1	0,3
19	1,76	1,5	1,76	1,2	1,2	3	19	1	1	1	0,5	1,5	1	1
20	0,38	0,5	0,38	0,2	0,2	3	20	0,2	0,5	0,2	0,2	1,5	1	0,3
21	0,3	0,5	0,3	0,2	0,2	3	21	0,2	0,5	0,2	0,2	1,5	1	0,5
22	0,36	0,5	0,36	0,2	0,2	3	22	0,2	0,5	0,2	0,2	1,5	1	0,3
23	1,41	1,5	1,41	1,2	1,2	3	23	0,7	0,7	0,7	0,5	1,5	1	0,7
24	0,35	0,5	0,35	0,2	0,2	3	24	0,2	0,5	0,2	0,2	1,5	1	0,3
25	1,27	1,5	1,27	1,2	0,7	3	25	0,7	0,7	0,7	0,5	1,5	1	0,7
Odd non mult .of 3 >25	2,27 (17/h) - 0,27	n/a	2,27 (17/h) - 0,27	0,2 +1,0(25/h)	0,2+ 0,5*(25/h)	3	Odd non mult. of 3 >25	0,2 + 0,5 (25/h)	n/a	0,2+ 0,5*(25/h)	0,2+ 0,3*(25/h)	1,5	1	0,2 + 0,5 (25/h)
THD	8	8	8	6,5	4	5	THD	3	3	3	3	2,5	1,5	3

B6. SUMMARY OF COMPARISON OF EXISTING FLICKER INDICES (CIGRE C4.07)

Table B4

FLICKER INDICES		International standards or guidelines		Regional or national standards and guidelines				
Standard / Document		IEC 61000-3-7: 1996 [2]	IEC 61000-4-30:2003 [4]	EN50160:1999 [5]	NRS048-2:2003 [6]	EDF Emeraude contract – A. 2 [8]	ER P28: [13]	H.-Q. Voltage Characteristics [10]
Status		Technical report type 3	International Standard	European standard	National standard	Premium power contract	National Standard	Voluntary
Where it applies		International	International	19 European countries	Southern African countries	France	UK	Québec, CA
Purpose		Indicative planning levels for emission limits.	Power quality measurement methods	Supply Voltage characteristics for public networks	Minimum standard used by the regulator	Supply voltage characteristics	Planning levels for controlling emissions.	Supply voltage characteristics
Indices / assessment	Short term (10-min)	P_{st} 99% weekly	P_{st} 99% weekly (or X% as agreed)				P_{st} (no further specification)	
	Long term (2-hour)	P_{lt} 99% weekly	P_{lt} 95% weekly (or X% as agreed)	P_{lt} 95% weekly	P_{st} 95% weekly	P_{lt} (no further specification)	P_{lt} (no further specification)	P_{lt} 95% weekly
	Other		Number or % of values exceeding contractual values					
Period for statistical assessment		One week minimum	At least one week or more as agreed	One week	One week min.	At least one week or more	Sufficient to capture full operating cycle of the load	One week
Measurement method		IEC 61000-4-15	IEC 61000-4-15	IEC 61000-4-15	IEC 61000-4-15	IEC 61000-4-15 (formerly 868)	IEC 868	IEC 61000-4-15
Remarks		Covers MV to EHV.	Indices proposed as guidelines for contractual applications in informative annex A6	Applies to LV and MV.	Applies to LV and MV.	HTA is 1 to 50kV and HTB > 50kV	Published in 1989	Applies to LV-MV and to HV-EHV

B7. SUMMARY OF COMPARISON OF FLICKER OBJECTIVES BETWEEN DIFFERENT STANDARDS AND GUIDELINES (CIGRE C4.07)

Table B5

FLICKER OBJECTIVES		International standards or guidelines		Regional or national standards or guidelines				
Standard / Document		IEC 61000-3-7 [2]	IEC 61000-2-12 [11]	EN50160:1999 [5]	NRS048-2:2003 [6]	EdF Emeraude contract – A. 2 [8]	ER P28: [13]	H.-Q. Voltage characteristics [10]
Purpose		Defines planning levels for controlling emissions	Defines compatibility levels for MV public networks *	Supply voltage characteristics for public networks	Minimum standard used by the regulator	Supply voltage characteristics	Planning levels for the connection of disturbing loads	Information on supply voltage characteristics
Objectives at MV	P_{st}	0,9	(1,0) **			--	V≤ 132 kV = 1,0	
	P_{lt}	0,7	(0,8) **	1,0	1,0	1,0	V≤ 132 kV = 0,8	1,0
Objectives at HV-EHV	P_{st}	0,8*	Not applicable	Not applicable	--	--	V≤132 kV = 1,0 V>132 kV = 0,8	
	P_{lt}	0,6*	Not applicable	Not applicable	--	1,0	V≤132 kV = 0,8 V>132 kV = 0,6	0,6
Remarks		Covers MV to EHV (* assuming an attenuation factor of 1 between HV-EHV to MV-LV)	** No compatibility levels for flicker are defined at MV, however it refers to IEC 61000-2-2 for flicker that can be transferred at LV	Applies to LV and MV only	High flicker values flagged according to IEC 61000-4-30 to be removed	HTA from 1 to 50 kV and HTB > 50 kV		Covers LV-MV and HV-EHV

B8. Summary of comparison of existing unbalance indices (Cigre C4.07)

Table B6

Voltage unbalance indices		International documents		Regional or national standards and guidelines				
Standard / Document		IEC 61000-4-30:2003 [4]	Cigre 1992 Paper 36-203 [14]	EN50160:1999 [5]	NRS048-2:2003 [6]	EdF Emeraude contract – A. 2 [8]	ER P29: [16]	H.-Q. Voltage Characteristics [10]
Status		International Standard	Cigre 36.05 work	European standard	National standard	Premium power contract	National Standard	Voluntary
Where it applies		International	--	19 European countries	Southern African countries	France	UK	Québec, CA
Purpose		Power quality measurement methods	Assessing voltage quality in relation to harmonics, flicker and unbalance	Supply Voltage characteristics for public networks	Minimum standard used by the regulator	Supply voltage characteristics	Planning levels for controlling emissions.	Supply voltage characteristics
Indices / assessment	Very-short time (3-sec)		$U_{neg\,vs}$ 95% daily					
	Short time (10-min)	$U_{neg\,sh}$ 95% weekly (or as agreed)	$U_{neg\,sh}$ Max weekly (left under consideration)	$U_{neg\,sh}$ 95% weekly	$U_{neg\,sh}$ 95% daily	$U_{neg\,sh}$ (No further specification)	Maximum value of negative sequence measured over any 1 minute period	
	Long time (2-hour)	and/or $U_{neg\,lt}$ 95% weekly (or as agreed)						$U_{neg\,lt}$ 95% weekly
Period for statistical assessment		At least one week or more as agreed	Min. of a few days including a week end	One week	One week min (7 continuous days)	At least one week or more	Sufficient to represent effect on rotating plant (could be a full year)	One week
Remarks		Indices proposed as guidelines for contractual applications in informative annex A.6.	Covers LV to EHV.	Applies to LV and MV.	Covers LV to HV.	1kV to 50kV and > 50kV	Applies at 132 kV and below	Applies to LV-MV and to HV-EHV

B9. SUMMARY OF COMPARISON OF UNBALANCE OBJECTIVES BETWEEN DIFFERENT STANDARDS AND GUIDELINES (CIGRE C4.07)

Table B7

VOLTAGE UNBALANCE OBJECTIVES		International documents		Regional or national standards and guidelines				
Standard / Document		IEC 61000-2-12 [11]	Cigre 1992 Paper 36-203 [14]	EN50160:1999 [5]	NRS048-2:2003 [6]	EDF Emeraude contract – A. 2 [8]	ER P 29: [16]	H.-Q. Voltage Characteristics [10]
Purpose		Compatibility levels on public systems at MV	Assessing voltage quality in relation to harmonics, flicker and unbalance	Supply Voltage characteristics for public LV and MV networks	Minimum standard used by the regulator	Supply voltage characteristics	Planning levels for controlling emissions.	Supply voltage characteristics
Objectives at MV	Very short time (3-sec))	-	2%					
	Short time (10-min)	-	2%	2%	2%	2%	2% (1-min. values)	
	Other	2%	-					2% (2-hr)
Objectives at HV-EHV	Very short time (3-sec)	n/a	1%	n/a				
	Short time (10-min)	n/a	1%	n/a	2%	1%	2% (1-min. values)	
	Other	n/a		n/a				HV=1,5% (2-hr); EHV=1% (2-hr)
Remarks		(up to 3% may occur in some areas)	Covers LV to EHV.	(up to 3% in some areas)	(up to 3% may occur in some areas)	HTA is 1 to 50kV and HTB > 50kV	Applies at 132 kV and below. Lower emission limits are specified for unbalanced loads.	Covers LV-MV and to HV-EHV