Investigation of data reporting techniques and analysis of continuous power quality data in the Vector distribution network

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Investigation of Data Reporting Techniques & Analysis of Continuous Power Quality Data in the Vector Distribution Network

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Certification

I, Glenn C Nicholson, declare that this thesis, submitted in fulfilment of the requirements of Master of Engineering (Research), in the School of Electrical, Computer & Telecommunications Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Glenn C Nicholson

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List of abbreviations

Abbreviation	
AVD	Absolute Voltage Deviation
CBEMA	Computer and Business Equipment Manufacturers Assoc
CT	Current Transformer
EPRI	Electric Power Research Institute
FFT	Fast Fourier Transform
GXP	Grid Exit Point
HI	Harmonics Index
HoLI	Harmonics outside Limits Index
IEC	International Electrotechnical Commission
IEPQRC	Integral Energy Power Quality & Reliability Centre
ITIC	Information Technology Industry Council
LV	Low voltage (< 1 KV)
MV	Medium voltage (1KV – 35 KV inclusive)
PCC	Point of Common Coupling
PQ	Power quality
PWM	Pulse Width Modulation
rms	Root mean square
THD	Total Harmonic Distortion
UoLI	Unbalance over Limit Index
UoW	University of Wollongong
UPQI	Unified Power Quality Index
VDF	Voltage Distribution Factor
VI	Voltage Index
VoRI	Voltage outside Range Index
VT	Voltage transformer
VUF	Voltage Unbalance Factor
WT	Wavelet Transform

Abstract

Power quality (PQ) has been defined as the study of the sources, effects and control of disturbances that propagate via the electric power supply. The three principal stakeholders in power quality are the electricity user, the electricity supplier and the electrical equipment manufacturer, each of which has a different perspective on power quality.

This thesis looks at power quality primarily from the perspective of the electricity utility. Power quality has traditionally been considered in terms of reliability of supply, and this has been assessed in terms of frequency and duration of interruptions to the supply. However, with the proliferation of electrical equipment that is sensitive to a variety of disturbances in the supply, the reliability of the supply can no longer be defined solely in terms of interruptions. A supply that suffers from disturbance levels that damage or cause misoperation of equipment can be just as expensive and inconvenient to a customer as a supply that suffers from sustained interruptions.

Despite routine power quality monitoring by utilities becoming more common, there is still little standardisation in the methodology for carrying out such surveys. Standard methods for data acquisition, analysing and reporting the data are required. Standardisation is necessary to allow benchmarking of PQ levels between utilities and to allow the determination of typical disturbance levels.

This thesis is an investigation into the practice of routine PQ monitoring by utilities, and in particular the monitoring and reporting of power quality by Vector Ltd (New Zealand). Vector owns and operates the lines network that supplies electricity to most of the Auckland area. Vector has made a significant commitment to PQ monitoring and a large amount of data has been gathered since monitoring began in 1999. The main purpose of this study has been to look at present PQ monitoring and reporting methods at Vector, compare these methods with current industry best practice, and to suggest ways in which these methods could be improved to better meet the needs of Vector.

The focus of this study has been on continuous PQ disturbances (continuous voltage variation, voltage unbalance and harmonic distortion) as opposed to discrete disturbances (voltage sags/swells, transients). Deficiencies in existing analysis techniques have been identified, and an alternative index for voltage variation has been proposed. Methods for deriving seasonal and annual site PQ indices have also been implemented using data from the Vector network covering one full year. Statistical analysis of the data has also been carried out to determine the degree of influence of individual PQ disturbance types on the overall PQ level at a site, and to investigate the influence of each of the known physical characteristics of a site on its power quality performance.

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Chapter 1: Introduction

1.1 What is Power Quality?

Since the term “power quality” was first used in the late 1970s, power quality has evolved into an area of electrical power system analysis of growing importance. Initially, the term power quality was most often used in a negative context, being associated with problems of equipment malfunction. The focus tended to be on assigning responsibility for these problems, with users and equipment manufacturers blaming the electric power being supplied to equipment, and the electricity supplier blaming the equipment manufacturers for supplying equipment with insufficient immunity to unavoidable disturbances.

The three principal stakeholders in the area of power quality are the electricity user, the electricity supplier, and the electrical equipment manufacturer, each of which has a different perspective on power quality. In more recent years there has been considerable effort put into resolving the problems of power quality as seen by the principal stakeholders. Rather than boundaries, there is now discussion relating to the interface between involved parties in power quality issues. Other important stakeholders have been brought into the discussion, namely manufacturers of power quality monitoring equipment, manufacturers of line conditioning equipment, and consultants called upon to solve power quality problems [1].

What is power quality? In the course of this study, several different definitions of power quality have been encountered. Among them are:

- Any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipment [2].
- The study of the sources, effects and control of disturbances that propagate via the electric power supply [3].

The International Electrotechnical Commission (IEC) has defined power quality as:

- Set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude, waveform).

Note 1: Power quality expresses the user’s satisfaction with the supply of electricity. Power quality is good if electricity supply is within statutory and any contractual

limits, and there are no complaints from users, and vice versa it is bad if the power supply is outside of limits and there are complaints from users.
Note 2: Power quality depends not only on the supply but can be strongly affected by the users' selection of equipment and installation practices. [1]

The first definition is somewhat restrictive in that it only refers to power quality in terms of failure or misoperation of equipment. Some power quality phenomena may not cause equipment failure or misoperation, but may still be of concern. An example is harmonic distortion. Harmonic levels may not be high enough to cause equipment failure, but may still result in increased power losses and premature aging of equipment. The second definition takes a broader approach to power quality and includes such aspects as the study of power quality for the purpose of gaining greater understanding of power system operation.

This thesis looks at power quality primarily from the perspective of the electricity utility. Many utilities have assessed (and many still do) service quality using sustained interruption indices such as SAIFI and CAIDI (System Average Interruption Frequency Index and Customer Average Interruption Duration Index respectively). In more recent times, as power systems experience fewer interruptions, the term power quality has come to embrace a range of disturbances, of which sustained interruptions are only one type. The indices based on sustained interruptions are now often referred to as Reliability Indices. However, a supply that experiences few (or even no) interruptions is no longer necessarily a reliable electricity supply. Damage to, or malfunction of sensitive electronic equipment due to variations in the supply voltage may be just as inconvenient and expensive for a customer as a sustained interruption [4].

1.2 Types of Power Quality Disturbances

Power quality disturbances can be broadly divided into the following three categories:

Deviations in frequency of the waveform. System frequency is (under normal conditions) determined by the system generator (as opposed to the electricity distributor) and is thus beyond the control of the distributor, and will not be discussed in any detail in this thesis.

Deviations in voltage magnitude.

Distortions in voltage waveshape.

Disturbances can be further classified according to duration, magnitude and spectral content. Such a classification system is defined in the standard IEEE 1159-1995 (refer to Appendix A, Table 1).

Examples of waveforms of some of the disturbance types are shown in Fig.1-1 below.

Plesae see print copy for Figure 1.1

Fig.1-1: Common PQ disturbance waveforms [3]

The steady-state voltage changes slowly over a time scale of minutes, while transients such as lightning strikes or oscillations due to capacitor switching may have rise times in the microsecond range.

Disturbances can also be classified as being either continuous or discrete. Continuous disturbances are those that are present in every cycle of the waveform, while discrete disturbances can be considered as separate events that are only present in a few cycles of the waveform.

Examples of these two types are given in Table 1-1 below.

Table 1-1: Continuous and discrete disturbances.

Continuous disturbances	**Discrete disturbances**
Voltage variation	Supply interruptions
Voltage unbalance variation	Voltage sags/swells
Harmonic distortion	Transients (impulsive and oscillatory)
Voltage fluctuation (flicker)	

1.3 Power Quality Monitoring and benchmarking

Until recently, the monitoring of electrical power quality was usually a response to a specific problem or customer complaint. Continuous power quality monitoring by utilities is now becoming more common. Facilitated by the availability of affordable monitoring equipment, this proactive approach to the study of power quality has been further encouraged by increased customer awareness of power quality, and in some cases by the requirements of a state regulatory body.

Despite continuous monitoring becoming more common, there is still little standardisation in the methodology for carrying out such surveys. The key questions that need to be answered are:

1. What to measure?
2. How to measure it?
3. Where to measure?

Having acquired power quality data, standard methods for analysing and reporting the data are required. Power quality monitoring (especially in the case of continuous monitoring) generates large amounts of data that must be condensed and analysed so that levels can be assessed against limits, trends can be identified, and problem areas prioritised for attention. Data reduction is commonly in the form of trend lines plotted against time, and the calculation of numerical indices that are representative of the measured levels. Again, there is little standardisation in how these indices should be derived and how the results of the survey should be reported. Standardisation of indices and reporting techniques is necessary so that power quality levels can be compared between utilities. Benchmarking of power quality between utilities will allow the determination of typical disturbance levels so that limit values can be set at realistic and achievable levels.

1.4 The Vector Power Quality Analysis Project

This thesis is a study into the practice of routine power quality monitoring by electricity utilities, and in particular the monitoring and reporting of power quality by Vector Networks Ltd. The study forms the research component for a masters degree (research) in electrical engineering at Wollongong University. The work has been carried out in conjunction with Vector Ltd, which is an electricity, gas distribution and communications utility company in Auckland, New Zealand. Vector owns and operates the lines network that supplies electricity to all of the Auckland and Wellington regions. Vector has been active in routine monitoring of power quality since 1999 and now has 13 PQ monitors permanently installed at MV level (11 kV) in zone substations in Auckland, and a single monitor connected at LV at an extreme end of the network. Additionally, there are a number of monitors connected at transmission grid exit points to monitor the incoming supply from the national grid. Vector has made a significant commitment to the measurement of power quality levels on the network, and a large amount of data has now been gathered.

The main purpose of this study has been to look at present power quality monitoring and reporting methods at Vector, compare these methods with current industry best practice, and to suggest ways in which the monitoring and reporting methods could be modified or improved.

Vector have primarily used the PQ data to record discrete system events (e.g. voltage sags/swells, interruptions, transients) and to assist in the study of general network behaviour. The research for this thesis focuses on the study of continuous power quality disturbances. Continuous power quality disturbances include:

- Continuous voltage variations (those variations that are less than 0.1 p.u. and cannot be classified as voltage sags/swells, and excluding impulsive or oscillatory transients).
- Voltage unbalance.
- Harmonic distortion of the waveform.
- Voltage fluctuations (often incorrectly referred to as voltage flicker, as the most common symptom of voltage fluctuations is light flicker).

Voltage fluctuations are not being measured at all PQ monitoring sites due to limitations in the capability of installed monitors, and so is given lesser emphasis in this study.

1.5 Methodology

This project started out with a very general research question: what can we find out by analysing power quality data from Vector? Having little prior knowledge of the Vector network and no outstanding power quality problems being reported, the initial approach was one of general data analysis to identify any trends or abnormalities in the data. This led to the next question: what is the best way to analyse the data and summarise the results? And having summarised the data, what useful information can be obtained from the results? Is it possible to determine which power quality phenomena are most influential in determining the overall PQ performance of a site, and which physical characteristics of a site are most influential on the overall site PQ performance?

The following methodology was adopted for this project:

1. Carry out a literature review on the subject of power quality, with emphasis on power quality for electrical utilities. The purpose of the literature review was to become familiar with power quality issues from the perspective of the electricity distributor, and to determine current best practice in the measuring, analysis and reporting of PQ data. This literature review included national (New Zealand) and international power quality standards documents.

2. Obtain a sample of PQ monitor data from the Vector network and trial data analysis and reporting techniques. The first stage of this involved analysing PQ data from one site on the network for a period of one month. This was later extended to cover 13 monitored sites, again for a duration of one month. This stage in the project enabled the data analysis and reporting techniques to be refined and streamlined. A preliminary report on the findings of this one month study was presented to Vector Ltd. It was decided to limit the data analysis and reporting to the continuous disturbance types of voltage variation, voltage unbalance and total harmonic distortion. This decision was made to limit the

scope of the project to manageable proportions, and also reflects the PQ parameters that are being monitored by Vector. Discrete disturbances (voltage sags/swells, transients) are being recorded, but the analysis of these discrete disturbances could easily constitute a separate research project in itself. Additionally, the analysis of continuous variations is an area that has received much less attention than discrete disturbances and thus had the potential for more original contributions.

3. Extend the project, this time with analysis of PQ from the 13 sites, but over a duration of one year. The one-year duration was to enable the identification of any long-term trends or seasonal variations. Again, a report on the findings of this one-year study was presented to Vector.

4. Carry out statistical analysis on the data to determine the degree of influence of individual power quality phenomena on the overall PQ level at a site. Also investigate the influence of each of the known physical characteristics of a site on its power quality performance.

The monitor data analysed for this research covers the period from July 2003 to June 2004. By using data covering a full year, the intention is that typical daily, weekly, monthly and seasonal variations in power quality levels can be identified. With power quality being continuously monitored by Vector, there is the potential for on-going study to identify annual trends in power quality levels.

1.6 Scope of this thesis

In chapter 2 current literature on the topic has been reviewed in order to establish current best practice and to identify shortcomings in these practices, and to look at proposals for changes and improvements in PQ survey methodology. Knowledge gained from this review has been applied in the analysis and reporting of data from the Vector survey.

In chapter 3, existing PQ standards are discussed. The measurement and analysis of power quality levels is incomplete without reference to specified conformance limits.

Established international standards exist for the measurement and quantifying of PQ data. The details and implications of these standards do not appear to be widely known or understood. To further confuse the issue, there are some inconsistencies between some standards, both at international and national level.

The instrumentation requirements for the monitoring of power quality are discussed in chapter 4. The issues of what should be measured and where are discussed. The requirements of power quality instruments are described with reference to relevant standards. Details of the monitoring instruments used by Vector are provided and these are compared with the requirements of the standards. Issues affecting the validity of the data (such as abnormal or missing data, possible instrument errors) are detailed and their impact on the findings of the study assessed.

The methodology for the analysis of the Vector survey is described in chapter 5. This includes the algorithms for deriving summary indices for each of the measured parameters for each site. This has mainly involved the application of techniques described in international standards and further developments by researchers at the Integral Energy Power Quality & Reliability Centre at the University of Wollongong. Deficiencies in these methods are identified, and alternative methods for calculating disturbance indices are proposed and applied. Novel methods are proposed for obtaining monthly, seasonal and annual PQ indices for continuous disturbances.

Factor analysis of the power quality data has been carried out and this is described in chapter 6. The aim of the factor analysis is to determine the influence of known physical characteristics of a site on the actual measured power quality levels. The analysis uses statistical techniques to determine the influence of factors such as kVA loading, fault level, predominant load type (e.g. residential, industrial, commercial), and length of lines connected downstream from the monitored site. If the influence of each of these factors can be determined, it may be possible to estimate the disturbance levels at unmonitored sites. It could also enable the utility to prioritise remedial measures aimed at improving overall power quality levels at a site.

Chapter 7 summarises the overall conclusions of the study, and provides suggestions for future work that will build on this study. There are still many unanswered questions relating to power quality on utility networks. The study of power quality is an evolving field. Alternative methods for analysing PQ data can be applied. In particular, as the amount of PQ data accumulated by Vector increases, there is a need for analysis to determine long-term trends in power quality levels (over several years).

The appendix presents information relating to relevant international PQ standards that have been referred to in the thesis. Numerical summaries and histograms of the Vector power quality data are also presented.

1.7 Original Contributions in this Thesis

Given below is a concise list of original contributions to the study of power quality that are contained in this thesis.

1. In-depth analysis of results from a New Zealand power quality survey has been carried out. This is the first documented analysis of a long-term continuous PQ survey in New Zealand.

2. The use of primary and secondary power quality indices has been trialled. These power quality indices were proposed by the Integral Energy Power Quality & Reliability Centre at the University of Wollongong.

3. An alternative voltage variation index has been proposed and implemented using data from the Vector survey. This index is seen as an improvement on traditional indices in that it ignores voltage deviations that are within specified limit values (and thus are considered to have no adverse impact on customers). Future work would include refining the limit values of this index.

4. A method for derivation of site seasonal and annual disturbance indices has been proposed and implemented. Two variations of this method have been considered.

The first uses the raw 15 minute measured data, while the second uses daily 95th percentile values to derive the seasonal or annual index.

5. A method for deriving a universal (steady-state) site index that combines indices for voltage deviation, voltage unbalance and THD has been proposed and trialled. This method uses indices for the individual parameters that have been normalised with respect to the network average, and then takes the mean of these as the site PQ index. An alternative of normalising the individual parameter indices with respect to a specified limit value has also been proposed.

6. Power quality data factor analysis has been carried out in an attempt to assess which known physical parameters of a monitored site in a network are most influential in determining the overall level of power quality at that site. Further work in this area could lead to an effective method of estimating power quality levels at non-monitored sites. Factor analysis has also been used to assess the influence of individual PQ disturbance types in determining the overall PQ levels at a site.

7. Current power quality standards have been reviewed. In the case of the New Zealand power quality standards, Electricity Regulations and Electricity Governance Rules, inconsistencies were identified and a recommendation for amendments to the Governance Rules has been made to bring them into line with the requirements of the AS/NZS 61000 series standards.

8. A review of current literature on the topic of utility power quality surveys, data analysis and survey reporting has been carried out. The literature has been discussed in relation to the Vector study and current electricity utility practices.

Chapter 2
Power Quality for Utilities: A Literature Review.

2.1 Introduction

For many electricity utilities, the monitoring of power quality has become a necessary part of their operation. As electricity supply systems have become more reliable, attempts to improve the quality of supply have become more focused on minimising disturbance levels as well as improving continuity of supply. At the same time, supply networks have been subjected to an increase in the number of disturbance sources, mainly in the form of non-linear customer loads. These distorting loads are themselves typically sensitive to disturbance levels, creating a demand from customers for acceptable levels of power quality.

Effective management of disturbance levels on the electricity supply requires the ability to measure these disturbances. A range of affordable dedicated power quality monitoring instruments is now available, which has further contributed to the increase in activity in power quality measurement. As power quality monitoring activity has increased, international standards specifying measurement practices, instrument requirements, and maximum disturbance levels have been developed.

The monitoring of power quality by utilities is still an evolving practice. While standards exist for measurement techniques, instruments and disturbance levels, there is still little consistency in the actual implementation of power quality surveys (particularly on-going routine surveys), and there is no standardisation in how the results of such surveys should be reported.

Considering that routine power quality monitoring by utilities is no longer unusual, there is surprisingly little information regarding these studies available in the public domain. This is perhaps due to the commercial sensitivity of the information. In other cases, power quality surveys have been conducted by private research institutes, and there is significant cost involved in obtaining the literature relating to these surveys.

This chapter will review current practices in power quality monitoring, analysis and reporting. The review is based on information gathered from journal articles, conference papers, textbooks and selected websites. The chapter will also relate these practices to those being proposed and trialled as part of this study. The review is divided into the following subsections:

1. Methodologies for utility power quality surveys and utility power quality monitoring methods
2. Power quality analysis techniques.
3. Power quality indices and reporting formats.

The focus of this study is on continuous, routine power quality monitoring, with particular emphasis on monitoring of steady-state conditions (as opposed to monitoring of discrete power quality events such as sags, transients, interruptions). For this reason, this review will predominantly focus on power quality literature that lies within this scope.

2.2 Methodologies for utility power quality surveys

It is first necessary to distinguish between the two main types of power quality (PQ) survey. A survey may be initiated in response to customer complaints. Such a survey will typically concentrate on the specific customer site or point of common coupling (PCC), and the objective is to identify the nature and source of the problem. Such surveys are often referred to as being *reactive*. An increasingly common practice among utilities is continuous monitoring, which is a proactive approach to power quality. There are several reasons why a utility might carry out a continuous power quality survey. It may be for the purposes of establishing conformance with standards, to gain a better understanding of system performance, or the objective might be to inform customers of what power quality levels can be expected on the network. The objectives of the monitoring programme determines the choice of measuring equipment, the method of collecting data, selection of disturbance thresholds, the data analysis requirements, and the overall level of required effort [5]. It should be added that the purpose of the survey will influence the method of reporting the results to suit the intended audience.

For the utility that is about to undertake a programme of continuous PQ monitoring, a methodology needs to be defined that will produce meaningful results and satisfy the initial objectives of the survey. The fundamental questions that face the survey planner are where to measure, what to measure, and how to measure it.

2.2.1 Where to measure

PQ monitoring is expensive. In addition to the cost of the instrument, there are costs associated with data communication and data storage, and the time required to process and analyse the data. In the foreseeable future, utility power quality surveys will by necessity be limited to a small sample of sites.

Given that only a sample of sites can be studied, a methodology is required for selecting the best sites for installing monitors. What is considered to be the best site depends on the objectives of the survey. If the objective is to characterise the PQ levels being experienced by customers, monitoring at actual customer service entrance locations is preferred as it includes the effect of step-down transformers supplying the customer, and can also characterise the customer load current variations and harmonic distortion levels. If the objective is to characterise power quality on electric utility distribution feeders, then the monitoring locations should be on the actual feeder circuits [5]. This was the strategy used in the EPRI Distribution Power Quality (DPQ) Project, which collected data from 24 utilities with 277 monitoring sites across the U.S. between June 1992 and September 1995. This study used a controlled site selection process to ensure that both common and uncommon characteristics of the U.S national distribution systems were well represented in the study sample. When relating the results of the study to the utility population, weighting was applied to reflect the resulting unequal probabilities [6].

Whether to monitor at LV or at MV is a critical issue. LV monitoring shows the level seen by domestic customers while MV monitoring shows the disturbance levels seen by larger industrial and commercial customers. MV monitoring appears to be the favoured choice of metering point internationally, presumably because one monitoring site covers many customers. However, some PQ disturbances originate in the LV system and will not be seen at their worst extent at MV [7]. To answer the question of whether to monitor at MV or LV, it is necessary to go back to the original objectives of the survey and determine exactly what questions the survey results will answer. A possible compromise is to monitor at MV at the substation and at selected customer entry points. This is similar to the approach currently being taken by Vector, with monitors located in some zone substations, and with a single LV monitor installed at the extreme end of a rural feeder.

The next question to be considered is the number and location of individual monitors. Cost constraints will inevitably be the major consideration, but within that constraint it is necessary to determine the best possible monitor locations to obtain representative measurements. An indication of the overall utility PQ performance can be obtained provided the monitoring 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 [8]. The objective is to minimise the cost of required instrumentation while still achieving an indication of PQ levels throughout the network.

A methodology has been proposed [7] to estimate the required number of monitoring sites. By considering the main factors that are likely to affect PQ levels, possible monitoring sites can be categorised. Customer type (industrial, commercial, residential, rural, remote) is one factor. If sites expected to experience average and worst case PQ levels are selected for each customer type, this gives a total of 10 categories. If two sites are selected for each of the 10 categories, this gives a total of 20 monitoring sites per utility.

In order to reduce the required number of monitoring sites (and therefore the cost), there has been some work into the use of predictive models to assist in monitor site selection. One approach has been to modify a power system simulation tool to predict PQ disturbance levels through the network. The system collects data from installed PQ monitors and this data is then used to obtain state estimation and prediction for specified un-monitored locations in the network [9].

Another technique for assisting in selecting monitoring sites [10] uses calculation of a Voltage Disturbance Factor (VDF). The VDF for a prospective site is calculated by assigning equivalent lengths to each part of the distribution system. The equivalent lengths are then converted into Voltage Disturbance Increments which are summed together to give the VDF. The calculated site VDF has proved to be a useful tool in estimating the relative PQ levels in a network, and this information can be applied to ensure that selected monitor sites are representative of the range of conditions that exist in the network.

The methodology adopted by Vector is one of monitoring power quality primarily at MV level at zone substations (there are also several monitors connected at transmission grid exit points to monitor the incoming supply from the grid, and a single monitor connected at LV at an extremity of the network). From the literature it is clear that while monitoring at MV has the advantage of a single monitor covering a larger section of the network, the disturbance levels recorded may not accurately reflect what is being experienced by customers connected to LV. The monitoring of PQ at MV at zone substations is a common international practice, and does allow the results to be benchmarked against other similar surveys.

2.2.2 What to monitor

Power quality encompasses a wide variety of conditions on the network. Disturbances can range from high frequency impulses caused by lightning strikes, to long-term sustained overvoltages resulting from poor voltage regulation. The wide range of conditions that must be characterised presents challenges in both the requirements of the monitoring equipment and the data collection process. When deciding which disturbance types to monitor, it is necessary to go back to the original objectives of the survey. If the objective is to monitor those disturbances that have the most impact on customers, it is likely that the emphasis will be on recording voltage sags. In terms of continuous variations, voltage variation and harmonics are of significant concern to customers. The capabilities of the monitoring instrument will also influence the choice of which parameters to measure. Some instruments do not have the capability to measure voltage fluctuations, while others may not have sufficiently fast sampling rates to accurately capture high frequency disturbances such as impulsive transients.

Surveys designed to evaluate conformance with harmonic standards may only require steady-state monitoring of harmonic levels. Other surveys focused on specific industrial problems may only require monitoring of rms voltage variations such as voltage sags. Monitoring projects for the purpose of benchmarking system performance should involve a reasonably complete monitoring effort [5]. In this case it is recommended that the following disturbance types be monitored:

- Transients
- Sags/swells
- Interruptions
- Undervoltage/overvoltage (steady-state variation)
- Harmonic distortion (harmonic spectrum and total harmonic distortion)
- Voltage fluctuations (causing light flicker)

2.2.3 How to measure

Two main issues arise regarding how to make the required measurements for a PQ survey. The type of instrument used will determine what can be measured as well as the degree of accuracy. This topic is discussed in greater depth in chapter 3 which deals with instrumentation. The other question is how long to monitor for i.e. the survey period.

For the purpose of monitoring continuous variations, several international standards refer to a one-week minimum monitoring period. Over the last decade, many utilities worldwide have installed permanent PQ monitoring systems. There are numerous reasons for undertaking continuous monitoring (enhanced customer service, system benchmarking, real-time alarming on PQ events) but it also presents several problems (data collection and storage requirements, large amounts of data to be analysed and reported) [11].

Ideally, the duration of a power quality survey should be one-two years, but it has been established that a survey period as short as one week will give useful preliminary results for continuous disturbances. A minimum survey period of one month is considered better to allow for the possibility of events such as abnormal weather, public holidays etc which may make the results from one week atypical [7].

Vector have undertaken a programme of continuous monitoring, and so the issue of survey duration does not arise. Continuous monitoring is appropriate for system benchmarking, a general study of network behaviour, and for providing disturbance level information to customers. It has the disadvantages of requiring significant investment in data communication and storage infrastructure, and imposing additional workload on those responsible for analysing and reporting the data.

2.3 Power quality analysis techniques

Power quality monitoring generates a lot of data. The aim of a power quality index is to summarise this data into a few meaningful numbers. The majority of the known indices have been developed with the intention of summarising the degree of distortion of a sinusoidal waveform, how much power loss occurs due to this distortion, and the impact that the distortion has on electrical equipment. The derived indices also provide a basis for comparison (benchmarking) and trend analysis. One of the inevitable disadvantages of indices is the inherent loss of information as compared to the raw data. Indices can obscure critical factors, and can be misused (designed for one application but erroneously used in another) [12].

Much of the work that has been done in developing analysis techniques for power quality has focused on analysis of discrete events such as interruptions and voltage sags. This is understandable, as it is interruptions and voltage sags that cause the most immediate (and often most expensive) inconvenience to the customer. Many papers have been written on techniques for characterising voltage sags by analysing the shape, depth and duration of voltage sag events, and in some cases expert systems have been developed to automate the sag characterisation process. Much less has been written regarding analysis of continuous disturbances. While the measurement and analysis of discrete PQ events is outside the scope of this study, this section will include a brief review of current research in that area. This will be followed by a review of current developments in the measurement and analysis of continuous PQ disturbances.

2.3.1 Measurement and analysis of discrete PQ events

Discrete PQ events include such occurrences as voltage sags/swells, transients (impulsive and oscillatory) and interruptions. The most common method of monitoring such events is by logging (with time stamp) each event, with many monitors also having the ability to capture the waveform of events that exceed specified limit values. Reporting of the events may take the form of a simple log, while in some cases the events are plotted against the CBEMA (or ITIC) curve as an indication of customer impact caused by the disturbance (described in more detail later in this section). One of the problems associated with this approach to the monitoring of discrete events is the possibility of data overburden. Some utilities that are monitoring at distribution substation level can record hundreds of PQ disturbances per day [13]. The challenge for the network manager is to analyse this data and summarise it so as to obtain a meaningful indication of service quality at a particular site. Ideally, this index should reflect the impact of the voltage variations on the customers served from the site [13]. Discussion regarding discrete power quality events has centred on how to accurately measure these disturbances, and on how best to characterise the events and so arrive at a suitable power quality index. The following discussion represents only a small selection of literature dealing with analysis of discrete PQ events as this topic is outside the main focus of this thesis.

Several of the papers reviewed deal with the techniques used to analyse voltage variations. A common theme is that the use of the Fourier transform to extract the harmonic spectrum of the disturbance waveform does not give a true measure of the harmonic content [14], [15], [16], [17]. To ensure the accuracy of the Fast Fourier Transform (FFT), the analysed waveform must be periodic and stationary, and the sampling interval must be an exact integer multiple of the waveform fundamental period. Transients however are typically high frequency, non-periodic waveforms. Further problems can arise when there are sub-harmonic or inter-harmonic frequencies present with the result that the recreated waveform may not be accurately representative of the original [16].

The use of wavelet transforms (WT) has been proposed as an alternative analysis technique that overcomes the deficiencies of FFT. Wavelet transforms are an effective method for assessing the spectral content of non-periodic and time-varying power system waveforms [12]. The wavelet transform represents time-dependent signal behaviour in both the time and frequency domains (the wavelet domain). The transformation kernels of the wavelet transform are generated by dilating a single prototype function (mother wavelet). The set of transformation kernels consists of various scaled versions of the mother wavelet. The smaller scale version of the mother wavelet has a high time resolution but poor frequency resolution. However the larger scale version is a dilated version of the mother wavelet, which loses its time resolution but has high frequency resolution. According to [16], wavelet transform analysis is sensitive to signals with irregularities but ignores steady-state signal behaviour.

There appears to be some dispute in the literature regarding which disturbance types are better monitored using wavelet transforms as opposed to Fourier transform techniques. The authors of [14] state that because wavelet transforms effectively decompose the monitored signal from high frequency bands to the low frequency end through an iterative process, wavelet transforms are not so suitable for directly monitoring or analysing low frequency disturbances such as interruptions, sags, swells, or flicker [14]. A paper describing classification of both high and low frequency disturbances using Hidden Markov Models concludes (from results from simulated disturbances) that there is comparable accuracy using either FFT or Wavelet Transform, and that FFT may outperform WT [18]. In [16] it is concluded that WT is better for analysing non-periodic signals, while FFT is better for analysing periodic signals (such as steady-state THD), and this is supported by results presented in [17]. What can be said is that while the discussion regarding the pros and cons of the Fourier Transform versus the Wavelet Transform continues, the method currently used almost universally in power quality monitoring is the Fourier Transform [19].

Another area of interest in the analysis of discrete voltage variations is the automated classification of events. The aim is to reduce the data overburden by automatically determining whether a discrete event is a transient or a voltage sag or swell, and to group these disturbances into categories such as fault-induced events, induction motor events, interruptions, and step-change events. A number of techniques employing rules-based expert systems, neural networks, genetic algorithms and Hidden Markov Models have been proposed [16], [18], [20]. The accuracy of a rules-based system is based on the knowledge of human experts and so is only as good as the validity of the rules. Such systems should improve over time as more rules are added and clarified [16].

Regardless of the mathematical method used for triggering and recording a discrete disturbance, the question remains as to how to quantify this data and summarise it by a meaningful index. The generally accepted method of characterising voltage sag events is to measure the depth and time duration of the sag. This information can then be recorded as a set of diary entries, plotted on a histogram (number of sag events versus event magnitude), or plotted against an equipment immunity curve such as the CBEMA or ITIC curve. These curves are shown below in Figures 2-1 and 2-2. Because these curves are so often referred to in discussions on power quality, they will be discussed in more detail.

Please see print copy for Figure 2.1

Fig.2-1: CBEMA Equipment Immunity Curve

The CBEMA (Computer and Business Machine Manufacturers Association) curve is an equipment immunity curve. The area enclosed by the curve represents the values of time duration and voltage variation that computer and business equipment should be able to withstand and continue to function without any negative impact. The ITIC (Information Technology Industry Council) curve has in recent years replaced the

CBEMA curve in much of the literature, and likewise represents the level of equipment immunity to voltage sags.

Please see print copy for Figure 2.2

Fig. 2-2: ITIC Computer Equipment Immunity Curve

It is worth noting that both of these curves have been developed to indicate voltage sag immunity levels for equipment that is connected to low voltage. While plots of voltage sag events on MV networks are often overlaid on scaled versions of the CBEMA or ITIC curves, this is not the application that the curves were developed for and the validity of the scaled curves can be questioned. Additionally, the curves have been developed for single-phase equipment, and do not take into account the effect of voltage sags on equipment that is connected across 2 or more phases of the supply. In applying these equipment immunity curves to analysis of voltage sag data from a network site, there is the problem that a site that has a single sag event outside the curve will be assessed as having worse PQ performance than another site with hundreds of sag events just within the curve.

The ESKOM approach is to divide up the voltage-duration plane into several windows and to give a count of the number of sags in each window. This can then be compared against a target number of sags for each window. Several deficiencies in these methods have been identified in [21] and alternative methods of analysing voltage sags and deriving a voltage sag index are proposed.

A methodology for analysis and a series of indices for discrete voltage variation events have been proposed in [22], based on voltage variation definitions given in the IEEE Standard 1159-1995, Recommended Practice on Monitoring Electric Power Quality (ref. Appendix A, Table 1). These proposed indices are described in detail below.

IEEE Standard 1159-1995, Recommended Practice on Monitoring Electric Power Quality classifies voltage variations according to magnitude and duration. Time durations for instantaneous, momentary, temporary, and long duration variations are specified, as are voltage magnitudes for voltage sags and swells. The problem in implementing these classifications is in defining the time duration for non-rectangular voltage variation events (i.e. the voltage variation is not constant over the duration of the event). The authors propose a method called the 'specified voltage method', which allows the time duration to be measured for specified levels of voltage variation (where the residual voltage is expressed as a percentage of the nominal voltage).

The specified voltage method is the first step in characterising the voltage variation (characterisation being the process of extracting useful information from a measurement which describes the event without having to retain every detail of the event). For each rms variation measurement, the magnitude and duration are designated as the magnitude and duration of the phase with the greatest voltage deviation from the nominal voltage. Time aggregation is applied, whereby any measured deviations occurring over a defined time period are considered part of the same aggregate event (the time period for aggregation chosen is one minute).

Having characterised the voltage variation, the paper goes on to give examples of the calculation of four rms voltage indices:

1. System Average RMS (Variation) Frequency Index ($SARFI_X$): represents the average number of specified rms variation measurement events that occurred over the assessment period per customer served.

$$SARFI_X = \frac{\Sigma N_i}{N_T} \quad (2-1)$$

where

x = rms voltage threshold; possible values – 140, 120, 110, 90, 80, 70, 50 and 10

N_i = number of customers experiencing short duration voltage deviations with magnitude above X% for X> 100 or below X<100 due to measurement event i

N_T = number of customers served from the section of the system to be assessed

2. System Instantaneous Average RMS (Variation) Frequency Index $_{voltage}$ ($SIARFI_X$): $SIARFI_X$ represents the average number of specified instantaneous rms variation measurement events that occurred over the assessment period per customer served. The specified disturbances are those with a magnitude less than X for sags or a magnitude greater than X for swells and a duration in the range of 0.5 – 30 cycles.

$$SIARFI_x = \frac{\Sigma NI_i}{N_T} \quad (2-2)$$

where

X = rms voltage threshold; possible values - 140, 120, 110, 90, 80, 70 and 50

N_i = number of customers experiencing instantaneous voltage deviations with magnitudes above X% for X>100 or below X% for X< 100 due to measurement event i.

3. System Momentary Average RMS (Variation) Frequency Index $_{voltage}$ ($SMARFI_X$): this index is similar to $SIARFI_X$, but is defined for variations having durations in the range of 30 cycles to 3 seconds for sags and swells and in the range of 0.5 cycles to 3 seconds for interruptions.

4. System Temporary Average RMS (Variation) Frequency Index $_{voltage}$ ($STARFI_X$): again similar to the above indices, but defined for temporary variations which have durations in the range of 3 – 60 seconds.

It should be noted that these indices are referred to variations having time durations as defined in IEEE 1159-1995. This standard has not been adopted in New Zealand

(New Zealand has chosen to follow the lead of Australia in adopting the IEC 61000 series EMC regulations to specify power quality requirements).

Calculation of the SARFI, SIARFI, SMARFI and STARFI indices requires knowledge of both the number of customers affected by the voltage variation, as well as the total number of customers served by the section of network being assessed. Where monitoring is at the MV level (as is the case with the Vector monitoring programme) it may be difficult to accurately estimate the number of customers affected by a particular voltage variation event.

2.3.2 Analysis of Continuous Power Quality Data

As stated in the introduction, much of the literature on analysis of power quality data focuses on discrete voltage events. Relatively little has been published on the subject of continuous or steady-state variations in utility distribution systems. The following section will discuss work that has been published on this topic, and relate it to the methods used in the Vector study.

Power system conditions encompassed within the category of continuous variations include continuous voltage variations, voltage unbalance and harmonic distortion. Techniques for analysing each of these conditions and deriving an appropriate power quality index will be discussed.

Some common practices in the measurement and analysis of the continuous variations given above have been established and documented in [23]. The basic measurement window for variations is 10 cycles. These measurements are then combined into an rms value over a period of 3 seconds to give ‘very short time’ values. Their values over 10 minute intervals can be further combined by rms averaging to give ‘short time’ values. It is these ‘short time’ values that are the basis for the reporting of continuous variations.

International standards such as the IEC 61000 series EMC standards and the CENELEC EN50160 standard use cumulative probability values such as 95%, 99% or 100% when specifying acceptable levels of variations i.e. the specified level of variation will not be exceeded for more than (say) 95% of the duration of the survey period. The survey duration period most commonly cited in the standards is one week.

Continuous voltage variations

Utilities specify a nominal voltage at which electricity will be supplied to customers. Variation in conditions on the network (usually changes in load) will inevitably result in some deviation from the nominal value. Assessment of continuous voltage variations aims at quantifying the degree of voltage deviation from the target value and comparing this against a specified acceptable range. Analysis of continuous voltage variations will also identify long-term trends in voltage variation so that remedial action can be taken if required.

The ideal value of voltage variation from the target value is zero. A method for deriving a voltage variation index has been proposed by the Integral Energy Power Quality & Reliability Centre [24]. This method uses what is referred to as the Absolute Voltage Deviation (AVD). This is defined as the absolute difference between the measured voltage and the voltage in the middle of the desired range, expressed as a percentage of the nominal voltage. The 95% value of this quantity can then be found, with the maximum value over the three phases being taken as the 'Primary Voltage Index'.

There are two main shortcomings associated with this index. The first involves the use of the 95% statistic. For a survey period of one week, the 95% value effectively ignores voltage deviations that occur in the remaining 5% of the week, which equates to a possible 8.4 hours continuous per week. To overcome this, the authors recommend that the 95% value be calculated for each day, with the weekly statistic being the maximum of the daily 95% values. Additionally, a secondary voltage index has been proposed called the Voltage outside Range Index (VoR), which is derived from the rms value of voltage measurements that exceed a specified limit value over the survey period. The Primary Voltage Index is an index that is directly referenced to international standards (in this case, the European Standard for Voltage Characteristics of Electricity Supplied by Public Distribution Systems, CENELEC

EN 50160:1994, refer to Appendix A, Table 2), while the secondary index is a non-standards based index and is intended to give an indication of extreme behaviour outside the 95th percentile.

The second problem with this primary voltage index is the use of absolute values for the voltage deviation. This means that the resulting voltage index gives no indication of whether the voltage is typically higher or lower than the target value (or a combination of both). Alternatives based on a modification to this index have been proposed as part of this thesis (refer Chapter 5: Utility power quality data analysis, section 5.9 – Another voltage index p.107).

Voltage Unbalance Variations

The procedure proposed in [24] (and used in the Vector study) for analysis of voltage unbalance is similar to that for voltage, and is based on the 95% value of the 10-minute readings over each day or week. The actual voltage unbalance measurements can be found from the sequence components or directly from the measured values. The main difference between deriving an index for voltage unbalance as compared to voltage magnitude is that the ideal value for voltage unbalance is zero. A secondary index Unbalance over Limit (UoL) is also proposed, being the rms value of unbalance measurements that exceed a specified limit value. This secondary index gives a measure of the voltage unbalance measurements that fall outside the 95%.

An alternative to the conventional concept of voltage unbalance has been proposed in [14]. While voltage unbalance is defined as the ratio of negative to positive sequence components in a three phase system, this paper proposes a Symmetrical Components Deviation Ratio (SDR). The SDR is defined as:

$$SDR = \frac{\sqrt{\left|V_{mp} - V_1\right|^2 + V_{mn}^{\ 2} + V_{mz}^{\ 2}}}{V_1} \times 100\% \quad (2-3)$$

where V_1 is the rated amplitude of the fundamental component and V_{mp}, V_{mn} and V_{mz} are the measured instantaneous values of the fundamental positive, negative and zero sequence components respectively. The SDR indicates the degree of waveform deviation in a three phase system from the ideal sinusoids consisting of only a fundamental positive sequence component which has the system rated amplitude and frequency. The first term in the numerator represents the amplitude deviation of the fundamental positive sequence component from the system rated amplitude. The second and third terms represent the degree of instantaneous imbalance in a three phase system. Different impacts of each of these three terms on the power system or customers can be taken into account by the application of weighting factors from 0.0 to 1.0 (default value).

While the SDR index primarily characterises system unbalance, it combines this with any measured deviation in fundamental voltage amplitude. The rationale provided for this is that under practical circumstances, a PQ event usually consists of a combination of the classical power quality disturbances as defined by the IEC (i.e. harmonics, voltage fluctuations, voltage dip and interruptions, induced low frequency voltage, voltage imbalance, power frequency variations, oscillatory transients). Waveform distortion is usually caused by several different power disturbances in these categories occurring simultaneously.

The SDR is just one of a series of novel PQ indices proposed in [14]. The Waveform Deviation Ratio (WDR) which is also proposed in [14] will be discussed later in this section.

Harmonic Distortion

Techniques for analysing harmonic distortion are well established and are described in several international standards. AS/NZS 61000-4-7 Testing and Measurement Techniques – General guide on harmonics and interharmonics measurements and instrumentation [25] (this standard is a clone of the IEC standard of the same number and title) clearly specifies the measurement requirements (3 second measurements aggregated into 10 minute values). The standard also recommended the use of 95% and 99% cumulative probability values for presenting the statistical data. These principles are built upon in [24], which goes on to propose methods of both time and phase aggregation for further data compression. In [24] it is recommended to measure, for each phase, THD and individual harmonics up to about the 40^{th}

harmonic. For each harmonic, it is recommended to take the 95% value, and then take the maximum over the three phases.

The point is made that in Australia, harmonic measurement focuses on just THD and the 5th harmonic, as the levels of all other harmonics tend to be low. From this, it can be assumed that THD is a reliable indicator of harmonics levels. This assumption can be checked by calculation of a Harmonics Inclusiveness Index [24], which effectively checks whether the measured harmonics give sufficient explanation for the value of THD. The Harmonics Inclusiveness Index (HII) is defined as follows:

1. Determine the Harmonics Inclusiveness Value (HIV) for each week for each phase using

$$HIV = \frac{95\% V_5}{95\% THD} \quad (2-4)$$

2. Obtain a weekly value by taking the minimum value across the phases.
3. HII is the minimum of the weekly values across the survey period.

The numerator can be expanded to include harmonic orders other than the 5th harmonic where these are being measured. A small value of HII indicates that the measured harmonics are too small to explain the THD value, and that another order harmonic is a significant component of the THD.

Assuming an appropriate value of HII is obtained, a Harmonics Index can be calculated based on the 95% values of THD. Briefly, the algorithm used to calculate the Harmonics Index for a particular site is:

1. Find the 95th percentile value of THD for each phase for each day.
2. Daily THD value is the maximum of the individual phase 95th percentile values.
3. Harmonics Index for the survey period is the maximum of the daily 95th percentile values (in the case of long duration surveys such as three-monthly seasonal or annual, the Harmonics Index may be taken as the 95th percentile value of the daily values)

This is the method of harmonic analysis that has been used in the Vector study. Calculation of the Harmonics Index has proved to be straightforward, and the resulting index is useful for comparison of numerous sites across a network. If the 95% THD values are normalised against a limit value, the index gives a relative indication of impact of harmonic levels on customers as well as the degree of conformance with standards or internal planning levels.

Significant work has also been carried out in the study of harmonic distortion and the development of harmonic disturbance indices by the Electric Power Research Institute (EPRI) (U.S) as part of the Distribution System Power Quality Project [26]. The harmonic disturbance indices proposed as part of this work share some similarities with the methods described in [24], but there are some significant differences. In [26] the site and system harmonics index is also based upon the 95% cumulative frequency value, but the derivation of the actual index value from this 95% value differs from the method proposed in [24]. The method is detailed in [26] and is summarised below:

- For each circuit segment that is part of the system being assessed, find the 95th percentile value of THD for each phase for each day.
- If considering harmonic distortion in a three phase system, the harmonic distortion is characterised by the average of the THD measurements over the three phases.
- Two Harmonics Indices are calculated for the system consisting of discrete circuit segments: System Total Harmonic Distortion CP95 (STHD95) and System Average Total Harmonic Distortion (SATHD). These two indices are defined as:

- STHD95:

$$\frac{\sum_{-\infty}^{STHD95} f_t(CP95)\times L_S}{\sum_{-\infty}^{\infty} f(CP95)\times L_S} = 0.95 \quad (2-5)$$

$$\frac{\sum_{-\infty}^{CP95} f_s(x_i)}{\sum_{-\infty}^{\infty} f_s(x_i)} = 0.95 \quad (2-6)$$

where

s = circuit segment number

x_i = steady-state THD measurement number

L_s = connected kVA served from circuit segment s

$f_s(x_i)$ = probability distribution function comprised of sampled THD values for circuit segment s

$CP95_s$ = 95th cumulative probability value of the THD measurements for the segment s

$f_I(CP95_s)$ = probability distribution function comprised of the individual circuit segment THD CP95 values

Effectively, the STHD95 index is found by first calculating the 95th percentile value of THD for each site in the system, and then taking the 95th percentile of the individual site indices across the system as the system THD index.

- SATHD (System Average THD)

$$MEANTHD_S = \frac{\sum_{I=1}^{N_{mw}} THD_i}{N_{MW}} \qquad (2-7)$$

$$SATHD = \frac{\sum_{s=1}^{k} L_s \cdot MEANTHD_S}{L_T} \qquad (2-8)$$

where

s = circuit segment number

$MEANTHD_s$ = statistical mean of the steady-state measurement windows for circuit segment s

THD_i = voltage total harmonic distortion calculated for measurement window i

N_{MW} = total number of steady-state measurement windows collected for a given circuit over the duration of the monitoring period

k = total number of circuit segments in the system being assessed

L_s = connected kVA served from circuit segment s

L_T = total connected kVA served from the system being assessed

i = steady-state measurement number

While the STHD95 index is based on 95th percentile values of THD for each circuit, SATHD is based on the mean value of the distribution of voltage THD measurements recorded for each circuit segment. It can also be seen from the above definitions that each of the harmonic indices are weighted by the connected kVA of the measured site in relation to the kVA of the total system. The rationale behind this is to give more weight to sites that are considered more important. It is suggested that alternative weighting factors could be applied, such as sensitivity of customer loads on the circuit being monitored.

The application of a kVA load-weighting factor is the main aspect of the above indices that differs from those proposed in [24]. Some merit can be seen in applying such a weighting factor in that it allows for the assumed higher priority of circuit segments that are supplying greater load. However, it does have the adverse effect of distorting the picture of what the actual THD disturbance levels are at individual sites. It may be difficult to convince a residential customer that a high level of THD in their supply is satisfactory simply because the residential feeder supplying that customer has less connected load than an industrial feeder with higher connected load (and possibly lower THD).

A third harmonics index is proposed in [26]. The System Average Excessive Total Harmonic Distortion Ratio Index THD Level ($SAETHDRI_{THD}$) is a measure of the number of steady-state THD measurements during the assessment period that exceed a specified threshold. For each circuit segment, the number of measurements exceeding the THD threshold is normalised by the total number of measurements recorded for the segment. As with the previous indices, the average for each segment is then weighted by the ratio of the load served by that segment against the total system load.

$$SAETHDRI_{THD} = \frac{\sum_{s=1}^{k} L_s \cdot \left[\frac{N_{THD_S}}{N_{MW_S}} \right]}{L_T} \qquad (2-9)$$

where

s = circuit segment number

k = total number of circuit segments in the system being assessed

L_s = connected kVA served from circuit segment s

L_T = total connected kVA served from the system being assessed

THD = THD threshold specified for calculation of this index

N_{THDs} = number of steady-state measurements that exceed the specified THD threshold value, THD

N_{MW} = total number of steady-state measurements recorded for segment s over the assessment period

Given that the impact on customers of excessive THD levels is dependent not only on magnitude but also on the duration of the disturbance, the $SAETHDRI_{THD}$ index above is only partly representative of customer impact. The index as defined does not take into account the magnitude of the disturbance. To give a true indication of the customer impact of excessive THD levels, the index needs to be calculated based on the area under the THD – time curve for values of THD that exceed the specified threshold level.

Another concern about the indices proposed in this paper is the complexity of the indices, and the fact that three separate indices are proposed to represent site harmonic levels. To quote the Cigre C4.07/Cired Joint Working Group report on Power Quality Indices and Objectives [19]: “Quality indices provide a few representative numbers that are extracted from a large volume of power quality measurement data. As much as is feasible, the number of quality indices and parameters should be kept at their minimum without losing essential information. They should also be easy to assess, be representative of the actual impact of the disturbances they characterise, and they should last a ‘lifetime’ in order to allow comparison of performance with time.” The system of harmonics indices proposed in [26] will still result in a significant number of indices to be analysed by the network planner. Additionally, the assessment and calculation required is somewhat more complicated than that required for the indices described earlier in [24].

[26] also presents benchmark data from the EPRI DPQ Project [27] that utilises data from 277 measurement locations located on the primary distribution feeders of 24 electric utilities across the United States. It is interesting to compare the CP95 results of the survey with the calculated 95th percentile values from the Vector survey. From the U.S study, the average value of the CP95 value for V_{THD} was 2.18%. The 95th percentile value across the Vector sites was 2.29%. Given that the U.S study uses the average of the THD values across the three phases to calculate the CP95 value, whereas the Vector study has used the maximum of the phase THD values, the results of the U.S 1993 – 1995 study and the Vector 2003 – 2004 study are very similar.

Equally interesting are the results of the seasonal analysis of THD data presented in [26]. The seasonal trend in the U.S data is similar to that shown in the Vector data. THD tends to be lower during the winter months and also during the summer months. The periods of low THD correspond to peak loading periods of the year due to heating and air conditioning demand. Like the Vector harmonics data, the maximum variation of THD measurements over a 12 month for a particular site were typically around 0.5%. The authors also note that over the 27 month term of the survey, there was small trend towards increasing V_{THD}. On average, the project's sites showed a V_{THD} increase of approximately 10% from their previous value (e.g. from 1% V_{THD} to 1.1% V_{THD}). For the Vector survey, the average trend in V_{THD} was an average increase of 14.8% across the monitored sites over the 12 month survey period (it should however be noted that at three of the Vector sites, THD levels decreased over the survey period).

In summary, [26] proposes indices for harmonic distortion that are in many ways similar to those that have been used in the Vector study. There are no particular advantages to the indices proposed in the paper, although the principle of applying a weighting factor to an index based on the load share of the circuit segment being studied has some merit (if the required kVA data is readily available). The benchmark data presented from the 1993 – 1995 United States study confirm the trends that have been observed in the 2003 – 2004 Vector study.

There has been some discussion about whether THD is an appropriate indicator for harmonics levels due to the loss of information about individual harmonics that occurs in calculating THD. THD is widely used as an index to characterise the amplitude of harmonics expressed as a ratio of the fundamental.
THD is defined as:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \qquad (2-10)$$

where h denotes the harmonic order and I denotes the fundamental quantity (in this case current, but a similar expression is defined for voltage THD).

In [12] the point is made that the conventional THD index has several deficiencies. It does not convey any information about the phase angle of the harmonic waveforms. All harmonics are weighted equally, which leads to a loss of information regarding the individual harmonic order and magnitude (this issue has been addressed to some extent by the proposed Harmonics Inclusiveness Index in [24]). THD is not able to distinguish between two signals having the same number of harmonics with the same magnitude but different order. For example, a signal that has 5% THD with only the 3rd harmonic present could have the same THD as a signal where the only harmonic is the 47th. Yet these signals have very different effects on power systems [28]. Additionally, THD deals with the harmonic spectrum of the signal as estimated using FFT, the shortcomings of which have been referred to earlier.

An alternative index is proposed in [12] based on wavelet multi-resolution signal analysis. This analysis gives wavelet coefficients for the different frequency bands that exist in the signal. Different weightings are applied to the coefficients corresponding to the energy content at each level (the higher the level, the larger the weight). The alternative index (THD′) is the square root of the ratio of the sum of the squares of all of the weighted coefficients of the signal details to the sum of the squares of the lowest frequency band coefficients. However, no testing or results are presented in the paper, so it is not possible to evaluate this index against the traditional method of THD calculation.

Another alternative to the THD index is proposed in [14]. The Waveform Distortion Ratio (WDR) is defined as:

$$WDR = \frac{\sqrt{\left|V_{m1} - V_1\right|^2 + \sum_{i=2}^{M} V_{\text{integ}-h,i}^2 + \sum_{j=1}^{N} V_{\text{integ}-h,j}^2}}{V_1} \times 100\% \qquad (2-11)$$

Where V_1 and V_{m1} are the rated amplitude and measured instantaneous amplitude of the fundamental respectively, $V_{integ\text{-}h,i}$ is the measured instantaneous amplitude of the i^{th} integer harmonic component in the distorted waveform; similarly, $V_{integ\text{-}h,j}$ is that for interharmonic component (the j^{th} among the total N inter-harmonic components). WDR is said to be a global index which represents the degree of single phase waveform distortion from an ideal sinusoid with the rated amplitude and frequency. It gives an overview of a range of disturbance types (harmonics & inter-harmonics, voltage fluctuations, voltage sags and interruptions, voltage unbalance). The first term in the numerator, $\left|V_{m1} - V_1\right|$, represents the degree of waveform distortion caused by a low frequency disturbance such as an interruption, sag, swell, or flicker. The second and third terms represent the degree of waveform distortion caused by integer harmonics and inter-harmonic components. It is suggested that the varying impacts of the integer harmonics and inter-harmonic components can be taken into consideration by imposing weighting factors to their respective amplitudes. The conventional THD index on the other hand, represents only the contribution of signal components at the integer multiples of the rated frequency during the observation window regardless of the deviation of the power frequency. While the accuracy of the FFT is affected by variations in frequency, there is no such impact on the WDR index. If the power frequency has deviated from the rated value at the instant of measurement, V_{m1} and $V_{integ\text{-}h,i}$ are merely the amplitudes of the fundamental and harmonic components at that time. Clearly the claimed advantages of this new index rely on suitable measuring techniques which achieve accurate analysis of the distorted waveform. The authors propose the use of wavelet analysis rather than Fourier transform analysis.

If it is accepted that it is more appropriate to develop power quality indices that represent a combination of classical power quality categories, the proposed WDR is a good starting point in developing such alternative indices. Results presented in [14] using simulated input signals suggest that the proposed measurement techniques and index may have some advantages over the traditional approach to THD. However, further research is required to establish the relationship between the proposed index and the impact on customer equipment.

A Universal PQ index

One of the objectives of a power quality index is to effectively represent large amounts of raw data by a single number. The traditional approach is to measure the various power quality phenomena and assess these against the specified limits. The power quality at a site can then be quantified by an index for each disturbance type. Depending on the parameters being monitored, this would typically result in the power quality of the site being characterised by six indices as listed below:

1. Harmonics (may be a single index for THD, or a series of indices for each individual index up to say the 40^{th} harmonic).
2. Voltage variations (steady-state)
3. Voltage variations (sags/swells)
4. Voltage unbalance
5. Voltage fluctuation
6. Oscillatory transients

Ideally, this information could be further condensed by characterising power quality at a site by a single universal index that combines all of the above. Deriving such an index is problematic due to the multi-dimensional nature of the parameters involved. An attempt at resolving this has been attempted in [29].

The first step in deriving this index is to specify the power quality determinant factors (PQDF) and to define quantitatively and qualitatively the impact of each of these factors on the overall power quality levels at a site. This was achieved by means of a literature search and by consultation with subject experts using a technique known as concept mapping. The PQDFs (for steady-state conditions) identified were $THD_{voltage}$, $THD_{current}$, power factor, and short circuit (fault) level.

The second step consists of using fuzzy linguistic variables (low, medium, high, very high) to specify three or four levels for each PQDF. The subject experts were asked to define a maximum value, minimum value and unity value for each PQDF for the membership functions of each fuzzy linguistic variable (FLV).

The analytic hierarchy processing (AHP) step consisted of asking each subject expert to do pair-wise comparisons, where the importance of each PQDF was measured using a scale with which one PQDF dominated another. THD_v was found to be the most important factor in determining power quality under steady-state conditions, while frequency of undervoltage events and load stiffness were the most important PQDFs for occasional events and load-related characteristics respectively.

In a further step, fuzzy inference techniques were used to determine the most significant PQDF. For the steady-state module, THD_v was found to have the most influence on the outcome of the overall Power Quality Level (PQL) (Interestingly, this agrees with the findings of the Vector study, where THD levels were found to be the most influential factor in determining the overall PQ levels at a site under steady-state conditions).

Finally, the results of the AHP and fuzzy inference were used to apply weightings to each of the PQDFs so that they could be combined to arrive at an overall Power Quality Level (PQL). The system has been field tested at a number of loading points having different operating conditions, and the numerical values presented are said to be compatible with engineering sense and field experience.

The utilisation of techniques such as concept mapping, analytic hierarchy processing and fuzzy inference is a novel approach to the problem of deriving a universal PQ index. The results seem to confirm what many electricity engineers would suspect intuitively. Despite this, there has not been widespread implementation of this method of deriving an overall PQ index for a site.

In [30], several approaches to deriving a universal site PQ index are compared. The use of arithmetic averaging of ‘component’ indices for (for example) voltage, voltage unbalance, voltage fluctuation and harmonics is discounted as it assumes that the overall effect of power quality is directly related to the sum of the individual disturbance levels, and that excessive levels of one disturbance type can be offset by lower levels of other types of disturbances. The use of the maximum of the component indices is likewise discounted, as it does not adequately take into account the effects of individual disturbance types.

The paper introduces the concept of 'Exceedance', which is a measure of how much a disturbance type exceeds the maximum acceptable value. If the (normalised, where a value of one indicates the limit of acceptability) value of a component PQ index is less than one, the corresponding Exceedance is zero, while if the component PQ index is greater than one, the Exceedance value is equal to the PQ index minus one (e.g. if the harmonics index is 1.4, the Exceedance value is 0.4). The 'Unified Power Quality Index' (UPQI) is then defined as:

1. If all of the component PQ indices for a site are less than one, the UPQI equals the maximum of the indices.
2. If one or more of the component indices is greater than one, the UPQI equals one plus the sum of the Exceedances.

At the time of writing, the UPQI had only been applied to continuous disturbance types, but with the intention of extending the techniques to include discrete disturbances. Application of the proposed UPQI to data for a large number of sites suggests that it effectively indicates the headroom of the dominant disturbance type at a site, and that for sites with high levels of PQ disturbances, it gives a measure of the levels of all disturbances that are excessive. It should also be noted that the UPQI index resulted in a similar site ranking as that obtained from using a site index based on a simple arithmetic average of component indices (as employed in the Vector study). However, the proposed UPQI appears to be a worthwhile improvement on the method of simple averaging.

Overall comments on PQ data analysis literature

While the analysis of discrete PQ events is an area of vibrant activity, there appears to be less interest in the analysis of continuous PQ phenomena. Some clear shortcomings have been identified in the indices that are in common use. These shortcomings largely involve the measurement techniques and possible errors that are introduced. In particular, there is considerable discussion in the literature as to whether the Fourier Transform is an appropriate technique for determining the harmonic composition of power system waveforms. Alternative methods of determining the degree of waveform distortion have been proposed, mostly based on Wavelet Transform techniques.

Some discussion revolves around the ability of the established indices to give a meaningful representation of the impact on customer and power system equipment. Several systems of alternative indices have been proposed with the aim of eliminating the identified deficiencies of the current indices. Additionally, a universal PQ index for characterising the overall PQ level at a site has been proposed.

While the discussion continues, there are well-established techniques and indices that are documented in widely-accepted standards. Until there is recognition and acceptance by the standards-setting bodies of any proposed alternative, instrument manufacturers and utility network planners will continue to define power quality levels using the established indices (regardless of the deficiencies). These indices do have the advantage that they are widely understood, easy to implement, and provide a common basis for benchmarking purposes.

2.4 Power Quality Network Indices and PQ Reporting

The previous section covered measurement and analysis of power quality disturbances. This included proposals for alternative methods of deriving indices for the various types of disturbance as well as a description of the more accepted indices that are recommended for use by international standards. The purpose of all of the indices discussed so far is to summarise a large amount of raw data relating to a particular disturbance type for a particular site.

Having calculated indices for each disturbance type for each site, the utility that is monitoring at a large number of sites may still require a means of further summarising this information. Additionally, the information must be put into an appropriate form so that it can be reported to the interested parties i.e. the network manager, the customer, and the regulatory body (if required). Ideally, the reporting format should be consistent across utilities to allow comparison of results. This benchmarking process will enable utilities to determine what levels of disturbances are typical, and what levels are realistically achievable.

This section will look at proposed methods for using site disturbance indices to derive network or utility indices. It will also look at proposed methods for reporting the results of utility power quality surveys.

2.4.1 System Indices

Given that it is not possible to monitor all utilisation points in a system, the monitored sites will inevitably be a sample of the possible range of sites. The data used to derive a system index must come from a sample of sites that adequately represents the diversity of conditions that exist within the network. If the primary factors that are likely to influence power quality levels are identified, it is possible to categorise sites and install monitors to cover each of these categories.

In [19] it is suggested that for steady-state disturbances, two categories of indices can be used. Planning level indices can be used for assessing internal quality objectives, while indices for voltage characteristics can be used for external reporting of system performance. It goes on to recommend that two levels of indices for external reporting:

1. Site indices: for reporting the performance at a specific site.
2. System indices: for reporting the performance of a system.

The recommended system index is the value of the site index not exceeded for a high percentage of sites (e.g. 90, 95 and 99%), for each individual index and parameter. The use of maximum values (100%) is not recommended due to the possibility of being inflated by transients.

Weighting factors can be introduced to take into account the sites not monitored and the relative importance (e.g. number of customers served, total kVA/MVA loading) between monitored sites. Such a weighting system has been described in [26].

The Cigre C4.07/Cired working group report goes on to suggest an alternative definition of a system index. This index defines the number of sites that exceed the target level of disturbance during the survey period. A disadvantage of this method is that at least 100 sites would need to be monitored for the uncertainty to be 1% or less, or more than 20 sites for the uncertainty to be 5% or less, and so on.

A three-level reporting structure has been proposed in [31], as shown in Fig.2-3 below.

Please see print copy for Figure 2.3

Fig.2-3: Three level PQ reporting structure.

The site report contains sufficient raw data for each site to suggest if limits are met and to allow causes of PQ problems to be identified. This paper suggests that graphs of trends against time are suitable means of presenting this information.

The network report lists each site together with its primary and secondary indices for each disturbance type (as described in [24]). Sites can be ranked to allow easy prioritisation for remedial work. The network report is oriented to showing whether a site is compliant with the relevant PQ standards (and the internal planning levels of the utility if these exist).

The utility report presents a single index for the utility for each disturbance type. This single utility index is calculated as a weighted average of the site indices across the network. The downstream kVA loading of each site is used as the weighting factor. This approach is similar to that recommended in [19], the main difference being that the resulting utility or system index is a weighted average of site indices, whereas the Cigre C4.07/Cired working group approach reports a particular percentile value of the site indices. There is no clear advantage to one approach or the other. What is required is agreement on a consistent method of reporting so that the results can be easily compared between utilities.

The approach that has been used in this thesis is to use the 95% percentile value of the site indices as the system index. This follows the recommendations of [24]. No weighting has been applied to the site indices. While there is significant variation in the loading of the 13 monitored sites (average loading ranges from 14 MVA up to 45 MVA), there are other equally valid criteria that the site indices could also be weighted by (for example, load type, with perhaps a higher weighting given to industrial users rather than residential).

A novel format for reporting of utility PQ performance has been developed in [32]. This consists of a ‘utility scorecard’ that tabulates indices for the various disturbance types. These utility indices are normalised to allow comparison and ranking against other utilities. An example of such a table is given in Table 2-1.

Table 2-1: Utility scorecard with rankings

Utility	Normalised Index				Overall Index	Rank
	Voltage (AVD)	Unbalance	Harmonics (THD)	Sags		
A	1.04	1.08	0.98	0.87	0.99	2
B	0.71	0.56	1.22	1.89	1.09	3
C	1.31	1.62	0.97	0.64	1.14	4
D	0.94	0.74	0.83	0.60	0.78	1

The key advantages of this method of reporting are that the large amount of data from a utility survey are condensed into a few summary indices, and (through a

normalisation process) these indices allow easy identification of how the utility compares with others in regard to PQ performance. At the same time, the identity of individual utilities is not revealed so that confidential information is not divulged to other utilities.
The scorecard also includes a Utility Indices Table that provides the individual utility with indices for each disturbance type, as well as indices normalised against the overall average across all utilities. This allows easy identification of which disturbance types are of most concern.

2.5 Conclusion

The study of power quality is an area of increasing importance for electricity utilities. Routine power quality surveys are becoming a more common practice. Several large international PQ surveys have been carried out and the methodology and results of these studies have been documented. While clear standards exist for some aspects of carrying out such surveys, there are other aspects (such as location of monitoring equipment) that are not so well specified. However, there is a common philosophy of ensuring that monitoring locations are representative of the variety of conditions that exist in a network.

Indices for characterising the survey data have been clearly specified in a number of international standards. Deficiencies under certain conditions have been identified in some of these indices, and alternative analysis techniques and indices have been proposed. Much of the debate is centred on the use of the Fourier Transform for extracting the harmonic content of the waveform and its shortcomings in analysing non-periodic waveforms. Despite this, the traditional methods are still those in most common use, and this situation is likely to continue until changes are made to the international standards.

Benchmark data from two international power quality surveys has been compared to the results from the Vector study. Results from these international studies support some of the findings of the Vector survey.

The reporting of the results of power quality surveys is an area that has received relatively little attention. A common methodology for the reporting of results is necessary to facilitate the comparison of results from different surveys. A three-level reporting format has been proposed and trialled in Australia.

While a range of PQ data analysis and reporting methods have been proposed in the literature, none of these methods fully meet the needs of Vector Ltd. What is required is a system of indices that accurately represents the disturbance levels on the network and the resulting impact on customers, and a concise reporting format that facilitates benchmarking of PQ performance against other utilities.

Chapter 3: Power Quality Standards

3.1 Introduction.

Power quality standards are required to ensure that utilities deliver, and that their customers receive, the quality of power that they need. The increased use of sensitive electronic equipment and non-linear devices, deregulation of the electricity supply industry, and the development of increasingly complex and interconnected power systems all contribute to the need for power quality standards. The purpose of power quality standards is to protect utility and end-user equipment from failing or maloperation when the voltage, current, or frequency deviates from normal. Power quality standards provide this protection by setting measurable limits as to how far the voltage, current, or frequency can deviate from normal. By setting these limits, power quality standards help utilities and their customers gain agreement as to what are acceptable and unacceptable levels of service. Clearly, a knowledge and understanding of the relevant standards by the electricity supplier is essential in effectively managing power quality on a supply network.

Maintaining an acceptable level of power quality is a joint responsibility. It is the responsibility of the electricity supplier to minimise system impedances so as to reduce propagation of disturbances through the network. It is the responsibility of electricity consumers connected to the network to keep disturbance emission levels within acceptable limits. On most networks, the majority of consumers are small domestic users, who cannot be expected to have the technical knowledge required to manage disturbance emission levels (in contrast to larger industrial consumers who may be connected directly to the MV network, and are required to restrict emission levels at the point of common coupling). This is where the third party in electromagnetic compatibility (EMC) plays a role. It is the responsibility of electrical equipment manufacturers to ensure that their products are able to function appropriately in the electromagnetic environment. Power quality standards are the regulatory interface between these three parties, and define the responsibilities of each. Environment standards define the requirements of the electricity supplier. Emission standards define the responsibilities of the consumers connected to the network. Equipment standards define the responsibilities of the equipment manufacturers.

This chapter will cover the following aspects of power quality standards:

- The role and scope of power quality standards in managing network power quality.
- Organisations responsible for the development of power quality standards.
- List and briefly describe the international power quality standards that have been developed.
- List and explain the New Zealand power quality standards, rules and regulations.
- Compare the results of the Vector power quality study to the regulatory requirements and the requirements of the standards, and determine the level of compliance with the regulations/standards.
- The Vector Distribution Code, which contains details of power quality requirements and objectives specific to the Vector network.

3.2 The role of power quality standards.

One of the primary motivations for a utility to carry out power quality surveys may be to demonstrate conformance with national or international power quality standards. Standards provide limits against which a utility can compare its PQ performance. Knowledge of the relevant PQ standards is essential in order to gain the maximum benefit from a PQ survey. Standards can also be applied where there is dispute between the utility and the customer regarding responsibility for power quality problems.

Power quality standards have been developed to cover the following aspects of power quality analysis:

- Instrumentation: standards specify the requirements of measuring instruments and how the measurements should be made.
- Utility limits: specify the maximum allowable levels of PQ disturbances that may be present on the utility network.

- Customer limits: these specify the maximum allowable levels of disturbances in installation load currents in order to meet the utility's requirements.
- Equipment limits: specify both the emission and immunity levels for customer equipment.

In addition to specifying maximum values for disturbances on the utility network, PQ standards should also clarify the responsibilities of the utility, the customer, and the equipment provider in maintaining acceptable levels of power quality for all users.

Power quality standards are concerned with maintaining electromagnetic compatibility (EMC) between end-user equipment and the utility's supply system. EMC is defined as the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment. There are two aspects to EMC:

1. An item of equipment should be able to operate normally in its environment (EMC immunity).
2. It should not pollute the environment to the point where it affects the operation of other equipment (EMC emission).

There are standards for both aspects of EMC. Immunity standards define the minimum level of electromagnetic disturbance that a piece of equipment shall be able to withstand. Emission standards define the maximum amount of electromagnetic disturbance that a piece of equipment is allowed to produce.

3.3 Organisations responsible for the development of power quality standards.

Organisations responsible for developing and authorising power quality standards include the Institute of Electrical and Electronic Engineers (IEEE, U.S) [33], International Electrotechnical Commission (IEC) [34], CENELEC (European Community Standards Organisation) [35], and EURELECTRIC/UNIPEDE (International Union of Producers and Distributors of Electrical Energy) [36]. Other organisations that are active in the research, development and analysis of power quality standards are:

- CIRED (Congress International de Reseaux Electriques de Distribution) [37]: an international non-governmental, non-profit organisation based in Belgium and the U.K. that covers all aspects of the electrical distribution industry.
- CIGRE (International Council on Large Electric Systems) [38]: a non-governmental, non-profit organisation based in France. The aim of CIGRE is to facilitate and develop the exchange of engineering knowledge and information. CIGRE study committee C_4 covers system technical performance including power quality performance and EMC issues.
- ANSI (American National Standards Institute) [39]: ANSI does not develop standards, but facilitates standards development by qualified groups such as IEEE. Many authorised IEEE standards have the dual designation of ANSI/IEEE.
- EPRI (Electric Power Research Institute – U.S) [40] standardisation in the Information Technology field.
- NEMA (National Electrical Manufacturers Association – U.S) [41]: develop electrical equipment standards.
- ITIC (Information Technology Industry Council – formerly CBEMA) [42]: develop emission and immunity guidelines for information technology equipment. Incorporates the U.S-based International Committee for Information Technology Standards (INCITS). INCITS also serves as ANSI's technical advisory group for ISO/IEC Joint Technical Committee 1. JTC1 is responsible for international standardisation in the IT field.

Some organisations have developed their own standards. For example, ESKOM in South Africa has developed power quality standards based on recognised international standards, plus the addition of other requirements that other organisations have not yet adopted.

3.4 International Power Quality Standards

This section lists the existing international power quality standards, and gives a brief description of the focus and contents of these standards. It should be noted that some of these standards have been cloned and adopted by various countries, and that the name of the originating organisation may not be included in the title e.g. the AS/NZS 61000 series regulations originate from the IEC 61000 series standards.

3.4.1 IEC Standards

The IEC refer to power quality standards as electromagnetic compatibility (EMC) standards. This illustrates that IEC's primary concern is the compatibility of end-user equipment with the utility's electrical supply system. The IEC have developed a comprehensive framework of standards on EMC.

Electrical power quality is a subset of EMC, in that it deals with disturbances at the lower end of the frequency spectrum. The IEC 61000 series standards are progressively being adopted by Australia and New Zealand (although they are not yet cited in any New Zealand electricity regulations).

The IEC 61000 series standards manage EMC for each PQ disturbance type by defining a boundary value known as the compatibility level. For a given disturbance type, the compatibility level is in between the emission level (or the environment) and the immunity level. The compatibility level is chosen such that compatibility is achieved for most (95%) equipment most (95%)of the time. The relationship between compatibility levels, immunity levels and planning levels is illustrated in Fig.3-1.

Please see print copy for Figure 3.1

Fig.3-1: Compatibility levels (from AS/NZS 61000.2.2).

The IEC standards also define limits for some power quality parameters. The voltage characteristics are also based on a 95% value, but now only in time, and hold for any location on the network. There is also provision for planning levels which are specified by the supply utility and can be considered as internal quality objectives of the utility. Planning levels are set at less than or equal to the corresponding compatibility level for that parameter.

For the network operator, IEC standard 61000.2.2 is perhaps the most encompassing of the 61000 series standards. This standard specifies the compatibility levels for the following power quality disturbance types that are likely to be found in low voltage public power supply systems:

- Voltage fluctuation and flicker
- Harmonics up to and including order 50
- Interharmonics up to the 50^{th} harmonic
- Voltage distortions at higher frequencies (above the 50^{th} harmonic)
- Voltage dips and short supply interruptions
- Voltage unbalance
- Transient overvoltages
- Power frequency variation
- d.c components
- mains signalling levels

While the standard is for low voltage supply systems, for many of the disturbance types the compatibility levels given are also appropriate for (and are applied to) MV networks.

The following IEC standards give emission limits for harmonic currents:

- IEC 61000.3.2 - low voltage systems (equipment input current ≤ 16A)
- 61000.3.6 - MV and HV power systems

and for voltage fluctuations:

- IEC 61000.3.3, 61000.3.5 - 3.3 and 3.5 (equipment current >16A) refer to LV supply systems
- 61000.3.7 - MV and HV power systems

As these standards have been (or are in the process of being) adopted as the New Zealand power quality standards, the relevant individual standards are described in more detail in the section on New Zealand standards.

3.4.2 IEEE Standards

In order to help those involved in measuring and analysing power quality phenomena to compare the results of power quality measurements from different instruments, the IEEE developed IEEE Standard 1159-1995 , Recommended Practice for Monitoring Electric Power Quality. This standard defines various power quality terms and categorises IEEE standards by the various power quality topics. A summary of the requirements of 1159-1995 is given in Appendix A, Table 1.

The IEEE standard for harmonics is IEEE Standard 519-1992, Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. This standard includes a table of installation harmonic current allocations versus short circuit ratio (ratio of fault level to customer maximum demand). However, these currents are not compatible with the harmonic voltage standards given in AS/NZS 61000.3.6.

3.4.3 CENELEC Standard

CENELEC is the European electrical standards association. European standard EN50160, 'Voltage characteristics of electricity supplied by public distribution systems', describes electricity as a product, and gives the main characteristics of the voltage at the customer's supply terminals in public low voltage and medium voltage networks under normal operating conditions. While EN50160 is not referred to in any of the New Zealand power quality standards or regulations, it requires mention here due to it being frequently referred to in power quality literature and in the specifications for many power quality monitoring instruments.

The EN50160 standard specifies the following:

Voltage variations

- Voltage magnitude: 95% of the 10 minute averages during one week shall be within ±10% of the nominal voltage.

- Harmonic distortion: For harmonic voltage components up to the 25th order, values are given which shall not be exceeded during 95% of the 10 minute averages obtained in one week. The total harmonic distortion shall not exceed 8% during 95% of the week.
- Voltage fluctuation: 95% of the 2 hour long term flicker severity values obtained during one week shall not exceed 1.
- Voltage unbalance: the ratio of negative and positive sequence voltage shall be obtained as 10 minute averages, 95% of those shall not exceed 2% during one week.
- Frequency: 95% of the 10 second averages shall not be outside the range of 49.5Hz to 50.5Hz.
- Signalling voltages: 99% of the 3 second averages during one day shall not exceed 9% for frequencies up to 500 Hz, 5% for frequencies between 1-10 kHz, and a threshold decaying to 1% for higher frequencies.
- Discrete events (sags, swells, transients, interruptions): EN50160 does not give any voltage characteristics for discrete events, but for some an indicative value of the event frequency is given.

A frequent criticism of EN50160 is that it only gives limits relating to conditions that exist for 95% of the time. There is no consideration of conditions during the remaining 5% of the time (8 hours 24 min per week). Considering voltage magnitude and a nominal low voltage value of 230 V, so long as the voltage is within ±10% of 230V (207V – 253V) for 95% of the time, it will conform with the voltage characteristic requirements of EN50160. For the remaining 5% of the time, the voltage could be zero or could be 1000V, and it would still conform to the standard. Math Bollen replies to this criticism: "The voltage magnitude (rms value) is obtained every 10 minutes, giving a total of $7 \times 24 \times 6 = 1008$ samples per week; all but 50 of those samples should be in the given range. If we only consider normal operation (as is stated in the document) it would be very unlikely that these are far away from the ±10% band" [43].

Another significant limitation of the standard is that it only applies under 'normal operating conditions'. This excludes situations such as operations after a fault, or interruptions to the electricity supply due to external events. A summary of the requirements of EN50160 is given in Appendix A, Table 2.

An important point about the EN50160 standard is that, as stated in its title, it describes the voltage characteristics of electricity supplied by public distribution systems. It does not specify the requirements of a *good* electricity supply. It describes the present worst-case electromagnetic environment, rather than specifying what it should be or what it will be in future. For these reasons, it is not appropriate for utilities to make claims of good power quality on the basis of conforming to the EN50160 standard.

3.5 New Zealand Power Quality Regulations and Standards

The rules and regulations that cover power quality issues in the supply and use of electricity in New Zealand are contained in three documents:

1. The Electricity Governance Rules (EGR) [44], administered by the NZ Electricity Commission. Part C of the Rules covers 'common quality' and the principal performance obligations of the system operator and asset owners.
2. The NZ Electricity Regulations 1997 [45]. Section 4 of the Regulations covers systems of supply and requirements for voltage levels, frequency, and harmonics.
3. In addition, the NZ Electrical Codes of Practice (NZECP) includes NZECP36 (1993) [46]: Harmonic levels, which specifies the acceptable levels of harmonic voltages and currents which may be introduced into an electricity supply system by a consumer's installation. It should be noted that while the NZ Electricity Regulations are Acts of Parliament and are enforceable by law, there is no legal requirement to comply with the NZ Electrical Codes of Practice so long as the underlying regulations are not breached. However, it is common practice to comply with the requirements of the Codes of Practice, as this is seen as compliance with the relevant Electricity Regulations.

The following section will detail the regulations, standards and codes of practice that relate to the continuous power quality disturbance types.

3.5.1 Voltage Rules and Regulations.

- Rule 3.3.1 of the Common Quality Obligations within the Electricity Governance Rules requires the *system operator* to maintain 11kV lines within the limits of 10.75kV and 11.25kV. The system operator is defined as the service provider responsible for scheduling and dispatching electricity, in a manner that avoids fluctuations in frequency or disruption of supply. The New Zealand system operator is currently Transpower. So strictly speaking, the voltage deviation limits on 11kV lines of ± 250V only apply to Transpower, and not to asset owners (lines companies).
- A more relevant rule for an electricity distributor such as Vector can be found in Part 4 (Systems of Supply) of the NZ Electricity Regulations 1997. Regulation 53 states that:
  "The supply of electricity to electrical installations operating at other than the standard low voltage (230/400V) must be at a voltage agreed between the electricity retailer and the customer. Unless otherwise agreed between the electricity retailer and the customer, and except for momentary fluctuations, must be maintained within 5% of the agreed supply voltage" [45].
  In the case of 11,000 V, this gives a permissible range of 10.45 kV up to 11.55kV. While this rule only applies where customers are being supplied directly at 11 kV (which is only the case for large industrial consumers), it could be considered good practice to maintain voltages on the 11 kV network within these limits, even if not explicitly required to by law. Where customers are being supplied at standard low voltage (which applies to the vast majority of customers), the regulations only apply to the voltage limits at the point of supply and there are no specified tolerances for voltage levels on the 11 kV distribution network.

It must be noted that for the purposes of this study, the voltage deviation limit at the 11kV bus in zone substations has been set at of ±3% (10670V up to 11330V). This is still a wider tolerance than the ±250V that Transpower are expected to maintain, but is significantly tighter than the ± 5% tolerance specified in the Electricity Regulations. The assumption has been made that Vector should be able to achieve a voltage tolerance significantly better than ±5%, based on an assumed tap changer step of 1.5% (±3% allows for the voltage to be maintained within two tap changer steps). This has proved to be an accurate assumption. Only one site on the Vector network has voltage levels that occasionally deviate outside the 3% limit. Setting the threshold at 5% would result in this site being grouped with all of the other conforming sites. With the threshold set at 3%, this site can be identified as one displaying voltage deviations beyond those of the other sites. The 3% threshold can be considered to be a 'planning level' power quality objective internal to the Vector organisation. Planning levels are discussed in more detail in relation to the 61000 series standards.

3.5.2 Voltage fluctuation ('flicker') levels:

EGR 2.3.1.1 refers to the Australian Standard AS2279.4 1991 as being the relevant standard for levels of voltage fluctuation. It should be noted that in Australia, this standard has since been superseded by AS/NZS 61000.3.7. AS2279.4 is in fact a flicker emission standard rather than an environment standard. This aim of this standard is to provide guidelines on the connection and assessment of effects of fluctuating loads. The standard makes reference to the standard flicker curve which shows the level of flicker from a 60W incandescent lamp at which 50% of the population will be irritated. The degree of irritation depends on both the frequency of the fluctuations and the magnitude of the voltage variation.

The standard flicker curve can only be used where the voltage fluctuations are regular. Where this is not the case, it is necessary to assess the flicker level using a flickermeter. A flickermeter gives an output that is proportional to the standard flicker curve. A value of short-term flicker P_{st} =1 corresponds to the standard flicker curve for regular (periodic) fluctuations.

3.5.3 Voltage Unbalance Rule:

Rule 2.3.1.3 of the EGR requires the use of reasonable endeavours to maintain negative sequence voltage at less than 1% and to ensure that negative sequence voltage will be no more than 2% in any part of the grid.

3.5.4 Harmonics Rule:

EGR Section II 2.3 requires asset owners to 'maintain other standards'. Harmonic levels are referred to the New Zealand Electrical Code of Practice (NZECP 36, 1993). NZECP 36 specifies the following requirements:

- The phase to earth harmonic voltage at any point of common coupling (PCC) with a nominal voltage less than 66kV shall not exceed 4% for any odd numbered harmonic order, or 2% for any even numbered harmonic order.
- The total harmonic voltage distortion at any PCC with a nominal system voltage of less than 66kV shall not exceed 5%.

3.5.5 Transient overvoltages:

EGR Clause 3.3.2 of the Common Quality Obligations requires the system operator, generators, and ancillary service agents during a contingent event, to use reasonable endeavours to return the voltage to within the extreme limits, and within 5% of the pre-event voltage.

In addition to the above documents, New Zealand (in conjunction with Australia) is in the process of adopting the IEC 61000 series of EMC standards. These have been cloned as AS/NZS 61000 series standards. These standards can be accessed from the Standards New Zealand website (www.standards.co.nz). However, there is no reference to these standards in any of the regulations or rules that regulate the supply and use of electricity in New Zealand. The Energy Safety Service was contacted to clarify the status of the 61000 series standards in New Zealand. The following section summarises the comments made by a representative of the Energy Safety Service:

1. Performance requirements for aspects of power quality for transmission and distribution are specified in the Electricity Governance Rules and the NZ Electricity Regulations.
2. Compliance with the requirements of the 61000 series standards is considered to be evidence of compliance with the requirements of the NZ Electricity Regulations.

3. Asset owners (lines companies) should endeavour to satisfy the requirements of the 61000 series standards, as these standards are considered to be current 'best industry practice'.
4. The AS/NZS 61000 standards could be called upon in the event of a dispute between the lines company and customers (but only where compliance with the AS/NZS 61000 standards has been cited in the supply agreement with the customer).

Points 2 and 3 above are clearly incorrect. There are significant inconsistencies between the requirements of the 61000 series standards and the requirements of the NZ Electricity Regulations. For example, AS/NZS 610003.6 states a maximum voltage THD level of 8%, while the NZ Electricity Regulations (in referring to NZECP 36) require a maximum voltage THD level of 5%

The AS/NZS 61000 series standards are divided into seven main sections:
61000.1.XX: General – fundamental principles and definitions.
61000.2.XX: Define the electromagnetic environment and specify compatibility levels. By defining the maximum levels of disturbances that may exist on the supply network, these standards effectively define the required immunity levels for electrical equipment in that environment.
61000.3.XX: Specify maximum emission limits for customer connected loads within the electromagnetic environment. The standards cover emission limits for voltage variation, voltage fluctuation, and harmonic currents.
61000.4.XX: Testing and measurement techniques.
61000.5.XX: Installation and mitigation guidelines.
61000.6.XX: Generic standards – general procedures for testing equipment.
61000.9.XX: Miscellaneous.

Of the above standards, the 61000.1.XX through to 61000.4.XX standards have been adopted in New Zealand. Within this range, not all standards are relevant to this study of power quality levels on MV networks. Some apply only to low voltage networks, immunity to radiated fields, electrostatic discharge immunity, and other phenomena that are beyond the scope of this study.

The AS/NZS 61000 EMC standards that are relevant to this study of power quality phenomena in medium voltage networks are described in more detail below:

3.5.6 AS/NZS 61000.2.2: Environment – compatibility levels for low-frequency conducted disturbances and signalling in public low voltage power supply systems [47].

This standard is concerned with conducted disturbances in the frequency range from 0 Hz to 9 kHz (with an extension up to 148.5 kHz specifically for mains signalling systems). It gives compatibility levels for public low voltage a.c. distribution systems. While this study focuses on disturbance levels on the medium voltage (MV) network, there is no corresponding environment standard specifically for MV networks (although disturbance levels for MV are specified in the Electricity Governance Rules and the NZ Electricity Regulations). Additionally, other standards in the AS/NZS 61000 series specify environmental compatibility levels for MV networks.

The compatibility levels specified in the standard are for 'normal circumstances'. There is an acknowledgement that there are times when the compatibility levels will be exceeded due to extraordinary circumstances. The environment compatibility level of a disturbance type is the level that can be expected not to be exceeded 95% of the time, and it is the level of disturbance against which equipment operating in the environment must have immunity.

The compatibility levels specified by 61000.2.2 are:

- The value of rapid voltage changes (step changes) is limited to 3% of nominal voltage.
- Voltage excursions outside of the normal operational tolerances (±6% at LV in New Zealand) are possible for a few tens of seconds following exceptional load changes.
- Voltage fluctuation (flicker) levels are:

  Short term flicker P_{st} =1

  Long term flicker P_{lt} = 0.8

- Harmonics: The standard differentiates between the effects of long-term harmonic levels (10 minutes or more) and short-term levels (3 seconds or less). The compatibility level for long-term THD is 8%, short-term THD 11%. The standard also gives compatibility levels for individual harmonic orders up to the 50^{th} harmonic. Guidelines on interharmonic levels and the resulting flicker effects are given.
- Voltage unbalance: the compatibility level is a negative sequence component of 2% of the positive sequence component (with an allowance that in the case of large single-phase loads, voltage unbalance may reach 3%).
- Transient over-voltages: no compatibility levels given.
- Frequency variations: compatibility level of ± 1 Hz. Frequency variations are beyond the control of the electricity distributor, and are therefore beyond the scope of this study.

The corresponding maximum disturbance levels (compatibility levels) for MV networks as specified in the NZ Electricity Governance Rules and the Electricity Regulations are:

- Voltage tolerance with respect to nominal value: ±5%
- Voltage fluctuations: Refer to AS2279.4; $P_{st} < 1$
- Voltage unbalance: 1%
- Harmonics: Maximum THD = 5%
- Transient over-voltages: no limits given

3.5.7 AS/NZS 61000.3.6: Limits – Assessment of emission limits for distorting loads in MV and HV power systems [48].

This standard outlines the requirements for connecting large distorting loads (producing harmonics and interharmonics) to MV and HV public power systems, with the aim of ensuring adequate power quality levels for all connected consumers. While the primary focus of the standard is in assessing the effects of harmonic emissions from large loads, it also includes compatibility levels and planning levels of harmonic distortion that the utility can use as reference values for the MV/HV network. The compatibility levels are given in Table 3-1:

Table 3-1: Compatibility levels for harmonic voltages (in percent of the nominal voltage) in LV and MV power systems.

Odd harmonics (non-triplen)		Odd harmonics (triplen)		Even harmonics	
Order	Harmonic voltage %	Order	Harmonic voltage	Order	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%					

For the Vector study, the most relevant level is the 8% level for THD. The PQ monitors that are installed in the MV substations on the Vector network are configured to record THD levels rather than individual harmonic levels. It should also be noted that the compatibility level of 8% is significantly more tolerant than the maximum of 5% THD as specified in the New Zealand Electricity Regulations.

AS/NZS 61000.3.6 also gives utility planning levels for harmonic voltages. The planning levels can be considered to be internal quality objectives for the utility. The planning levels are indicative only, allowing for variation in network structure and circumstances. The recommended planning levels for MV are given in Table 3-2.

Table 3-2: Indicative values of planning levels for harmonic voltages (in percent of the nominal voltage) in MV power systems.

Odd harmonics (non-triplen)		Odd harmonics (triplen)		Even harmonics	
Order	Harmonic voltage %	Order	Harmonic voltage %	Order	Harmonic voltage %
5	5	3	4	2	1.5
7	4	9	1.2	4	1
11	3	15	0.3	6	0.5
13	2.5	21	0.2	8	0.4
17	1.6	>21	0.2	10	0.4
19	1.2			12	0.2
23	1.2			>12	0.2
25	1.2				
>25	0.2+0.5(25/h)				
Note: Total harmonic distortion (THD) 6.5%					

Given that the New Zealand Electricity Regulations (in referring to Electrical Code of Practice 36) require a maximum THD level of 5% at the point of common coupling in systems where the nominal voltage is less than 66kV, it would seem that both the compatibility levels and the planning levels require some adjustment for the New Zealand situation. Alternatively, the maximum THD level specified in ECP 36 should be amended to be compatible with the levels given in AS/NZS 61000.3.6.

The remainder of AS/NZS 61000.3.6 outlines procedures for using the planning levels to evaluate the connection requirements for individual customers having distorting loads. This is outside the scope of this study.

3.5.8 AS/NZS 61000.3.7: Limits – Assessment of emission limits for fluctuating loads in MV and HV power systems [49].

This standard outlines principles that are intended to be used as the basis for determining the requirements for connecting large fluctuating loads (producing voltage fluctuations) to public power systems. As with the harmonics standard described earlier, the focus of this voltage fluctuation standard is to assist utilities in assessing the likely impact on system voltage levels due to the connection of large fluctuating loads, and to assist in determining the requirements to mitigate these effects. The standard includes compatibility levels and planning levels for voltage fluctuation on MV networks. The compatibility levels given in this MV standard are the same as those in the low voltage EMC environment standard AS/NZS 61000.2.2. While this study has not included voltage fluctuation levels in the analysis of power quality, this could be included in any future surveys on the network.

The compatibility levels for voltage fluctuation in MV (and LV) networks are:

$$P_{st} = 1$$

$$P_{lt} = 0.8$$

AS/NZS 61000.3.7 also gives indicative planning levels for voltage fluctuation in MV networks. The planning levels are lower than the compatibility levels, and can be considered to be internal power quality objectives for the network operator. The given planning levels are:

$$P_{st} = 0.9$$

$$P_{lt} = 0.7$$

3.6 Instrumentation standards

The 61000 series standards include a number of standards covering measurement techniques and instrumentation requirements. Two standards are relevant to this study:

- AS/NZS 61000.4.7 [25]: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.
- This standard is described in detail in the chapter on instrumentation.

- IEC 61000.4.30 [23]: Testing and measurement techniques – power quality measurement methods.
- This standard has not been adopted as a New Zealand standard. It is described in more detail in the chapter on instrumentation.

3.7 Standards and power quality on the Vector network

From the perspective of the network operator, there are several motivations for monitoring power quality. It allows the tracking of long-term trends in power quality performance. Data from power quality monitoring instruments can be useful in fault diagnosis, and for prioritising maintenance on the network. With reference to regulations and standards, power quality monitoring can be used to establish compliance with recognised power quality standards, and compliance with internal power quality objectives (planning levels).

This section will compare measured values of power quality phenomena on the Vector network with the requirements of the New Zealand standards and regulations. As this study has analysed levels of voltage variation, voltage unbalance, and total harmonic distortion, only the standards relating to these quantities will be looked at.

3.7.1 Voltage variation

The New Zealand Electricity Regulations state the following requirement for voltage at MV levels:

- The supply of electricity to electrical installations operating at other than the standard low voltage (230/400V) must be at a voltage agreed between the electricity retailer and the customer. Unless otherwise agreed between the electricity retailer and the customer, and except for momentary fluctuations, must be maintained within 5% of the agreed supply voltage [45]. This gives a permissible range of 10.45kV up to 11.55kV for a nominal 11kV supply. It should be noted that these limits only apply if the customer's point of common coupling (PCC) is at 11 kV. There are no tolerance limits for MV voltages present in the distribution network.
- At low voltage (230/400V in New Zealand), the voltage must be kept within 6% of the nominal voltage, except for momentary fluctuations.

The requirement of AS/NZS 61000.2.2 is that the supply voltage (at low voltage) should stay within ± 6% of the nominal value for 95% of the time.

Maximum values and 95% values of voltage deviation for each of the monitored sites on the Vector network are given in Table 3-3. 95% values have been given to align with the requirement of AS/NZS 61000.2.2. Maximum values of voltage deviation are also shown.

Table 3-3: Maximum and 95% values of voltage deviations for each of the monitored sites on the Vector network.

Site	Maximum value of voltage deviation (% of nominal)	95% value of voltage deviation (% of nominal)
Bairds	4.5	2.4
Carbine	4.23	3.13
Greenmount	2.73	1.23
Howick	4.93	2.89
Manurewa	3.92	2.52
McNab	2.61	1.57
Otara	6.41	1.74
Quay	2.01	1.16
Rockfield	4.45	2.70
Rosebank	4.14	1.56
Takanini	6.18	2.75
Victoria	4.63	1.31
Wiri	8.89	2.77

From Table 3-3, Otara and Takanini are the only sites that have a maximum voltage deviation outside the ± 6% range. For all sites, the 95% values of voltage variation are well within the ± 6% requirement of AS/NZS 61000.2.2.

3.7.2 Voltage Unbalance

The Electricity Governance Rules require that the negative sequence voltage should be less than 1%, and must not be more than 2%.

AS/NZS 61000.2.2 requires that voltage unbalance must not exceed 2% for 95% of the time.

Maximum and 95% values of voltage unbalance from the Vector network are given in Table 3-4:

Table 3-4: Maximum and 95% values of voltage unbalance for each of the monitored sites on the Vector network.

Site	Maximum value of voltage unbalance (%)	95% value of voltage unbalance (%)
Bairds	0.68	0.49
Carbine	0.49	0.37
Greenmount	0.94	0.64
Howick	1.4	0.95
Manurewa	1.16	0.70
McNab	0.49	0.34
Otara	0.67	0.44
Quay	0.75	0.57
Rockfield	0.72	0.44
Rosebank	0.88	0.59
Takanini	1.01	0.56
Victoria	0.67	0.52
Wiri	1.54	0.51

A number of sites have maximum values of voltage unbalance in excess of 1%, and one site (Howick) has a 95% value that is close to 1%. Given that the voltage unbalance limit (according to both the Electricity Regulations and the AS/NZS standard) is 2%, all sites conform to the requirement.

3.7.3 Harmonics (Total Harmonic Distortion THD)

The Electricity Regulations refer to the Electrical Codes of Practice which specify a maximum level of 5% THD for the point of common coupling at supply voltages less than 66kV.

AS/NZS 61000.3.6 specifies a THD compatibility level of 8%, and a recommended planning level of 6.5%.

THD levels from the Vector network are given in Table 3-5 below.

Table 3-5: Maximum and 95% values of THD for each of the monitored sites on the Vector network.

Site	Maximum value of THD	95% value of THD
Bairds	2.44	1.52
Carbine	5.23	1.77
Greenmount	4.41	3.49
Howick	3.88	2.70
Manurewa	4.24	3.36
McNab	2.30	1.59
Otara	2.74	1.70
Quay	1.96	1.04
Rockfield	3.35	2.75
Rosebank	5.18	2.91
Takanini	3.97	2.97
Victoria	8.29	2.21
Wiri	2.57	1.70

Three sites (Carbine, Rosebank and Victoria) have maximum values of THD that exceed the 5% limit given the Electrical Codes of Practice. Greenmount and Manurewa are also approaching this limit value. For all sites, the 95% values of THD are well within the 8% compatibility level and the 6.5% planning level given in AS/NZS 61000.3.6.

3.7.4 Vector Power Quality Objectives and Planning Levels

The Vector Distribution Code [50] is a document that specifies the technical, operational and planning requirements of the network. It is also a statement to the users of the network in relation to how they can expect the network to be operated and managed.

The internal power quality objectives and planning levels specified in the Vector Distribution Code relevant to power quality are described below.

2.2.1.2 Frequency and Voltage

The distribution network shall be designed to enable the normal operating frequency (50 Hz) and voltages to be supplied to users, and to comply with statutes, Regulations and the applicable Electrical Codes of Practice.

2.2.1.3 Network Disturbances and Waveform Distortion

a) Voltage fluctuations shall comply with the limits set out in relevant Regulations and Electrical Codes of Practice.

b) The harmonic content of any load or customer installation shall comply with the limits of the New Zealand Electrical Codes of Practice for Harmonic Levels (ECP 36:1993) and any subsequent amendments.

d) Voltage flicker shall comply with Australian Standards on disturbances in mains supply networks (AS 2279). In particular, users electric devices shall not cause voltage fluctuations at the point of common coupling in excess of the threshold of irritability as defined in AS 2279.3 and AS 2279.4.

Under fault and circuit switching conditions the rated frequency or voltage may fall or rise transiently… and this variation in voltage shall be taken into account in selecting equipment for installation on or connected to the user network.

3.3.2.1 Quality of Supply

Vector will from time to time determine the need to test and/or monitor the quality of supply at various points on the distribution network. The requirement for specific testing and/or monitoring may be initiated by the receipt of complaints.

Where the results of such tests show that the user is operating outside the technical parameters specified in any part of the Distribution Code, or any other statutory regulations or Electrical Code of Practice, the user will be informed accordingly. A user found to be operating outside the limits specified above will remedy the situation or disconnect from its network the apparatus causing the problem.

It has been shown that there are some instances where disturbance levels on the network exceed those specified in the New Zealand Electricity Regulations. Three sites exceeded the 5% limit on THD levels. Two sites recorded voltage deviations in excess of 6%. However the 6% voltage tolerance specified in the regulations refers to the nominal low voltage levels of 230/400V at the customer's PCC, not MV distribution voltages. All sites easily meet the requirements of the AS/NZS 61000 series standards, as these standards specify that the compatibility levels may be exceeded for 5% of the time.

Conformance with the New Zealand Electricity Regulations and the AS/NZS standards are a requirement of the Vector Distribution Code. It might appear that the limits specified in the regulations are being exceeded at several sites. However, it should be noted that the measured disturbance values are recorded on the MV network, and do not necessarily indicate that voltage variation or THD levels are being exceeded at the customer point of supply.

3.8 Conclusions

1. A number of organisations are involved in developing and authorising power quality standards. Several of these have been developed as international standards and have been adopted by a number of countries. The most relevant standards to the New Zealand power quality environment are the IEC 61000 standards, as they have been cloned as the AS/NZS 61000 series standards. EN50160 is also relevant as it is often quoted for its methodology and instrument requirements for power quality surveys.
2. EN50160 is often quoted as a standard to be conformed to. Rather than specifying limits, EN50160 describes a worst-case electromagnetic environment, rather than specifying limits that network operators should aspire to conform to.

3. In New Zealand, power quality rules, regulations and standards are contained in the Electricity Governance Rules, the Electricity Regulations, the Electrical Codes of Practice and the AS/NZS 61000 series standards. There are some inconsistencies in the requirements of these various documents, particularly between the Regulations and the AS/NZS standards. The most significant difference between the requirements of the Regulations and the AS/NZS standards is that the standards only require conformity for 95% of the time, making an allowance for the fact that there are circumstances and conditions beyond the control of the network operator. The Regulations only allow for 'momentary fluctuations' outside the specified limits.
4. The AS 2279.4 flicker standard that is quoted in the Electricity Governance Rules (May 2005) has now been superseded in Australia. This same standard is also quoted in the Vector Distribution Code. The Electricity Governance Rules and the Vector Distribution Code should be updated to refer to a current standard.
5. All monitored sites on the Vector network considered in this study meet the AS/NZS 61000 series standards for voltage variation, voltage unbalance, and THD. Two sites experienced maximum levels of voltage variation in excess of ±6% of the target voltage. However this is does not constitute non-conformance with the NZ Regulations. The NZ Regulations apply to variations in voltage measured at the customer's point of common coupling (PCC), and are referred to the nominal low voltage supply levels of 230/400V. The regulations do not apply to variations in voltage levels in the MV distribution system. A similar situation exists regarding THD levels. Three of the monitored MV sites have maximum THD levels that exceed 5% (the NZ regulations limit value for the customer PCC) but the same sites easily conform to the 8% compatibility level and 6.5% planning level given in the AS/NZS standard. All sites meet the requirements for voltage unbalance.
6. The Vector Distribution Code refers to the requirements of the Electricity Regulations, the Electrical Codes of Practice, and other statutes as its requirements for power quality. The results of the power quality survey on

the Vector network show that all sites conform to the requirements of the AS/NZS 61000 standards.

7. There is inconsistency between the AS/NZS standards and the Electricity Regulations due to the fact that the Regulations do not make provision for 95% conformity. In reality, there will always be times when the specified limits are exceeded due to circumstances beyond the control of the network operator. When 95% values of disturbances are assessed against the standards (rather than maximum disturbance values), the Vector network sites conform to the limits specified in the Electricity Regulations.
8. Measurements taken in this survey were recorded at the MV (11kV) level on the network. While voltage variation and disturbance levels exceed specified limits at some MV sites, this does not necessarily imply that disturbance limits are being exceeded for low voltage customers.

Chapter 4: Power Quality Monitoring Instrumentation and Data Acquisition

4.1 Introduction

It is only in recent years that the practice of power quality monitoring by utilities has become relatively common. This increase in monitoring activity can be attributed to three main factors:

1. The availability of affordable monitoring instruments with high levels of data processing and storage capacity.
2. The proliferation of distorting loads that are now connected to networks.
3. The demand by customers (with loads that are sensitive to power quality disturbances) for acceptable levels of power quality.

There are a number of possible reasons why a utility may need to monitor power quality disturbance levels:

1. To track the long-term power quality and reliability performance of the network over time.
2. In response to customer complaints regarding power quality disturbances.
3. To establish conformance with regulations or standards.
4. To assist in asset management and priortising of maintenance work.
5. To assess existing disturbance levels before the connection of high emission or sensitive equipment.
6. To assist in fault diagnosis.
7. To enable the utility to develop an understanding of what disturbances are present on the network, the typical magnitude of these disturbances, and what disturbance controls are achievable.

Power quality phenomena encompass a wide range of disturbance types and conditions on the system. They include everything from very fast transient overvoltages in the microsecond range, to long duration outages that may last for hours or days. Power quality also includes steady-state phenomena such as voltage variations and harmonic distortion, and intermittent conditions such as voltage fluctuations (flicker). The wide variety of conditions to be monitored make the development of standard measurement procedures and the design of suitable monitoring equipment very difficult. While some monitoring and analysis of power quality can be carried out using generic measuring instruments such as multimeters, oscilloscopes, spectrum analysers and energy meters, the use of specialised power quality monitoring instruments is rapidly becoming the norm. In future, the increased use of ‘smart’ tariff meters (revenue meters that include limited capability to monitor power quality phenomena) will enable utilities to carry out widespread and continuous monitoring of power quality.

This chapter will look at issues involved in planning a utility power quality survey. It will then detail the instrumentation requirements for such a survey with reference to the relevant international standards. Details are provided of the instruments used on the Vector network. Issues affecting the validity of the data such as missing or abnormal data, and possible instrument errors will be described and their impact on the survey assessed.

4.2 Planning a utility power quality survey.

In developing a plan for routine utility power quality monitoring, the following basic questions need to be considered:

1. What should be measured?
2. Where should the monitoring take place?
3. How long should the monitoring take place?

4.2.1 What should be measured?

Since the primary objective of power quality monitoring is to ensure that the quality of the supply is suitable for the customer, the phenomena to be measured will be determined firstly on the disturbance types that are most likely to cause problems for customers. Clearly, supply outages have the most impact on customers, but these do not require any sophisticated instruments for detection (and are more correctly categorised as a power reliability event rather than a power quality event). Other disturbances that can cause major disturbances to customers are momentary interruptions, voltage sags and swells, and transient overvoltages. Harmonic distortion can cause a variety of problems for customers, but this is much less common than problems associated with variation in voltage levels (although it could be argued that this is only because of a lack of customer awareness of harmonic-related problems, and the fact that the problems tend not to be so immediately obvious as voltage-related problems). Voltage fluctuations can cause annoying changes in the output of electric lights, but again this is not normally a common problem for customers.

4.2.2 Where to measure?

There are two main criteria in deciding where PQ monitoring should take place. Instruments should be located so as to:

1. provide data that is as close as possible to what is being experienced by customers.
2. to maximize coverage of the survey, so that as much of the network as possible is monitored.

These two objectives are in conflict. It is not possible to achieve 100% coverage and monitor every site on the network due to the cost of monitoring instruments and limitations on data transmission, storage and analysis capabilities. The best that can be achieved is to select a number of monitoring sites that are representative of the range of power quality environments that exist on the network. If portable instruments are being used, coverage can be extended by moving the meters at regular intervals.

An alternative approach is to move the monitoring site further upstream from the customer, so that the monitor covers a larger portion of the network. The disadvantage of this is that as the point of monitoring moves further from the customer, the measurements will differ more and more from what the customer sees. Where monitoring occurs only at the MV level on a network, recorded disturbance levels will be significantly different to (and always lower than) those experienced by customers on the LV network.

The approach that has been taken by Vector is to install monitors at a number of 11 kV zone substations. The monitors are connected to the 11 kV busbar via voltage and current transducers. Vector also have monitors connected at the Transpower grid exit points to monitor disturbance levels that are present at the point of supply for the network. There is also a single monitor connected at a low voltage point which is supplied from the most remote of Vector's 11 kV feeders, the objective being to monitor the worst-case conditions on the network. Only the zone substation MV monitors have been included in this study.

4.2.3 How long should the monitoring take place?

There are differing opinions as to the minimum duration of a power quality survey. Ideally, the duration should be between one and two years, but one study has established that a survey period as short as one week will give useful preliminary results for harmonics, and it is likely that this will apply to the other continuous disturbances [51]. A survey period of one month is suggested as a suitable minimum period for monitoring continuous disturbances, but a longer survey period is more likely to include a range of conditions that may affect disturbance levels e.g. public holidays, industrial strikes, changing weather conditions.

The question of survey duration is not a major issue for the Vector survey. Vector is involved in continuous PQ monitoring, using instruments that are permanently connected in zone substations. Vector commenced a programme of routine power quality monitoring in 1999 and have been expanding the monitoring system since then. The data used in this study covers a 12 month period, and it is expected that monitoring will continue on an on-going basis.

4.3 PQ Instrument Requirements

A wide range of instruments is available for monitoring power quality. These range from relatively inexpensive hand-held instruments up to expensive high-accuracy instruments intended for permanent connection and installation. The type of monitoring to be carried out will to a large extent determine the requirements of the instrument to be used. For example, a permanently connected instrument is more suitable for an on-going routine survey, while a portable instrument is more suitable for monitoring at a particular site in response to a customer complaint. Regardless of the application, there are some common considerations when selecting a power quality monitor:

- Cost: prices are in the range of $5000 for a basic instrument up to around $50,000 for a high-level instrument. If the measurements will be used to establish conformance with regulatory or contractual requirements, a high-level instrument will be required.
- Number of measurement channels, sampling rate and accuracy: seven channels are required to measure three phase voltage, current, and neutral current.
- The range of disturbance types recorded: Instruments with the capability to accurately measure voltage fluctuation and impulsive transients are more expensive due to the analogue-to-digital conversion, high sampling rate and peak value capture capabilities required.
- Type and amount of data stored: the instrument should have sufficient memory capacity to store all required data for the survey period, or be able to be interrogated and transfer data before the memory fills up. In the case of permanently connected instruments, the device will include a modem to allow data transfer to a central database. Typical on-board memory capacity is in the range of 4MB up to 512 MB.
- Ability to ride through disturbances: the instrument will require battery back-up to enable it to ride through supply interruptions. Adequate filtering and surge protection on the instrument supply lead is also required.
- Reporting capability: the instrument should be able to show trends for voltage and harmonics, and also voltage unbalance and flicker on the higher-end instruments. Because many power quality standards are based on 95% values, the reporting software should calculate these. Alternatively, it must be possible to export the data into a software application such as Microsoft Excel, Microsoft Access or Matlab so that summary statistics can be calculated and trend graphs and cumulative frequency histograms plotted.
- If the instrument includes transient capture, there will be provision for setting of threshold levels. Transients should be logged and time-stamped. Waveform capture is useful for fault diagnosis.
- Rugged construction: this is required if the instrument is to be installed in uncontrolled environments (such as a customer's premises). Weatherproofing is required if the instrument is to be connected outdoors.

- The development of smart tariff meters that incorporate limited power quality analysis capability presents the possibility of being able to acquire ‘low quality’ data from many parts of the network, while continuing to monitor with high quality instruments at important strategic locations.

For the purposes of an on-going utility power quality survey such as that being carried out by Vector, a high-level instrument is required. In addition to monitoring three phase voltage and current, there is a requirement to measure voltage unbalance and voltage fluctuation. Voltage transients are also being recorded.

4.4 Transducers

Where monitoring is taking place at low voltage, it is possible to connect the instrument voltage probes directly. If current is being measured, a current transformer (CT) is commonly used. Normal CTs are considered adequate for most applications, having a frequency response that is acceptable for harmonic measurements up to 2 kHz (40^{th} harmonic for 50 Hz). Other current transducer types are Hall Effect (as used in clip-on type probes), Rogowski coil (preferred if it is necessary to measure high frequencies) and resistive shunts (these must have negligible inductance to avoid attenuation of high frequencies).

If monitoring is taking place at voltages above low voltage (such as the Vector 11 kV monitoring), it is necessary to use instrument voltage transformers. Magnetic voltage transformers are considered appropriate up to frequencies of 5 kHz. For higher frequencies, resistor or capacitor voltage dividers can be used.

The accuracy requirements of transducers are discussed later in this chapter (refer to the section on power quality measurement and instrumentation standards).

4.5 Power Quality Instrument Standards

A number of international standards relate to power quality measurement and instrument standards:

- IEEE 1159-1995 “ IEEE Recommended Practice for Monitoring Electric Power Quality”.

- Standard IEC 61000-4-30 (note that this has not been adopted as a New Zealand standard): “Testing and measurement techniques – power quality measurement methods”.
- AS/NZS 61000-4-7:1999 “Testing and measurement techniques – General guide on harmonics and interharmonics measurement and instrumentation, for power supply systems and equipment connected thereto”
- AS/NZS 4376: 1996 “Flickermeter – Functional and Design Specification”
- AS/NZS 4377: 1996 “Flickermeter – Evaluation of Flicker Severity”. Note that instrument standards for flicker will not be discussed here as the instruments that are installed in all but one of the Vector zone substations do not have the capability to measure flicker.

4.5.1 **IEC 61000-4-30** [23]

IEC 61000-4-30 recognises two classes of PQ monitoring instrument:
Class A performance – very high accuracy instrument. This type of instrument is used where precise measurements are required. Examples are verifying compliance with standards, verification of fulfillment of contractual obligations, and where measurements could be used for resolving disputes between the electricity supplier and the customer.

Class B performance – suitable for applications where low uncertainty of measurements is not required. Class B instruments are considered suitable for statistical surveys and troubleshooting applications. For the purposes of the Vector power quality monitoring programme, Class B performance is adequate as this is primarily a statistical survey with possible application for faultfinding. The measurements are not being used (at this stage) to verify compliance with standards or contractual requirements.

Class A operation

Measurement and aggregation intervals

For Class A operation, IEC 61000-4-30 specifies methods for aggregating measurements over specified time periods (for Class B operation, these can be defined by the manufacturer). For a supply frequency of 50 Hz, measurements are to be made every 150 cycles (3 seconds). These 3 second values can then be aggregated and recorded as a 10 minute (short term) or 2 hour (long term) value. The 10 minute or 2 hour aggregate values are the r.m.s values of the 3 second measurements over that period.

Accuracy (measurement uncertainty)

Voltage: measurement uncertainty shall not exceed ±0.1%.

Voltage unbalance: evaluated using the method of symmetrical components. Under unbalance conditions, in addition to the positive sequence component, there is also at least one of the following components: negative sequence component u_2 and/or zero sequence component u_0. The algorithm given below for calculating unbalance is taken from the IEC 61000-4-30 standard [23]:

The negative sequence component u_2 is expressed as

$$u_2 = \frac{negative\ sequence}{positive\ sequence} \times 100\% \qquad (4-1)$$

For 3 phase systems, this can be written as (with $U_{ij\ fund}$ = phase i to j fundamental voltage):

$$u_2 = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \times 100\% \quad with\ \beta = \frac{U_{12\,fund}^4 + U_{23\,fund}^4 + U_{31\,fund}^4}{(U_{12\,fund}^2 + U_{23\,fund}^2 + U_{31\,fund}^2)^2} \qquad (4-2)$$

The zero sequence u_0 component is evaluated by the magnitude of the following:

$$u_0 = \frac{zero\ sequence}{positive\ sequence} \times 100\% \qquad (4-3)$$

Voltage Harmonics: The basic measurement of voltage harmonics is defined in AS/NZS 61000-4-7: class 1 (see the section on this standard below).

Class B operation

Measurement and aggregation intervals

The manufacturer shall indicate the method, number and duration of aggregation time intervals.

Accuracy (measurement uncertainty)

Voltage: the manufacturer shall specify the uncertainty. In all cases, the measurement uncertainty shall not exceed ±0.5%.

Voltage unbalance

The manufacturer shall specify the algorithms and methods used to calculate unbalance.

Harmonics

The manufacturer shall specify measurement uncertainty and aggregation methods.

IEC 61000-4-30 goes on to give some useful information regarding selection of appropriate voltage and current transducers, techniques for the detection and classification of sags/swells and transients, and guidelines for contractual applications of power quality measurement. Also included are minimum assessment periods for measurement of the various power quality parameters. For the parameters relevant to this study (voltage, voltage unbalance, harmonics), the standard recommends a minimum survey period of one week.

4.5.2 AS/NZS 61000-4-7 [25]

Much of the content of this standard is beyond the scope of this study (for example: special requirements for time-domain and frequency-domain instrumentation). The relevant sections of AS/NZS 61000-4-7 are described below:

Classification of instruments – accuracy classes (A and B) and types of measurement. The accuracy requirements for Class A and Class B instruments are given in Table 4-1:

Table 4-1: Maximum harmonics measurement errors.

Class	Measurement	Conditions	Maximum allowable error
A	Voltage	$U_m \geq 1\% \ U_N$ $U_m < 1\% \ U_N$	$5\% \ U_m$ $0.05\% \ U_N$
	Current	$I_m \geq 3\% \ I_N$ $I_m < 3\% \ I_N$	$5\% \ I_m$ $0.15\% \ I_N$
B	Voltage	$U_m \geq 3\% \ U_N$ $U_m < 3\% \ U_N$	$5\% \ U_m$ $0.15\% \ U_N$
	Current	$I_m \geq 10\% \ I_N$ $I_m < 10\% \ I_N$	$5\% \ I_m$ $0.5\% \ I_N$

U_m, I_m are the measured values, U_N, I_N are the nominal input ranges

Accuracy of transducers: the standard also gives the accuracy requirements for external voltage and current transducers: the accuracy shall match the requirements of the measuring instrument (i.e. error relative to the measured value ≤ 5%). This section of the standard states that considering the required amplitude accuracy requirement of 5%, VTs for MV seem to be appropriate up to 1 kHz (20th harmonic at 50 Hz fundamental), and about 60% of all VTs cover the full harmonic range. With the additional requirement of 5° accuracy, VTs for MV seem to be appropriate up to 700 Hz (14th harmonic); about 50% of all VTs cover the full harmonic range. If very precise measurements are required, the use of ohmic dividers or capacitive dividers is recommended.

Time ranges for statistical handling of measured values: for the purpose of voltage harmonic surveys in supply systems, the standard defines the following time intervals for data aggregation:

Very short interval – 3 s (recommended as effective measurement time)
Short interval – 10 min
Long interval – 1 hour
One day interval – 24 hours
One week interval – 7 days

For surveys of duration longer than one week, no specific recommendations are given, but the point is made that there may be large differences in harmonic levels between normal working days and weekend days.

Effect of environment – Immunity tests: this section of the standard deals with the rated operating conditions and the magnitude of possible errors introduced by changes in:

- temperature
- humidity
- instrument supply voltage
- common mode interference voltage
- static electricity discharges
- radiated electromagnetic fields

4.6 Power quality monitoring on a utility network

A typical utility network PQ monitoring system consists of the following main components:

1. PQ monitors installed in the network.
2. A communications network.
3. Central database.
4. Data analysis and data viewing facilities.

A typical configuration is shown in Fig.4-1.

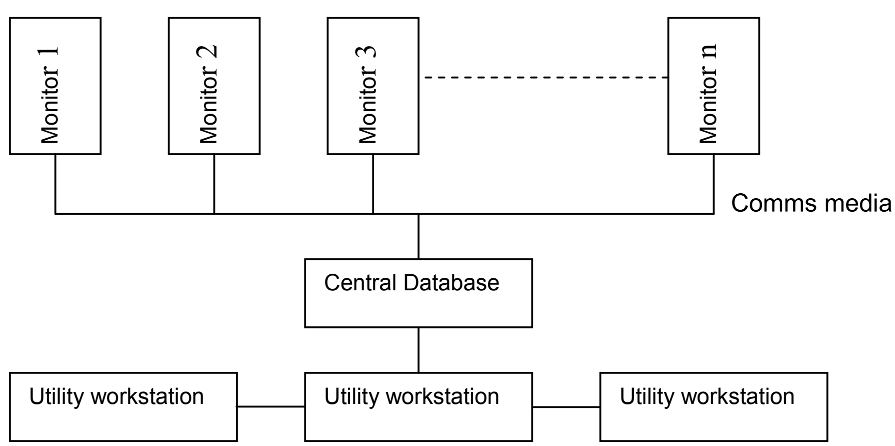


Fig.4-1: Utility PQ network monitoring configuration.

4.6.1 Power quality monitoring at Vector

Vector have been actively involved in monitoring power quality since 1999. The total monitoring system now consists of more than 30 permanently-connected instruments installed at strategic locations across the network. Monitors are connected at national grid exit points (monitoring the incoming supply for the Vector network), at distributed generating plant, and in some 11 kV zone substations. There is also a single instrument connected to the extreme end of the low voltage network to monitor worst-case conditions on the network.

The instruments used are all ION brand power quality monitors manufactured by Power Measurement Ltd. Several different models of ION meter have been used depending on the purpose of the monitoring and what is being measured. The Vector power quality monitoring system has been installed and configured by Quasar Electronics Ltd. Table 4-2 gives the locations and instrument types used on the network.

Table 4-2: Installed PQ meters on the Vector network.

Power Quality Monitors in Vector network				
	Site	Connection Voltage (kV)	Type of Ion Monitor	Purpose of installation.
1	ZS Rosebank	11	7600	PQ
2	TP Hepburn	33	7500	PQ and Check GXP tariff metering
3	Lichfield	11	7600	PQ
4	TP Mangere T1T2	33	7500	PQ and Check GXP tariff metering
5	TP Pac Steel 1	110	7600	PQ and Check GXP tariff metering
6	TP Pac Steel 2 (Arc Furnace)	110	7500	PQ and Check GXP tariff metering
7	ZS Bairds	11	7700	PQ
8	ZS Otara	11	7700	PQ
9	TP Otahuhu	22	7500	PQ and Check GXP tariff metering
10	ZS Greenmount	11	7700	PQ
11	ZS Howick	11	7700	PQ
12	TP Pakuranga	33	7600	PQ and Check GXP tariff metering
13	DG Greenmount	11	7330	Very basic PQ and Check tariff metering
14	ZS Carbine	11	7700	PQ
15	ZS McNAB	11	7700	PQ
16	ZS Rockfield	11	7700	PQ
17	TP Penrose - LIVERPOOL	110	7500	PQ and Check GXP tariff metering
18	TP Penrose - Quay St	110	7600	PQ and Check GXP tariff metering
19	TP Penrose - T11	33	7500	PQ and Check GXP tariff metering
20	TP Penrose - T8T9	33	7600	PQ and Check GXP tariff metering
21	ZS Quay	11	7700	PQ and Check GXP tariff metering
22	TP Roskill - Kingsland	110	7600	PQ and Check GXP tariff metering
23	TP Roskill - Liverpool	110	7500	PQ and Check GXP tariff metering
24	TP Roskill - T2T4	22	7500	PQ and Check GXP tariff metering
25	TP Roskill - T3	22	7500	PQ and Check GXP tariff metering
26	ZS Victoria	11	7700	PQ
27	TP Silverdale CB2732	33	8500	PQ and Check GXP tariff metering
28	TP Silverdale CB2892	33	8500	PQ and Check GXP tariff metering
29	LV Orere Point	11	7700	PQ
30	ZS Manurewa	11	7700	PQ
31	ZS Takanini	11	7700	PQ
32	ZS Wiri	11	7700	PQ
33	TP Wiri T1T2	33	7600	PQ and Check GXP tariff metering
	Spare Meter		7600	
	DG Southdown			

Data from the instruments can be viewed in real-time via a web browser using the ION proprietary Pegasus software. Additionally, the ION software produces monthly summary reports for each instrument which include trend graphs of the measured parameters, tables of significant discrete events (outages, interruptions, sags/swells, transients), and plots of discrete events overlaid against the ITIC electrical equipment immunity reference curve. At present, the monthly site summary report does not include any 95% statistics that can be referenced to international standards.

In 2004 Power Measurement Ltd released its EEM Enterprise Energy Management software. According to the information available at the Power Measurement website, EEM software can "conduct complex power quality analyses, including steady-state, waveform and variation analyses. Utilise data reduction capabilities to classify PQ events, in order to group and/or link many scattered events to a single root cause. Identify the system impact of key power quality variables such as substation location, voltage level, geography, load, and many more. Benchmark power quality to industry standards, such as ITI (CBEMA) and SEMI F47, and improve productivity with electrical system analysis that enables you to diagnose and repair power system faults." From this description, it would seem that this analysis software has the capability to do much of the analysis that is the subject of this research project. As this software is not being used by Vector, it has not been possible to assess the actual performance of the product. [52]

Table 4-3 shows the meters that are relevant to this power quality study. These are monitors that are installed in the 11 kV zone substations. There are 13 monitors installed in zone substations, and all instruments are of the ION 7700 or 7600 type.

Table 4-3: PQ meters installed in zone substations on the Vector network.

Power Quality Monitors in Vector network				
	Site	Connection Voltage (kV)	Type of Ion Monitor	Purpose of installation.
1	ZS Rosebank	11	7600	PQ
2	ZS Bairds	11	7700	PQ
3	ZS Otara	11	7700	PQ
4	ZS Greenmount	11	7700	PQ
5	ZS Howick	11	7700	PQ
6	ZS Carbine	11	7700	PQ
7	ZS McNab	11	7700	PQ
8	ZS Rockfield	11	7700	PQ
9	ZS Quay	11	7700	PQ and Check GXP tariff metering
10	ZS Victoria	11	7700	PQ
11	ZS Manurewa	11	7700	PQ
12	ZS Takanini	11	7700	PQ
13	ZS Wiri	11	7700	PQ

Comparing the two models of PQ monitor that are installed in the zone substations, the 7600 meter has the higher specifications. Table 4-4 summarises the main specifications of the two models of meter.

Table 4-4: Specifications for ION 7600 and 7700 PQ monitors (from ION Technology data sheet [53])

Please see print copy for Table 4.4

The main differences between the two instruments are that the 7600 has a faster sampling rate, can measure voltage fluctuations, is EN50160 compliant, and has a faster response time to triggering at set points.

4.6.2 Assessment of the ION 7700 and 7600 meters

Table 4-5 below assesses theION 7700 and 7600 instruments against the requirements of the IEC 61000-4-30 standard and the AS/NZS 61000-4-7 standards.

Table 4-5: 61000–4-30 and 61000-4-7 requirements and ION instrument specifications.

	61000-4-30 requirements			
Parameter	Class A	Class B	ION 7700 spec	ION 7600 spec
Accuracy				
Voltage (L-L)	0.1% of declared input voltage	0.5% of declared input voltage	0.5% + 0.01% F.S	0.1% + 0.01% F.S
Voltage unbalance	Calculated as per algorithm in standard	Manufacturer to specify	Not specified in data sheet	Not specified in data sheet
Voltage harmonics	Specified in AS/NZS 61000-4-7 For $U_m \geq 1\% \ U_N$: 5% U_m For $U_m < 1\% \ U_N$: 0.05% U_m	Specified in AS/NZS 61000-4-7 For $U_m \geq 3\% \ U_N$: 5% U_m For $U_m < 3\% \ U_N$: 0.15% U_m	1% F.S	Conforms with IEC 61000-4-7 (data sheet does not specify which class)

Neither the 7600 or the 7700 model appear to meet the criteria for Class A operation. The 7600 appears to conform to Class B operation, which is adequate for the statistical surveying application in which it is being used by Vector.

4.7 Data acquisition and recording issues

4.7.1 Abnormal Data

This study has focused on variation in continuously-varying power quality phenomena. Discrete events such as interruptions, transients and sags/swells are not intended to be part of the analysis. For this reason the site data has been filtered to remove data associated with interruptions (zero values), transients, and sags and swells (voltages outside a ± 10% threshold).

4.7.2 Missing data

For almost all monitored sites, there were intervals during the 12-month survey period when no data was available. This may have been due to events such as meter shutdown or disconnection during substation maintenance, or due to failure in the communications channel for transmitting the data. Short periods of missing data could be due to an interruption to the supply, although this should be recorded as zero values rather than no data at all (assuming that the instrument has battery back-up and can ride through an interruption to supply). The main periods for which data is missing from each site is given in Table 4-6.

Table 4-6: Main periods of missing data from PQ monitors.

Site	Missing Data
Rockfield	No data before October 2003
Greenmount	No data before October 2003
Bairds	No data before 10 August 2003 No data from 23 April – 10 May 2004
Quay	No data before 10 August 2003 No data from 23 April – 10 May 2004 No data from 03 June – 06 June 2004
Takanini	No data before 10 August 2003 No data from 23 April – 10 May 2004
Carbine	No data for January – March 2004 No data for 10 June – 12 June 2004
McNab	No data for 10 June – 13 June 2004 Harmonics data only covers V_1 and V_3, nothing for V_2
Howick	No data for 01 Oct – 27 October 2003 No data from 23 April – 10 May 2004
Victoria	No data from 23 April – 10 May 2004
Otara	No data from 23 April – 10 May 2004

From Table 4-6, it can be seen that the only sites with relatively complete data sets are Manurewa, Rosebank, and Wiri. With 10 of the 13 sites having significant amounts of data missing, it could be said that the effect of missing data is at least being distributed across most sites. It can also be seen that in many cases the intervals of missing data are common to several sites (e.g. the period 23 April to 10 May 2004 where six sites have no data recorded). All sites have instances where data is missing for short periods of time (up to several hours). Additionally, some sites have only partial measurements for the survey period e.g. McNab, which has no harmonics reading for V_2 during the survey period.

The question that arises is: how much difference does the missing data make? How much difference will it make to the calculation of summary statistics? The answer depends on how much data is missing, and how the summary statistic is calculated. Clearly, if a daily statistic is being calculated and there is no data for that day from a site, then no statistic can be calculated. Other studies have suggested that 95% of the data for a day should be present if a summary statistic is to be calculated for that day. It has likewise been suggested that if more than 5% of data is missing from a one week survey period, that the data should be discarded.

This study has involved the calculation of daily, monthly, 3-monthly, and annual summary statistics. If a general rule of ignoring data if more than 5% of the data is missing were applied, there would be very few sites and a relatively short survey period that would comply with this requirement. Instead, the following procedures have been followed in deciding when to discard incomplete data.

1. If summary statistics are being calculated on a daily basis: include all data, including incomplete days. The rationale for this is that in this study, daily summary statistics have only been used in producing an annual summary statistic e.g. a annual 95% value of the daily 95% index values. A few days of incomplete data is unlikely to have significant effect when combined over 365 days of data. Any days with no data at all are removed.
2. If a weekly statistic is being calculated, at least 6 days of data must be available. Note that one week's data is taken as a single data set, not as 7 sets of one day's data.
3. When calculating a monthly statistic, at least 2 weeks of data must be available. This may seem to be an excessive amount of missing data, but experience from other studies [54] suggest that where power quality performance is measured over a one month period, PQ levels are likely to be fairly consistent from one week to the next.
4. Calculation of a 3-monthly (seasonal) statistic: the 3-monthly index value has been taken as the maximum of the monthly indices over the 3-month period. A site must have monthly indices calculated for at least 2 out of the 3 months before a 3-monthly index can be calculated.
5. Annual statistics: Annual statistics have been calculated using two methods (for the purpose of comparison). The first method involves summarising the calculated daily 95% values, while the second method involves taking all the

measured values for a year as a single data set and calculating summary statistics from this.

It would seem sensible to impose a rule such as requiring that a site have at least 90% or 95% of the data for calculating an annual index. Another approach could be to require that a site at least have sufficient representative data for each seasonal period (data for at least 8 weeks for each 12 week ‘season) before calculating an annual index for that site. For the purposes of this study, it was not possible to impose any such rules. Three sites had no data at all for the first three months of the survey. Three more sites had data missing for a total of more than 7 weeks over the 52 week period. Excluding sites with insufficient data would have resulted in the survey only covering a subset of the Vector network. It should be kept in mind that this project is largely about developing procedures for conducting routine power quality surveys on the Vector network, and developing an appropriate summary reporting format and indices. It is hoped that in future the reliability of the monitoring equipment and data acquisition will improve, and the analysis and reporting techniques trailed in this study can be implemented on a more complete data set. For the purposes of this study, the best that can be said is that there is a significant amount of missing data, and that this may affect the validity of the analysis results.

Another aspect of missing data is where some data may have been recorded continuously, but measurements of a particular parameter(s) has been omitted. An example of this is at McNab zone substation, where THD has only been recorded on phases V_1 and V_3. As the Harmonics Index is taken as the highest of the 95% values calculated for each phase, the lack of data for V_2 could result in a Harmonics Index that is lower than it would otherwise be. McNab has ranked third from best across the network for THD levels. It is not possible to say definitively whether this result is affected by the lack of V_2 THD measurements.

4.7.3 Data aggregation and recording interval

All of the power quality meters installed in the zone substations are configured to aggregate and record measurements over a 15-minute interval. This is surprising given that the IEC and AS/NZS standards specify a 10 minute interval for the short term aggregation of data. Without any 10 minute data to compare against, it is not possible to estimate what effect the longer aggregation interval has on the recorded data values. However, it is recommended that Vector alter the aggregation interval to the 10-minute interval so that results can be correctly assessed against the standards.

4.7.4 Variation in instrument types

Twelve of the 13 monitored sites use ION 7700 monitors. Only one site (Rosebank) uses a different model instrument, the ION 7600. The 7600 is a higher-specification meter with a better accuracy, faster sampling rate, faster response to set-point triggers, and the ability to measure flicker. There is nothing in the data from Rosebank to suggest that the difference in instrument type has had any significant influence on the results.

4.7.5 Acquisition and recording of voltage harmonic distortion values

At all sites, the only harmonic distortion value being recorded is the total harmonic distortion (THD) value. While all of the monitoring instruments have the capability to measure and record individual harmonics up to the 63^{rd} harmonic, it is only the THD values that can be accessed from the database.

It should be noted that the recording of harmonic levels is not consistent across all sites. At most sites, the voltage THD levels recorded by the PQ monitor are the 15 minute average values. At Rosebank, Greenmount and Rockfield, the THD levels recorded are one hour average values. To test whether this makes a significant difference, a sample of the 15 min average recordings from one site were averaged over one hour periods, and 95% summary statistics were calculated and compared with the 95% statistics from the original 15 minute values. The difference has an average of 0.1%. This difference is not considered to be significant in evaluating the harmonic levels at the sites concerned.

4.7.6 Calculation of Voltage Unbalance

The method used by the ION 7700 meters to calculate voltage unbalance does not conform with the requirements of IEC 61000-4-30. The ION 7700 instrument calculates voltage unbalance in the following way (this information provided by Richard Schwass of Quasar Electronics):

1. The following equation is used by the Power Meter module output.

$$V_{unbal} = \frac{\text{largest deviation from } \mathrm{V}_{\mathrm{avg}}}{V_{avg}} \times 100\% \qquad (4-4)$$

Where;

V_{avg} = Average voltage of 3 phases calculated every second

This is an approximate method for calculating voltage unbalance, and can be out by as much as 30% [55]. Additionally, it is not clear from the above whether the average value used in the calculation (V_{avg}) is the normal arithmetic mean, or the r.m.s. mean as required by IEC 61000-4-30.

The ION 7600 meter (as used in the Rosebank substation) uses a different algorithm for calculating voltage unbalance:

2. The following equation is used by an Arithmetic module (found in the EN50160 Voltage Unbalance framework group on the ION 7600 meter).

$$V_{unbal} = \frac{NPS}{PPS} \times 100\% \qquad (4-5)$$

Where:

NPS = Negative Phase Sequence Magnitude for voltage or current

PPS = Positive Phase Sequence Magnitude for voltage or current

This is the preferred method for calculating voltage unbalance, but again it is unclear whether the voltage values used are the arithmetic average or the r.m.s mean.

4.8 Conclusion

This chapter has described the methodology in conducting a routine power quality survey on a utility network. The relevant international standards on measuring techniques and instrument requirements have been explained, and the monitoring equipment and practices implemented by Vector have been assessed against the requirements of the standards. The instruments being used by Vector are adequate for the purposes of a statistical survey but should not be used for establishing conformance with power quality standards, or for verification of fulfillment of contractual obligations. It is also recommended that the monthly summary reporting format be modified to display 95% cumulative probability values for continuous disturbances so that these can be compared to limit values specified in the national standards.

The validity of the results of the statistical analysis of this study is compromised by the large amount of missing measurement data. There are also some inconsistencies in instrument configuration between monitoring sites (although these do not appear to have a significant effect on the results). However, the primary objective of this study is in developing a methodology for implementation and result analysis and reporting for an on-going routine survey. The actual results of the data analysis from this study are of secondary importance, and are to some extent for the purpose of demonstration. Confirmation or rejection of the trends identified will be established by future on-going monitoring and data analysis.

Chapter 5: Power Quality Data Analysis and Reporting Techniques

5.1 Introduction

Perhaps the most important phase of a power quality survey is the process of data analysis and reporting. Essentially the problem is an exercise in data reduction: taking the immense amount of data that is produced by modern power quality analysers and condensing it down to a few summary statistics that accurately indicate the power quality performance of the network. These summary statistics can then be tracked by the network manager to identify long-term trends or non-conforming disturbance levels.

The current practice in reporting power quality surveys (rightly) emphasises conformance (or non-conformance) with recognized standards and/or regulations. What is equally useful to the network manager is to be able to track disturbance levels over a period of time so that preventative action can be taken ***before*** disturbance levels exceed the standards/regulations. While most power quality instruments include the capability to generate summaries of disturbance levels, discrete events and long-term trends, there is little standardisation in the reporting format and how any summary statistics are generated.

This chapter will look at several proposed techniques for generating summary statistics from the results of a routine power quality survey, and how these summary statistics can be used as indices of power quality performance for a particular site (or for an entire network). Power quality indices for each site can be compared, and this information may be useful for prioritising network maintenance. Where a site (or number of sites) is being continuously monitored, it may be useful to have a seasonal power quality index for that site so that performance can be tracked over the course of a year. On the longer term, an annual PQ index for a site (or network) would allow easy comparison of power quality levels from one year to another. This chapter will investigate options for determining appropriate monthly, seasonal and annual power quality indices, and evaluate each of these options.

The data on which this power quality survey is based was recorded by 13 ION power quality analyser instruments located in 11 kV zone substations on the Vector network. The survey covered a 12 month period, from 1 July 2003 to 30 June 2004. Three continuously-varying disturbances were analysed: voltage, voltage unbalance, and total harmonic voltage distortion. Preliminary discussions with Vector indicated that voltage variations were the continuous disturbance types that were of most concern to both Vector and its customers. Discrete voltage sags and swells are also of major concern because of the potential for harmful consequences to customer equipment. However, the analysis of discrete disturbances (voltage sags/swells in particular) requires totally different techniques to those used in this study, and is beyond the scope of this project.

5.2 Analysis considerations

5.2.1 Nominal voltage and Float voltage

In the analysis of voltage variations, it is necessary to have a reference value of voltage against which variations can be measured. The nominal voltage value (in this case, 11,000V for the MV network) might seem to be the obvious choice for the reference value. Use of the nominal voltage would be appropriate if the survey was carried out on the low voltage network and the voltages measured were equal to those experienced at a customer's point of common coupling. The 11,000V network is primarily a distribution network, with few customers supplied directly at 11,000V. The main concern of the network operator is to ensure that the MV distribution voltage is maintained at the appropriate level to ensure that customers connected to low voltage network receive the correct supply voltage.

When analysing at the MV distribution level of a network, it is necessary to use a 'float voltage' (V_{float}) when calculating voltage variation rather than the nominal voltage. The float voltage is defined as the target system voltage that will be maintained through the use of transformer tap changers or other voltage regulation devices. This power quality survey uses measurements made at the 11kV bus at zone substations. While the nominal voltage is 11kV, the utility may intentionally set the bus voltage at a higher float voltage to compensate for the effects of load, and to ensure that customers connected at the end of an 11kV feeder still receive the correct supply voltage. The float voltage can be different for each site, depending on factors such as impedance and length of feeders and other load characteristics. For the purposes of this survey, the difference between float voltage and nominal voltage is academic: Vector advise that the target bus voltage at all zone substations is equal to the nominal voltage of 11,000 V.

5.2.2 Line drop compensation

Another issue that needed to be considered is the use of line drop compensation in zone substations. Line drop compensation increases the voltage at the substation bus as load increases to compensate for voltage drop across the system impedance. A site that uses line drop compensation will typically exhibit higher bus voltages with increased load current. Vector advise that line drop compensation schemes are not used in their zone substations.

5.3 Initial analysis

Prior to commencing the 12-month survey, a preliminary one-month survey was carried out using data from the 13 monitors. The purpose of this one-month survey was effectively a trial of the statistical and reporting methods, and to demonstrate to Vector the potential for these methods to effectively condense a vast amount of data into a small number of summary statistics that would give a clear indication of power quality performance on the network. The data reduction techniques and reporting format used in this study were developed by researchers at the Integral Energy Power Quality & Reliability Centre at the University of Wollongong [56] and are documented in [24]. The implementations of these techniques are described in more detail later in this section.

Having completed a one-month survey of all sites, the next step was to extend the survey to cover a 12-month period. As this initial survey was based on a one-month period, one possible methodology for conducting a 12-month survey was to simply carry out twelve one-month surveys. From this an annual summary of power quality performance could be derived.

The reporting format developed by the University of Wollongong and used during this phase of the Vector study employs a combination of primary and secondary power quality indices to evaluate the disturbance levels at a particular site. The algorithm for calculating each of the indices is described below.

5.4 Primary Indices:

When summarising continuously varying quantities such as voltage, voltage unbalance, and harmonics, it is common to use statistical quantities such as maximum values, 95% values, or average values. Maximum disturbance levels may be due to a chance combination of factors that only occur very infrequently. As such, maximum values may be unrepresentative of levels occurring most of the time. The use of 95% values of 10 minute readings has become the accepted statistic in several international power quality standards. For this reason, the techniques described below are largely based on 95% values of disturbance levels.

1. Voltage Index (VI)

    Method: Calculate Absolute voltage deviation (AVD)

$$AVD = \frac{\left|V_{float} - V\right|}{V_{float}} \times 100\% \qquad (5-1)$$

    Find the 95th percentile value of AVD across the 3 phases for each day.

    Monthly Voltage Index VI is the maximum of the daily 95th percentile values.

2. Voltage Unbalance Index (VUI)

    The ideal value of voltage unbalance is zero.

    Find the 95th percentile value of voltage unbalance for each day.

    Monthly VUI index is the maximum of the daily 95th percentile values.

3. Harmonics Index (HI)

    The ideal value of voltage THD is zero.

    Find the 95th percentile value of THD for each phase for each day.

    Daily THD value is the maximum of the phase 95th percentile values.

    Monthly Harmonics Index is the maximum of the daily 95th percentile values.

5.5 Secondary Indices:

The primary indices described above are based on 95% values, and this allows the indices to be referenced to accepted international standards that also use 95% values (CENELEC 50160, IEC 61000 series EMC standards). A clear limitation of using 95% values is that they give no information about the behaviour of a site for the other 5% of the time (8.4 hours per week). While it could be argued that under normal operating conditions the remaining 5% of samples should not deviate drastically from the 95% value, this cannot be guaranteed. Rather than simply discarding the highest 5% of measured values, it perhaps makes more sense to use this data to gain some insight into the extreme behaviour of a site (and particularly the peak values of disturbances, as it is these peak values that will likely have the most impact on customers).

The Integral Energy Power Quality & Reliability Centre at the University of Wollongong have developed a series of secondary power quality indices that aim to represent this behaviour where values exceed pre-determined limit values. These limit values may be linked with regulatory or standards-based values, or may be an limit that has been developed by the network operator. This study has trailed the use of these secondary indices for analysing voltage variation, voltage unbalance, and harmonic distortion. The three secondary indices respectively are:

- Voltage outside Range Index (VoRI)
- Unbalance outside Limit Index (UoLI)
- Harmonics outside Limit Index (HOLI).

The algorithms for calculating each of these secondary indices are described below.

- Voltage-Outside-Range Index (VoRI):
  - Step 1: Caculate voltage outside range
    1. Let V_{max} and V_{min} be maximum and minimum acceptable voltages
    2. If $V>V_{max}$, VoR = $(V - V_{max})$
    3. If $V<V_{min}$, VoR = $(V_{min} - V)$
    4. Else, VoR = 0
  - Step 2: Calculate Voltage-outside-Range Index (VoRI):
    1. Determine rms of VoR for each phase for each week.

2. Obtain a weekly value by taking the maximum VoR across all phases.
3. VoRI is the maximum of the weekly values across the survey period.

- Unbalance-over-limit Index (UoLI)
  - Step 1: Calculate Unbalance over limit
    1. Let VUF_{max} be maximum acceptable voltage unbalance.
    2. If $VUF > VUF_{max}$ $\quad$ $UoL = (VUF - VUF_{max})$
    3. If $VUF < VUF_{max}$ $\quad$ $UoL = 0$
  - Step 2: Calculate Unbalance-over-Limit Index.
    1. Determine rms of UoL for each week.
    2. UoL is the maximum of the weekly values across the survey period.

- Harmonic-over-Limit Index (HoLI)
  - Step 1: calculate Harmonic-over-Limit.
    1. Let THD_{max} be the maximum acceptable THD
    2. If $THD > THD_{max}$ $\quad$ $HoL = (THD - THD_{max})$
    3. If $THD < THD_{max}$ $\quad$ $HoL = 0$
  - Step 2: Calculate Harmonic-over-Limit Index.
    1. Find rms of HoL for each week of each phase.
    2. Find a weekly value by taking the maximum across the phases.
    3. Combine across the weeks by taking the maximum of the weekly values.

The use of rms (root-mean-square) to obtain a weekly value of the secondary index (rather than a straight arithmetic average) is based on the assumption that the impact of disturbances on customers increases in a non-linear fashion as the magnitude of the disturbance increases. The use of an rms value effectively gives a 'weighted average' to the index.

Limit values were set at ±3% for voltage, 2% for voltage unbalance, and 6.6% for THD. The ±3% for voltage is based on an assumed tap changer step of 1.5%, and that under normal operating conditions system voltage should be able to be maintained within two tap changer steps of the target voltage. The limit for voltage unbalance is taken from AS/NZS 61000.2.2 which gives a maximum compatibility level of 2%. The 6.6% value for THD is a recommended limit value that has resulted from extensive utility power quality surveying in Australia carried out by the Integral Energy Power Quality & Reliability Centre.

The values for VoRI, UoLI, and HoLI proved to be so small as to be considered insignificant. Only one site on the Vector network experienced occasional voltage deviations outside the ±3% limits, and no site had voltage unbalance or THD levels in excess of the limit values. The use of secondary indices could still be useful to Vector if the limit values were aligned more closely with the actual measured disturbance levels on the Vector network. In the interests of keeping the reporting of power quality analysis relatively brief, this line of analysis has not been included in the final reporting format for Vector, but could be further developed in future.

Having arrived at monthly indices for voltage variation, voltage unbalance, and THD, it was then necessary to combine these indices into a single index that could indicate the overall power quality performance of each site. To do this, it is necessary to express each of the indices in the same 'unit'. A process of normalisation is required. Two possible methods of doing this are:

- Each index (voltage, voltage unbalance and THD) could be normalised with respect to the network average value for that index.
- Alternatively, each index could be normalised with respect to a specified limit value for that parameter.

Normalisation with respect to a system average is appropriate if the aim is to rank sites across the network. Normalising with respect to a specified limit value is more appropriate if the objective is to establish conformance with a specified limit value. Both methods of combining indices were used, and the resulting overall site indices can be used depending on the desired purpose of the analysis. The aim of this study is to establish a ranking of sites across the network, and then attempt to link the site ranking with the known physical characteristics of each site. For this reason, normalizing of indices with respect to the system average is considered to be more appropriate. Once the individual indices were converted to normalised values, the average of these three values was taken as the overall power quality index value for that site. It is worth noting that the use of an arithmetic average of component indices to arrive at the overall site PQ index only gives a rough overall indication of power quality performance. A site may have a very good voltage index and voltage unbalance index, but a poor harmonics index. If averaging of these three values results in an acceptable overall site index, this suggests that the poor harmonics index is counterbalanced by the good voltage performance. This is unlikely to be the view of the customer if they are experiencing problems due to high harmonic levels.

5.6 Ranking of sites by monthly index value.

Having calculated a monthly overall PQ index for each site, it was a simple matter to rank the sites from highest (worst) to lowest PQ index. This process was repeated for each of the 12 months of the survey period. The question that arose was: Is there a consistent pattern to the ranking of sites from month to month? Do some sites consistently perform better than others? If this is the case, it may be possible to look at the known physical characteristics of the sites to determine what it is that gives these sites better PQ performance.

Over the 12-month period, there were three or four sites that consistently returned lower PQ indices. Likewise, there were three or four sites that consistently returned higher PQ indices. However, in the middle range there was some variation in the ranking of sites from month to month. The overall trend is further confused by the absence of data for some sites for particular months. A graph of the monthly trend of site PQ indices is shown in Fig.5-1. Note that the plots for some sites (Greenmount, Carbine, Rockfield, McNab) are incomplete due to missing data.

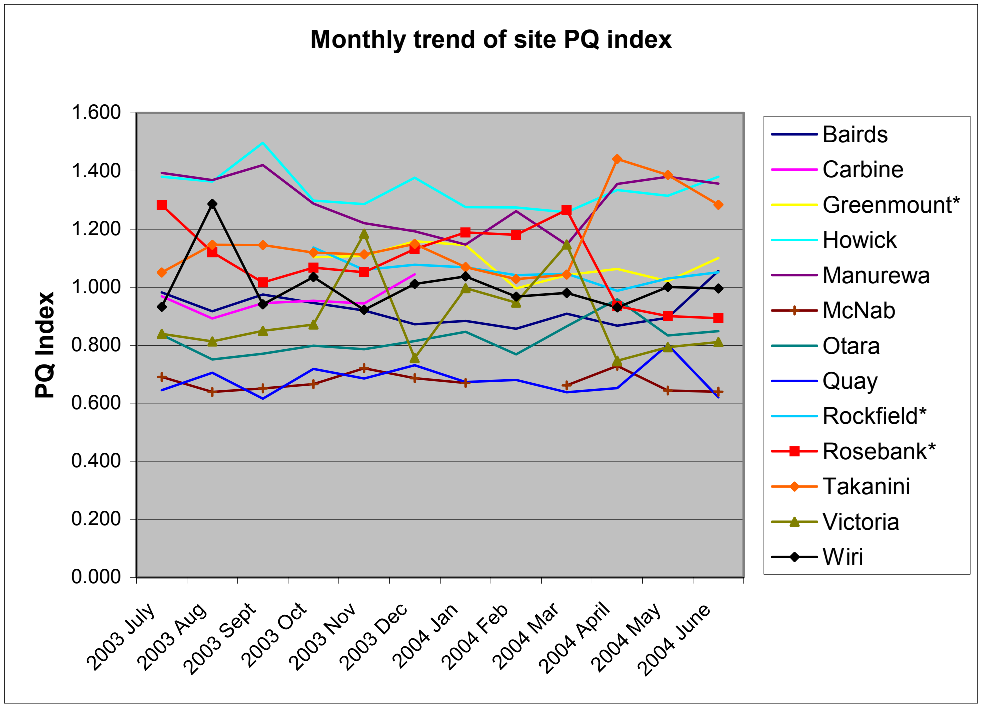


Fig.5-1: Monthly trend of site PQ indices.

5.7 Three-monthly ranking of sites and Seasonal Indices.

The month-to-month variation in PQ indices for each site makes it difficult to identify any trend in Fig.5.1. In order to clarify the trend in site ranking, the time frame was changed from monthly to 3-monthly. This would have the effect of smoothing the graph. Additionally, a 3-monthly site index can be used as a seasonal index for that site, giving an indication of variation in PQ performance between winter, spring, summer and autumn. The 3-monthly index for a site is taken as being the maximum of the monthly indices for that site over the three-month period. The resulting graph of 3-monthly indices is shown in Fig.5-2. To further clarify overall trends, sites with no data (or insufficient data) for any three-month period have been omitted.

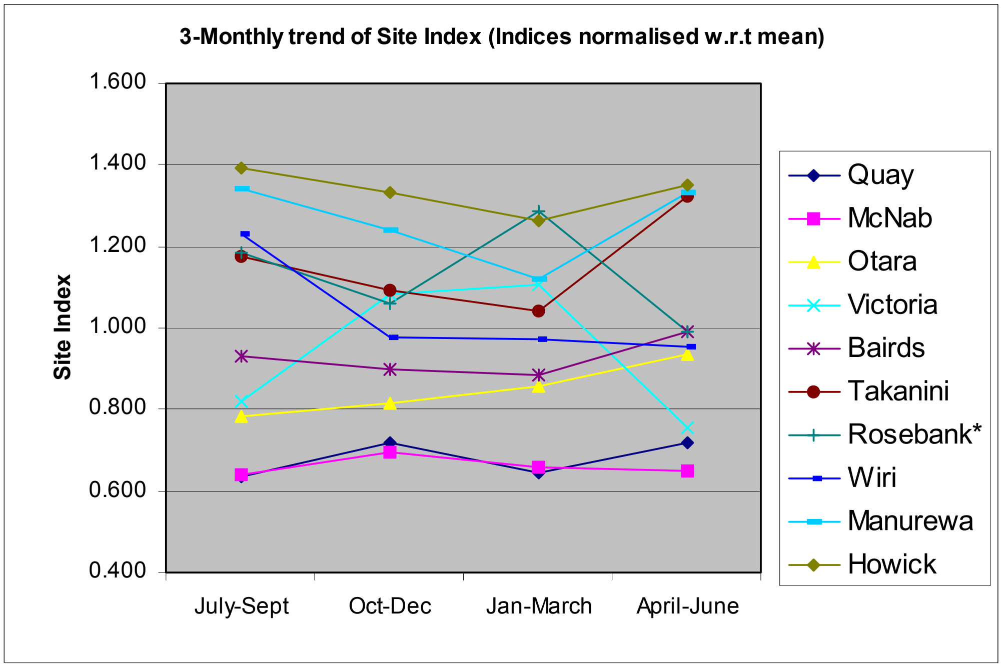


Fig.5-2: 3-monthly trend of site PQ indices.

From Fig.5-2 it can be seen that Howick, Manurewa and Takanini have consistently higher (worse) PQ indices, while McNab, Quay and Otara have better indices. While some sites clearly exhibit their worst PQ performance during the mid-winter months (July and August), this is not consistent across all sites. Rosebank had a definite peak in PQ index in the Jan-March quarter, due mainly to a higher than normal level of harmonics disturbance. Victoria experienced its highest PQ levels between October and March (perhaps due to air-conditioning load – the load on Victoria zone substation is predominantly commercial-retail).

In addition to looking at the overall PQ index for each site on a seasonal basis, the 3-monthly trend of each individual index was analysed.

5.7.1 Three-monthly voltage index:

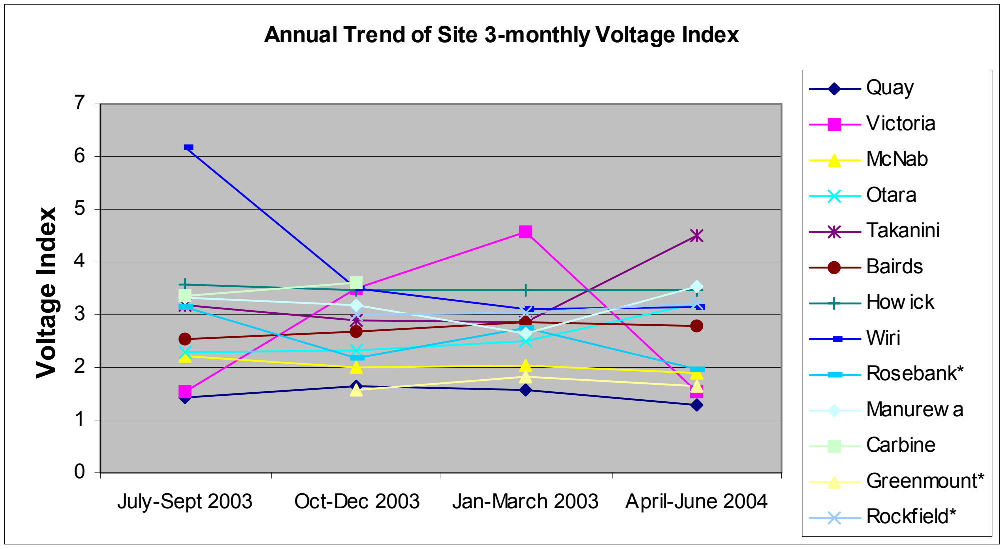


Fig.5-3: 3-monthly voltage index trend.

For most sites, there is no clear seasonal trend in the variation of voltage index. The exception to this is Victoria, which shows a clear peak in voltage index during the summer months. This coincides with the peak period of loading at this substation.

5.7.2 Three-monthly voltage unbalance index:

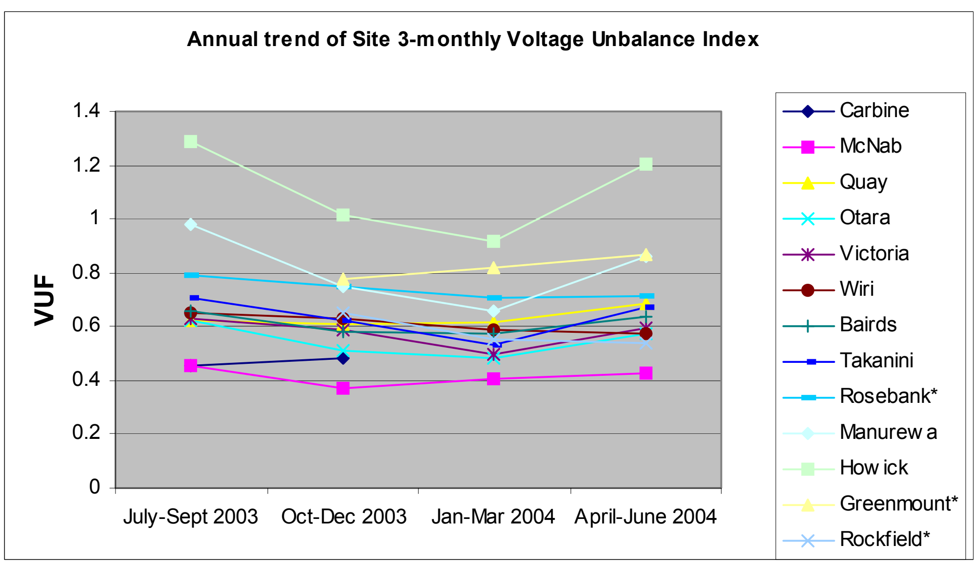


Fig.5-4: 3-monthly voltage unbalance trend.

A pattern of seasonal variation in voltage unbalance can clearly be seen across most of the monitored sites. Voltage unbalance is at its worst in the winter months of June and July, and falls to its lowest levels in the January-March period.

5.7.3 Three-monthly Harmonics Index:

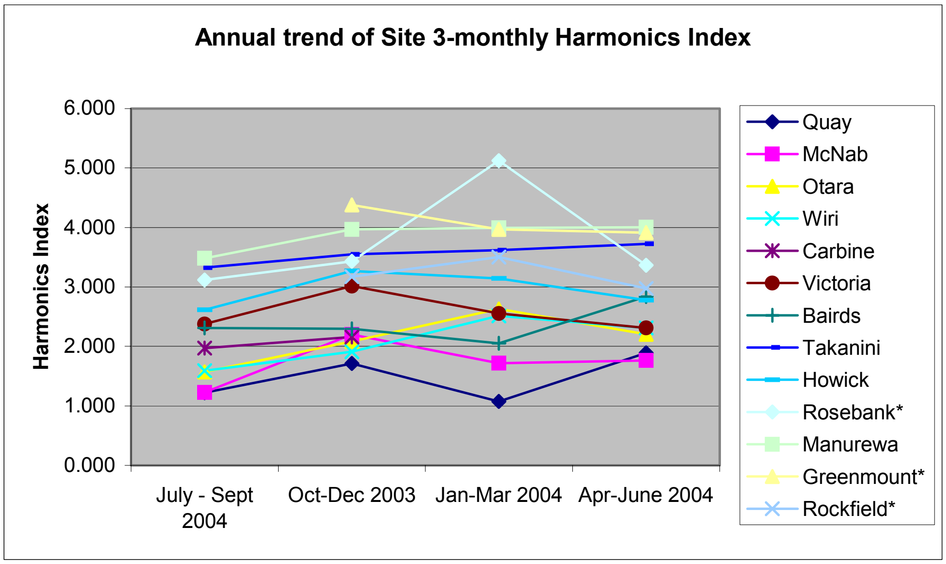


Fig.5-5: 3-monthly harmonics index trend.

A seasonal trend in the variation of harmonic levels can be seen in Fig.5-5, although the trend is not as consistent across all sites as that for voltage unbalance. Most sites experienced a seasonal peak in harmonic levels during the October-December quarter, followed by a seasonal low during January-March. One exception to this is the Rosebank site, which experienced a sharp peak in harmonics level between January-March. It would be interesting to see if this peak is repeated in later years.

Of most concern to the network engineer is that most of the sites show a general trend of increasing harmonics levels over the 12 month period. While harmonics levels are currently well within the recommended maximum levels, this situation could change in the foreseeable future if this trend continues or accelerates. Table 5-1 gives the Harmonics Index for each site during the first month of the survey (July 2003) and the last month of the survey (June 2004).

Table 5-1: Change in site Harmonic Index values over the survey period.

Site	Harmonics Index July 2003	Harmonics Index June 2004	Percentage change
Howick	2.59	2.47	-4.60
Manurewa	3.14	3.46	10.19
Otara	1.51	1.91	26.49
Takanini	2.50	3.23	29.20
Bairds	2.20	2.84	29.10
Rosebank	3.12	2.59	-16.99
Quay	1.06	0.92	-13.21
Victoria	2.14	2.31	7.94
Wiri	1.54	2.19	42.21
McNab	1.19	1.49	25.21
Carbine	1.97	2.51	27.41

Two sites (Greenmount and Rockfield) have been omitted from the above table as they did not have data available for July 2003. Of the remaining 11 sites, eight sites had a higher Harmonics Index at the end of the survey than at the start, while three sites had a lower Harmonics Index 12 months later. Over all of the 11 sites, the average change in Harmonics Index was an increase of 14.8%. Clearly it would be inappropriate to make any firm conclusions regarding long term trends in harmonics levels based on the above results, as further analysis of data over at least several years would be required. However, the overall trend of a slow but steady increase in harmonics levels agrees with results from other studies [26].

It should be noted that the recording of harmonic levels is not consistent across all sites. At most sites, the voltage THD levels recorded by the PQ monitor are the 15 minute average values. At Rosebank, Greenmount and Rockfield, the THD levels recorded are one hour average values. To test whether this makes a significant difference, a sample of the 15 min average recordings from one site were averaged over one hour periods, and 95% summary statistics were calculated and compared with the 95% statistics from the original 15 minute values. The difference was an average of 0.1%. This difference is not considered to be significant in evaluating the harmonic levels at the sites concerned.

The THD levels recorded in the Vector survey have been compared with the results of other international power quality surveys. Results were compared with those from the EPRI DPQ Project [26] which utilised data from 277 measurement locations located on the primary distribution feeders of 24 electric utilities across the United States, and significant similarities were found (refer to section 2.3.2, page 34 for details).

Comparison has also been made with benchmark data that is presented in the Cigre C4.07/Cired Joint Working Group report on power quality indices and objectives [19]. The data summary presented in this report is from past or on-going surveys and specifically covers MV, HV and EHV systems. The mean value of the 95th percentile THD value across the surveys was approximately 3.6%. The comparative value from the Vector survey is 3.42%, which supports the validity of the Vector measurements.

5.8 Ranking of sites on an annual basis.

While the ranking of sites on a 3-monthly or seasonal basis clarified the overall trend and also provided seasonal indices for each site, the network utility may also be interested in obtaining an annual PQ index for a particular site. This takes the process of data reduction one step further, enabling the following of long-term PQ trends without having to sift through large numbers of monthly or 3-monthly summaries.

To derive an annual PQ index for a site, the following options were considered:

1. Let the annual PQ index for a site be equal to the maximum of the monthly site PQ indices over the 12-month period.
2. Let the annual PQ index for a site be equal to the maximum value of the daily PQ indices over the 12-month period (note that the daily value of a PQ index is equal to the 95th percentile value of the 15 minute data for that day).
3. Let the annual PQ index for a site be equal to the 95th percentile value of the daily PQ indices over the 12-month period (i.e. the 95th percentile value of the daily 95% values).
4. Let the annual PQ index for a site be equal to the 95th percentile value of the original 15-minute data, taken over the entire 12 month period.

As the monthly PQ index for a site is equal to the maximum of the daily 95th percentile values, options 1 and 2 are effectively the same. Taking the maximum of the daily 95% values is considered to be a tough measure, as the utility is being rated according to the worst day of PQ performance over the entire 12 month period. A more reasonable approach would be to use either options 3 or 4, as these methods ensure that the resulting PQ index is indicative of the PQ performance of that site for 95% of the time during the survey period (which aligns with the requirements of standard EN 50160).

The methods described in options 3 and 4 were used to summarise the data, and the results were compared. The site rankings that resulted from the two methods are given below in Tables 5-2 and 5-3. Note that all index values are normalized with respect to the network average for that index. The main points from this comparison:

- Both methods result in the same six sites have the best PQ ranking, and the same three sites having the worst PQ ranking.
- In most cases, the final value of the overall PQ index for a site is very similar using either method. The exception to this is Wiri. Wiri has a lower PQ index and better ranking using option 4. The reason for this lies in how each of the methods eliminates the worst 5% of measurements. Option 3, which uses a 95% of daily values, allows the worst 5% of entire days to be eliminated. Option 4 eliminates the worst 5% of all values (irrespective on which day they occur). Wiri may display higher voltage variation on a daily basis, but if the worst 5% of each day is removed and the daily indices summarised, its lack of any very bad days gives it a better ranking.

Table 5-2: Annual summary of 15 min site data. Sites ranked best to worst (left to right)

	Quay	McNab	Otara	Victoria	Bairds	Carbine	Wiri	Rosebank*	Rockfield*	Greenmount	Takanini	Manurewa	Howick
Voltage Index VI	0.541	0.827	0.807	0.609	1.123	1.461	1.288	0.725	1.253	0.573	1.279	1.171	1.344
Voltage Unbalance Index VUF	1.040	0.624	0.800	0.957	0.891	0.664	0.935	1.073	0.807	1.173	1.020	1.274	1.741
Harmonics Index HI	0.453	0.693	0.742	0.963	0.662	0.773	0.786	1.269	1.198	1.531	1.293	1.463	1.175
Ranked mean of normalised data:	0.678	0.715	0.783	0.843	0.892	0.966	1.003	1.022	1.086	1.092	1.197	1.303	1.420

Table 5-3: Annual summary of daily 95% values. Sites ranked best to worst (left to right)

	Quay	McNab	Otara	Victoria	Bairds	Carbine	Rockfield*	Rosebank*	Greenmount	Wiri	Takanini	Manurewa	Howick
Voltage Index VI	0.518	0.732	0.778	0.567	0.960	1.232	1.102	0.795	0.530	2.000	1.461	1.144	1.179
Voltage Unbalance Index VUF	0.975	0.612	0.838	0.906	0.893	0.666	0.830	1.068	1.223	0.903	1.046	1.273	1.767
Harmonics Index HI	0.463	0.691	0.757	0.986	0.751	0.766	1.127	1.333	1.462	0.819	1.278	1.431	1.138
Ranked Mean of normalised values:	0.652	0.678	0.791	0.820	0.868	0.888	1.020	1.065	1.072	1.241	1.262	1.283	1.361

The question arises: which of the two methods should be used to rank sites on an annual basis. It is clear that the two methods arrive at different site rankings. Statistically, it is more correct to use the original 15 min data rather than using the daily 95% summaries. Using the 15 min data, all recorded data values have the same weighting. Using the daily 95% values, the weighting of a particular data value will depend on which day it occurs. On one day it may be included in the final value, while on another day an identical data value might be eliminated as being in the highest 5% (it should also be noted that using an annual summary of the original 10 min data is the method being used in similar surveys being carried out by the IEPQRC at UoW).

The disadvantage of using the original 15 minute data rather than the daily 95% values, is that the 5% of excluded values from a year's 15 minute data potentially represents the equivalent of a single block of 18.25 days. If daily 95% values are used, the excluded 5% is broken down into much smaller discrete periods of time.

5.9 Another Voltage Index

One deficiency with the Voltage Index as defined earlier, is that the index value gives no indication of whether the deviations from the nominal voltages are typically high, low, or a combination of the two. Having been alerted to a potential voltage problem by a high voltage index value, the network engineer then has to go back to the raw data to establish the direction of the voltage deviation. An additional index that would provide this information is needed.

A number of options were explored and experimented with in developing this secondary voltage index. The resulting value should clearly indicate both the magnitude and predominant direction of the voltage deviation from the nominal value. The following possible methods were considered for calculating the Voltage Deviation Index.

1. Take the average value of voltage over the survey period, and express this as a percentage of nominal.
2. Find the total time that the voltage is outside the specified limit values, and express this as a percentage of the total survey period time.
3. Use the magnitude of the maximum deviation of voltage from the nominal value (or alternatively the 95% value of the voltage deviations) as the basis for the voltage deviation index.
4. Consider the area enclosed under a voltage vs time curve, where the values of the voltage are above the specified limit value.

Considering each of these options in turn:

1. Average value of voltage: The algorithm used to arrive at a Voltage Deviation Index using the average value of voltage is:
    - Calculate mean value of voltage over the three phases for the duration of the survey period.
    - Voltage Deviation Index $VDI = \frac{V_{ave} - V_{float}}{V_{float}} \times 100\% \qquad (5-2)$
    - Proposed alert value: To be determined from future surveys.

This method has the advantages of simplicity to calculate and interpret. The sign of the index indicates whether the voltage is typically too high or too low, and the magnitude of the index gives an indication of extent of the excursion from nominal. However, the index does not discriminate between short-time excursions of large magnitude and smaller excursions of longer-time duration. It also has the disadvantage that low values and high values will tend to cancel out in the averaging process, so that it is possible that a site could have problems with both low and high voltage, but these will cancel to give a good (small) value of Voltage Deviation Index. This could be overcome by calculating the VDI separately for high deviations and low deviations.

A refinement of using the average voltage as the index is to consider only the measured values that exceed the limit values (in this case, ±3%). If the average value of these measurements is calculated, values that are within the specified limits are ignored, and so the resulting index focuses more on the problematic voltage deviations.

The algorithm for calculating this index becomes:

Step 1:

Let V_{max} and V_{min} be the upper and lower voltage limits.

- If $V > V_{max}$, voltage deviation (high) = $(V - V_{max})$
- If $V < V_{min}$, voltage deviation (low)= $(V_{min} - V)$
- Else voltage deviation = 0

Step 2:

Voltage Deviation Index (high) = average value of voltage deviation (high) over the survey period.

Voltage Deviation Index (low) = average value of voltage deviation (low) over the survey period.

Alert values for this index are to be determined from future surveys.

This is very similar to the method described earlier to calculate the secondary voltage index Voltage-outside-Range Index VoRI. However, for VoRI the rms value of the voltage deviations are used, so that both positive and negative deviations were considered together. The resulting index gives no indication of whether the deviations are positive or negative. The use of an rms value is intended to give a 'weighted' average, based on the assumption that the adverse effect on customer equipment of voltage deviations is not linear.

2. Consideration of the proportion of time that the voltage is outside specified limit values, and express this as a percentage of the total survey time. For the purpose of this survey, the limit value for voltage has been set at ±3% of nominal. While the New Zealand electricity regulations do not specify limits for MV distribution voltages, the default limits for supplying customers at MV are ±5%. The voltage levels on the Vector network are typically much better than this, and using a 5% limit would give little insight into the behaviour of the voltage.

   The disadvantage of considering only time duration in deriving the VDI is that does not take into consideration the magnitude of the voltage deviation.

   Alert values are to be determined from future surveys.

3. Derive the index using the maximum value of the voltage deviation. As this is likely to be a rather crude measure and may only reflect extreme voltage levels due to rare conditions, it may be more appropriate to take a 95% value of those voltage values that exceed the nominal voltage by greater than 3%.

$$For\ \ V < (V_{float} - 3\%):$$
$$Voltage\ Deviation\ Index_{Low} = Percentile[(V - V_{float}), 0.95] \qquad (5-3)$$
$$For\ V > (V_{float} + 3\%):$$
$$Voltage\ Deviation\ Index_{High} = Percentile[(V - V_{float}), 0.95] \qquad (5-4)$$

Problems:

As already mentioned, using the maximum value of positive and negative deviation can give a misleading impression of the behaviour of the site. These extreme values may be due to rare events that are not representative.

Using the 95% values of voltage deviations that are outside the ± 3% range, the resulting figures can also be somewhat misleading. For example, a site may only have one voltage excursion beyond the limit. If it is only deviations that are beyond the limit that are considered when calculating the 95% value, then the 95% value will be equal to the value of this single voltage deviation. So, a site that has a single measurement of 11500V over the survey period will have a higher VDI than a site that may have hundreds of measured values of 11400V.

4. Because the impact on customer equipment depends on both the magnitude and duration of any voltage deviation, ideally any voltage deviation index should use both voltage and time in its calculation. One approach is to consider the frequency of occurrence of each voltage value and the time duration that this number of occurrences represents. This can then be taken as a proportion of the total voltage-time product over the survey period to gain an indication of both the magnitude and time duration of voltage excursions from the nominal value. What this method is effectively doing is looking at the area under the voltage-time curve. It then expresses the area of voltage-time when the voltage is outside the limit values as a percentage of the total area. The algorithm is:

- Divide all recorded voltage values into equal divisions. 20V divisions have been used in this study.
- Calculate the frequency of occurrence of each voltage division over the duration of the survey period.
- Calculate the total frequency-voltage product for the whole survey period to get the total area under the curve.

- Calculate the frequency-voltage product for values of voltage that are above the limit value (gives area under the curve that is above the limit value).
- Calculate the frequency-voltage product for values of voltage that are below the limit value (gives the area under the curve that is below the limit value).
- The Voltage Deviation Index (high) is the percentage of the frequency-voltage product for values greater than the limit value with respect to the total frequency-voltage product.
- The Voltage Deviation Index (low) is the percentage of the frequency-voltage product for values less than the limit value with respect to the total frequency-voltage product.

In order to determine an appropriate alert value using this method, it is necessary to consider not only what is an acceptable magnitude of voltage deviation, but also what is an acceptable time duration for that level of deviation. For example:

- Assume that voltage deviation limit has been specified as ±3% for 5% of the time.
- If a voltage deviation of 5% from nominal (2% above the limit value) for 5% of the time is considered acceptable, this represents a percentage area under the voltage time curve of 2% × 5% = 0.1% of the area. This value becomes the reference value for normalization.
- In the example case of the voltage being 108% above the nominal value (i.e. 5% above the limit value) for 3 hours every day, the Voltage Deviation Index would be calculated as:

$$Area = 5\% \times \frac{3}{24} = 0.625\%$$
$$If\ reference = 0.1\%,$$
$$Voltage\ Deviation\ Index = \frac{0.625}{0.1} = 6.25$$

This tells us that the magnitude and duration of the voltage deviation is 6.25 times worse than the acceptable base case of 2% too high for 5% of the time.

An example of using this method to calculate a Voltage Deviation Index is given below using annual data from one of the sites on the Vector network:

Table 5-4: Voltage Deviation Index – data and sample calculation.

Voltage	*Frequency*	Voltage*Freq	% Dev. outside 3% Limit	% of Total Time	% Area outside limit
10560	39	411840	0.9708	0.000431	0.000418
10580	0	0			
10600	0	0			
10620	0	0			
10640	0	0			
10660	0	0			
10680	4	42720			
10700	0	0			
10720	5	53600			
10740	18	193320			
10760	118	1269680			
10780	228	2457840			
10800	316	3412800			
10820	535	5788700			
10840	793	8596120			
10860	927	10067220			
10880	955	10390400			
10900	1237	13483300			
10920	1611	17592120			
10940	2390	26146600			
10960	2873	31488080			
10980	3201	35146980			
11000	2977	32747000			
11020	3273	36068460			
11040	4202	46390080			
11060	5629	62256740			
11080	6581	72917480			
11100	6476	71883600			
11120	5840	64940800			
11140	4630	51578200			
11160	4462	49795920			
11180	4836	54066480			
11200	5057	56638400			
11220	4189	47000580			
11240	3804	42756960			
11260	2807	31606820			
11280	1670	18837600			
11300	1397	15786100			
11320	1440	16300800			
11340	1005	11396700	0.088261253	0.011922905	0.001052331
11360	353	4010080	0.26478376	0.004195232	0.001110829
11380	149	1695620	0.441306267	0.00177391	0.000782837
11400	38	433200	0.617828773	0.000453202	0.000280001
11420	15	171300	0.79435128	0.000179209	0.000142355
11440	3	34320	0.970873786	3.59046E-05	3.48588E-05
11460	1	11460	1.147396293	1.19891E-05	1.37563E-05
11480	0	0	1.3239188	0	0
11500	0	0	1.500441306	0	0
More	1	1			

	86085	955866021			0.003416969
Voltage Deviation Index$_{high}$:					**0.034169686**
Voltage Deviation Index$_{low}$					**0.004183**
(normalised with respect to a baseline case of voltage 5% above nominal for 2 hrs being only just acceptable					
i.e. 5% times 2% = 0.1%					

Clearly the voltage deviation for this site is predominantly positive (high). To allow for sites that have significant voltage deviation both above and below the limit values, it is necessary to report the values for both high and low voltage deviations (although amongst the sites analysed in this study, no sites exhibit significant instances of low voltage. At all sites, the predominant voltage deviation is high).

This method has the advantage that the resulting statistic gives an indication of both the magnitude and the frequency of occurrence of either high or low voltage deviations, and so is more indicative of possible impact on customer equipment.

Using this method on the data set given above, and normalising against a reference value of 0.1% resulted in a VDI_{high} of 0.0342 (i.e. the magnitude and duration of the voltage deviation is 0.0342 times the base case of 2% too high for 5% of the time) and a VDI_{low} of approximately 0. Considering that this result was from one of the worst sites on the Vector network, it is clear that the reference value will need further adjustment (in consultation with Vector) in order to obtain meaningful results. At several of the better sites on the network, the results were that both VDI_{high} and VDI_{low} were 0, indicating that the voltage was within the 3% limit value for the entire duration of the survey.

Main points:

- Any site that has no voltage deviations beyond the limit value will return a VDI of zero. Any site that returns a non-zero value has voltage excursions beyond the limit. The value of the index will give a comparative measure of both the magnitude and frequency of occurrence of these excursions. The combination of magnitude and duration give a comparative measure of impact on customer equipment.
- By calculating the index separately for high and low excursions, the index will show whether the excursions are high or low.

- The index requires input from Vector to establish a suitable baseline case for normalization purposes. Is 2% outside limit for 5% of the time too much? What if the voltage were 4% too high? Would this be acceptable for 2.5% of the time, or for a different time duration? Initial results from this survey suggest that a tighter baseline (e.g. 1% outside limit for 3% of the time) might be appropriate. Vector's perspective on this question is simple: the voltage should never go outside the limit values. If it does, the reasons should be investigated and remedial action taken.
- The index gives no warning if voltage levels are hovering just within the limit values. However, an indication of overall voltage levels can be obtained from the primary voltage index.
- The same technique could be extended to the analysis of total harmonic distortion (THD). As with continuous voltage variation, customer impact from THD depends not only on the magnitude of the exceedance, but also on the time duration (or frequency) of occurrence. Indeed, analyzing both the magnitude and duration of excessive harmonics levels is easier than for voltage, as there is no lower limit to consider. This technique has not been applied as part of this study, as all recorded THD levels are below those required by the regulations/standards, so that the area under the THD – time curve that is beyond the maximum level would be zero. However, with the use of appropriate planning levels, another index for harmonic exceedance could be calculated.

5.10 Conclusions

1. The use of numerical power quality indices to summarise the large amounts of data produced by power quality analysers has been trailed. For each monitored site, 'primary' indices for voltage deviation, voltage unbalance, and THD were calculated. These indices are based on 95% probability values for the respective phenomena over the survey period. The use of 95% values allows the indices to be referenced to the international PQ standards EN50160 and the IEC 61000 series EMC standards. The indices calculated and reporting format used are a further development of techniques conceived by the Integral Energy Power Quality & Reliability Centre at the University of Wollongong, Australia.

2. By normalizing each of the primary indices against a network average value, it was then possible to develop a single overall site PQ index for the survey period. It should be noted that using the average value of the primary indices has the disadvantage that a high level of a particular phenomena type at a site could be masked by low values for the other two primary indices. The overall result is an acceptable site PQ index, and yet the customer is still experiencing a high level of one type of PQ disturbance.
3. The use of secondary indices was trailed. The purpose of the secondary indices is to give a measure of the frequency and magnitude of measured phenomena that exceed predetermined limit values. Limit values used were the result of previous utility power quality surveys in Australia carried out by the Integral Energy Power Quality & Reliability Centre. These values proved to be inappropriate for the Vector survey and the resulting values of the secondary indices (with the exception of the secondary voltage index at one site) were zero. This indicates that the sites never exceeded the limit values. The use of secondary indices certainly has the potential to yield some interesting information regarding the power quality behaviour of a site at its most extreme levels (which are excluded in the calculation of the 95% primary indices). This will require further refinement of the limit values so that they are appropriate relative to the typical disturbance levels experienced on the Vector network.
4. Monthly PQ indices were calculated for each monitored site, and each site was ranked across the network over the 12 month survey period. There was found to be significant month-by-month variation in the ranking. With the possibility that this variation could be due to statistical noise (random infrequent events at a site that are not representative of the overall behaviour), a longer time period for the ranking was appropriate.
5. A three-monthly ‘seasonal’ index was calculated for each site. This was found to give a more consistent ranking of sites across the network, and has the benefit of providing an index that can be tracked from year to year. Seasonal patterns in the levels of voltage unbalance and THD were evident from the seasonal analysis. Additionally, a slight general upward trend of harmonics levels over the survey period was observed.

6. Several techniques for determining an annual overall site PQ index were investigated. Apart from small variations, all methods returned similar index values and similar site rankings across the network (which reinforces the validity of the methods. If there were wide variation in the results, this would raise questions as to validity of any or all of the methods). It was concluded that the most statistically-valid method for deriving an annual index is to analyse the entire 12 months of data as a single survey, rather than splitting the survey into smaller discrete survey periods (seasonal, monthly or daily) and aggregating the results of the smaller survey periods into an annual index.
7. A deficiency in the primary voltage index is that it is based on the absolute value of deviation from the target voltage. As such, it gives no indication whether the voltage deviations are predominantly high, low, or a combination of both. A need for another voltage index was identified. If this index is to be truly representative of customer impact, it should indicate the nature of voltage deviation, its magnitude, and its frequency of occurrence. Several techniques for calculating this 'voltage deviation index' were tested. Calculation of a truly representative and relevant index value is dependent on the use of appropriate reference values and alert values. Determining these values will require further power quality surveys. In the interim, it is suggested that simply expressing the average percentage value of voltage deviation from the target value over the entire survey period will give an adequate indication of the predominant direction (high or low), magnitude, and frequency of occurrence of voltage deviation.

Chapter 6: Power Quality Data – Factor Analysis

6.1 Introduction

One of the problems with carrying out a routine power quality survey (as opposed to a survey in response to a particular problem or customer complaints) on a network is that it is only possible to survey a statistical sample of sites. Instrumentation costs, limitations on data processing, storage capacity, and communications infrastructure all require that power quality can only be monitored at a few sites that are hopefully representative of the overall power quality performance of the network.

Chapter 5 looked at how the data from these sites can be summarised and reported in the form of indices. The network manager can then use these indices to assess the power quality performance of the individual sites and to track trends in performance over time. However, the data obtained from a site is specific to that site. It would be useful to the network manager if the survey results from a particular site could be used to infer the power quality behaviour at other un-monitored sites having similar physical characteristics. This is only possible if it is known which physical characteristics are most influential in determining the power quality levels at a particular site. This requires the application of factor analysis techniques. If it is known which physical characteristics are most influential in determining the levels of particular power quality disturbances, it could be expected that other sites having similar physical characteristics will also exhibit similar disturbance levels.

The overall PQ index for a site is obtained by combining indices for voltage variation, voltage unbalance, and harmonic distortion (THD). It would also be useful to know which of these component factors is most influential in determining the overall PQ index for a site. Is a higher (worse) PQ index for a site typically due to high levels of voltage variation, voltage unbalance, harmonic distortion, or a combination of these factors.

This chapter will look at the levels of component power quality disturbances and the influence of each of these parameters on the overall site PQ index. It will also detail the physical characteristics of the sites that were monitored in this study, and investigate whether any relationship exists between those physical characteristics and the disturbance levels measured at those sites. This chapter will discuss the following influences on overall power quality performance:

- The relationship between individual PQ parameters and the overall PQ index for a site.
- The key physical characteristics of the monitored sites.
- The relationship between these physical characteristics and the overall PQ indices for the sites.
- The relationship between the physical characteristics and the individual PQ parameters of voltage variation, voltage unbalance, and harmonic distortion.

To put it concisely, the aim is find out what it is that makes the good sites good, and what makes the bad sites bad.

6.2 Relationship between individual PQ parameters and overall PQ Index.

The overall annual PQ index for a site is obtained by combining the individual indices for voltage, voltage unbalance and harmonics. Combining the individual indices is achieved by normalising the value of each index for each site against the average value for that index across the network. Using normalized annual site indices, correlation analysis has been used to establish which of the individual indices is most influential in determining the overall PQ index for a site. The results of this analysis are shown in Table 6-1 below:

Table 6-1: Correlation coefficients between individual PQ parameters and site overall PQ indices.

	Voltage Index VI	*Voltage Unbal VUF*	*Harmonics Index HI*	*Overall PQ Index*
Voltage Index VI	1			
Voltage Unbalance Index VUF	0.06978	1		
Harmonics Index HI	0.17703	0.34965	1	
Overall PQ Index	0.61315	0.65404	0.776576	1

As expected, all individual parameters display a positive correlation with the overall site PQ index. The Harmonics Index (HI) shows the strongest correlation with overall PQ index, indicating that it is the harmonic levels at a site that are most influential in differentiating between good sites and bad sites i.e. the sites that have been ranked worst across the network have typically done so due to high harmonic indices more than any other index.

Two of the worst three sites for Harmonics Index are Takanini and Manurewa. Both of these sites also rank in the worst three for overall annual PQ index.

It is also worth noting from Table 6-1 that there is no evidence of any linear association between the levels of voltage variation, voltage unbalance, and harmonic distortion i.e. having a high level of one type of disturbance does not necessarily mean that a site will also have high levels of the other types of disturbances.

6.3 Relationship between physical characteristics of sites and overall PQ index.

As stated earlier, one of the problems with power quality monitoring is that it can only be carried out at a sample of sites. The data obtained from a site will still be specific to that particular site, but it could perhaps be expected that another site having similar characteristics might exhibit similar power quality performance.

Key physical characteristics of the 13 monitored sites on the Vector network have been obtained from Vector, and an attempt has been made to establish whether there is any significant relationship between any of these characteristics and the power quality performance of these sites. For each site, the physical characteristics considered were:

- Fault level (prospective fault level) (MVA)
- Annual maximum demand (half hour average) (MVA)
- Predominant load type (commercial, industrial, residential)
- Total feeder length
- Proportion of overhead lines to underground reticulation

The process of analysing the relationship between each of these characteristics and the annual PQ index for each site is:

Step 1: Carry out correlation analysis of each of these physical characteristics against the overall site PQ indices to determine if a linear relationship exists between them.

Step 2: Carry out multi-variable linear regression analysis on these physical characteristics and the site PQ indices to determine if any statistically-significant relationship exists.

Both the correlation analysis and multi-variable linear regression analysis have been carried out using the data analysis tools in Microsoft Excel®. Another statistics software package called SPSS was also used to verify the outputs obtained using Microsoft Excel®.

The results of the correlation analysis are shown in Table 6-2:

Table 6-2: Correlation coefficients for site physical parameters and annual site PQ Index.

	Load category	*Fault Level (MVA)*	*Max Demand*	*Max Demand/Fault Level*	*Ave. Load Current*	*Length of Feeder*	*% O/Head Lines*	*Annual PQ Index*
Load category	1							
Fault Level (MVA)	0.491239	1						
Max Demand	0.241382	0.79863774	1					
Max Demand/Fault Level	-0.032283	0.45399252	0.89690608	1				
Ave. Load Current	-0.152158	0.13434563	0.04720949	-0.024352053	1			
Length of Feeder	0.8369	0.40107706	0.20124461	-0.027730312	-0.23041	1		
% O/Head Lines	0.469283	-0.0879873	-0.48355018	-0.673481742	-0.2528	0.43150031	1	
Annual PQ Index	0.818901	0.32029151	0.28527088	0.17602702	-0.01813	0.55416962	0.177882	1

The results of this analysis clearly indicate that load category is the most influential parameter in determining the overall PQ index of a site.

The correlation analysis was repeated, this time just looking at the three load categories and the overall site PQ index. The results are shown in Table 6-3.

Table 6-3: Correlation coefficients for site category and annual site PQ index.

	Industrial	*Residential*	*Commercial*	*Annual PQ Index*
Industrial	1			
Residential	-0.69282	1		
Commercial	-0.53936	-0.23355	1	
Annual PQ Index	-0.32652	0.786558	-0.47822	1

Of the three load categories (industrial, commercial, residential), residential shows the strongest correlation with overall PQ index.

To further analyse the relationship between the physical parameters and overall PQ index, multi-variate linear regression techniques were applied. Initial results indicated that length of feeder and percentage of overhead lines had no effect on overall PQ index, and so the process was repeated using the parameters of load type, fault level (MVA), maximum demand (MVA), maximum demand/fault level (sometimes referred to as the 'load ratio', or also 'Electrical Short Circuit Ratio' – ESCR), and average load current. For the purpose of integrating load type into the linear regression, the three load categories of commercial, industrial and residential were allocated numerical values of 1, 2, and 3 respectively, as shown in Table 6-4:

Table 6-4: Preparation of data for multivariate linear regression analysis.

Site	Load Type	Load Value	Fault level (MVA)	Maximum demand (MVA)	Max Dem/Fault Level	Average load current (A)	Annual PQ Index
Bairds	Industrial	2	161	15	0.0932	773.15	0.892
Carbine	Industrial	2	157	22	0.1401	402.10	0.966
Greenmount	Industrial	2	215	35	0.1633	1085.27	1.092
Howick	Residential	3	211	37	0.1753	319.16	1.42
Manurewa	Residential	3	208	45	0.2163	476.75	1.303
McNab	Industrial	2	234	42	0.1795	440.19	0.715
Otara	Industrial	2	170	14	0.0824	401.7	0.783
Quay	Commercial	1	155	27	0.1742	436.92	0.678
Rockfield	Industrial	2	165	19	0.1152	571.88	1.086
Rosebank	Industrial	2	169	25	0.1479	707.71	1.022
Takanini	Residential	3	173	16	0.0925	279.31	1.197
Victoria	Commercial	1	139	24	0.1727	380.14	0.843
Wiri	Industrial	2	221	36	0.1629	446.42	1.003

The results of this analysis are shown below in Table 6-5:

Table 6-5: Results of multi-variate linear regression on site physical parameters and PQ index.

Variable	Coefficient	P-Value
Constant	-3.98	0.058
Load type	0.45	0.00017
Fault level (MVA)	0.021	0.070
Maximum demand (MVA)	-0.146	0.043
Max.demand/fault level	28.099	0.032
Average load	0.00025	0.096
Significance F	0.0023	
Adjusted R value	0.825	

A P-value greater than 0.12 indicates that there is no evidence that the corresponding variable makes any significant difference to the dependent variable (site PQ index) [57]. The P-value is the probability that, if the null hypothesis were true (that the given site physical parameter has no influence on site PQ index), sampling variation would produce an estimate that is further away from the hypothesised value of the data estimate. The P-value measures the strength of the evidence against the null hypothesis. The smaller the P-value, the stronger the evidence against the null hypothesis.

The P-value for all parameters is less than 0.12, which indicates that they all have a significant influence in determining the overall PQ index for a site. Based on the P-values, load category shows the strongest evidence of influence on overall site PQ index, followed by maximum demand/fault level. The Significance F statistic is effectively another P-value indicating whether any of the individual factors are required in the model. The Adjusted R value indicates that 82.5% of the variation in overall site PQ index can be explained by the variation in the individual physical parameters.

Given the very strong evidence of the influence of load type on overall site PQ index, the analysis was repeated with just load category as an input and site PQ index as an output. The results of this analysis are given in Table 6-6:

Table 6-6: Results of linear regression analysis between site load category and site PQ index.

Variable	Coefficient	P-Value
Constant	0.4390	0.0092
Load type	0.284	0.000617
Significance F	0.000617	
Adjusted R value	0.641	

The P-value for load type again indicates the strong evidence of its influence on overall site PQ index. The Adjusted R value in Table 6-6 indicates that 64.1% of the variation in overall site PQ index can be explained by load type.

To determine the effect of each of the three load categories on the overall site PQ index, the multivariate linear regression process was repeated using only the load categories as input data. For the purpose of this analysis, the various load categories were binary coded as shown in Table 6-7. Using this method, it is possible to obtain coefficients and P-values for each of the load categories. Using binary coding, assigning a site a value of 1 for a particular load category means that the value for the other two load categories for that site must be zero. Note that for the purposes of this analysis, the constant term in the regression model has been set to zero. The reason for this is to avoid the software (Microsoft Excel) automatically (and in an apparently arbitrary manner) setting the coefficient of one of the categorical variables to zero. With the coefficient set to zero, it is not possible to obtain a valid P-value for that categorical variable.

Table 6-7: Preparation of load category data for multivariate linear regression analysis.

Site	**Load Type**	**Industrial**	**Commercial**	**Residential**	Annual PQ Index
Bairds	Industrial	1	0	0	0.892
Carbine	Industrial	1	0	0	0.966
Greenmount	Industrial	1	0	0	1.092
Howick	Residential	0	0	1	1.42
Manurewa	Residential	0	0	1	1.303
McNab	Industrial	1	0	0	0.715
Otara	Industrial	1	0	0	0.783
Quay	Commercial	0	1	0	0.678
Rockfield	Industrial	1	0	0	1.086
Rosebank	Industrial	1	0	0	1.022
Takanini	Residential	0	0	1	1.197
Victoria	Commercial	0	1	0	0.843
Wiri	Industrial	1	0	0	1.003

The results of the analysis are given in Table 6-8:

Table 6-8: Results of multi-variate linear regression: site load type and PQ Index.

Variable	Coefficient	P Value
Commercial	0.761	9.39×10^{-6}
Residential	1.310	8.95×10^{-9}
Industrial	0.945	1.77×10^{-9}
Significance F	4.609×10^{-9}	
Adjusted R	0.885	

The P-Values for each of the variables show that there is strong evidence for rejecting the null hypothesis that each of the variables has no effect on the overall site PQ value. The Significance F statistic indicates that there is very strong evidence that at least one of the variables is required in the model. The Adjusted R statistic indicates that 88.5% of the variation in the site PQ index can be explained by the variation in the load category. The values of the coefficients indicate that commercial sites will have the lowest (best) PQ index, followed by industrial sites, with residential sites having the worst PQ index.

Based on this analysis, the model for predicting the value of the PQ index for a site is:

$$\begin{aligned} \textit{Forecast PQ Value} &= 0.761(\textit{commercial}) + 0.945(\textit{industrial}) \\ &\quad + 1.31(\textit{residential}) + e_r \qquad (6-2) \end{aligned}$$

Summary of analysis of relationship between site physical characteristics and overall PQ Index:

1. In terms of the physical parameters of a site on the MV network, the overall PQ index of the site is mostly dependent upon the load type and the load ratio (maximum demand/fault level). The average value of load current also has some influence. The percentage of overhead reticulation (as opposed to underground), and length of feeder have little effect on the PQ index of a site.
2. Of the three categories of load, sites having commercial load type have the best PQ index, followed by industrial. Sites with predominantly residential load have the worst PQ index. This agrees with the ranking of annual PQ index given in Tables 5-2 and 5-3, where Takanini, Manurewa and Howick (all residential load types) have the worst overall PQ indices.
3. It should be noted that these calculations on which these conclusions are based only involve a small number of sites. Surveying over a larger number of sites could result in a different relationship becoming apparent.
4. The Adjusted R value in Table 6-5 indicates that 82.5% of the variation in the value of site PQ index can be explained by the load category, load ratio and load current. This begs the question: ‘what factors explain the other 17.5% of variation? All that can be said conclusively from this analysis is that the load category and load ratio have a very strong influence on the power quality performance of a site, but there are other factors (or combinations of factors)

involved. It may be that a combination of some of the other physical characteristics have some effect on the overall PQ index, but this effect may not be linear. There may be other influential site characteristics that have not been considered in this analysis.

6.4 Relationship between physical characteristics of sites and individual primary PQ indices.

Having investigated the relationship between site physical characteristics and the overall site PQ index, it is also worthwhile looking at the effect of the physical characteristics on the component primary PQ indices (voltage index, voltage unbalance index, and harmonics index).

The process for analysing this relationship is the same as that used for analysing the relationship between the physical characteristics and the overall site PQ Index i.e.

Step 1: Carry out correlation analysis of each of these physical characteristics against the particular component primary index to determine if a linear relationship exists between them.

Step 2: Carry out multi-variable linear regression analysis on these physical characteristics and the particular primary index to determine if any statistically-significant relationship exists.

6.4.1 Voltage Index:

1. Correlation analysis between each of the physical characteristics and the corresponding Voltage Index. The results are given in Table 6-9:

Table 6-9: Correlation between site physical characteristics and annual Voltage Index (significant statistics in bold).

	Load Type	*Fault Level (MVA)*	*Max Demand*	*Max Dem/Fault Level*	*Ave. Ld Current*	*Feeder length*	*% O/H Lines*
Load Type	1						
Fault Level (MVA)	0.491239	1					
Max Demand	0.241382	0.798638	1				
Max Demand/Fault Level	-0.03228	0.453993	0.896906	1			
Ave. Ld Current	-0.15216	0.134346	0.047209	-0.02435	1		
Feeder length	**0.8369**	0.401077	0.201245	-0.02773	-0.23041	1	
% O/H Lines	0.469283	-0.08799	-0.48355	-0.67348	-0.2528	0.4315	1
Ann. VI Index	**0.6535**	0.1400	-0.0388	-0.1877	-0.3890	0.3870	0.5152

From Table 6-9, the only physical characteristic that shows any significant correlation with the Voltage Index is the load type. This is the same result as for the site overall PQ index. It is also interesting to note the correlation between load type and length of feeder. Residential sites typically have longer feeders due to the lower load density. Surprisingly, in earlier analyses, feeder length does not appear to be a significant physical characteristic in determining PQ levels, but load category is the most significant characteristic.

2. Multivariate linear regression analysis between the physical characteristics and Voltage Index. The results of this analysis were:
   - No clear linear relationship was evident between the combined physical characteristics and the site Voltage Index.
   - No clear linear relationship was evident between any of the individual physical characteristics and the site Voltage Index.

6.4.2 Voltage Unbalance Index:

1. Correlation analysis between each of the physical characteristics and the corresponding Voltage Unbalance index for each site. The results are given in Table 6-10:

Table 6-10: Correlation between site physical characteristics and annual Voltage Unbalance Index (VUF).

	Load Type	Fault Level (MVA)	Max Demand	Max Dem./Fault Level	Ave. Load Current	Length of Feeder	% O/Head Lines
Load Type	1						
Fault Level (MVA)	0.4913	1					
Max Demand	0.2414	0.7986	1				
Max Dem./Fault Level	-0.03228	0.4540	0.8969	1			
Ave. Load Current	-0.15216	0.1343	0.0472	-0.0244	1		
Length of Feeder	0.8369	0.4011	0.2012	-0.0277	-0.23041	1	
% O/Head Lines	0.4693	-0.0880	-0.4836	-0.6735	-0.2528	0.4315	1
Annual VUF Index	0.4652	0.2663	0.3933	0.3954	0.0123	0.3470	-0.3326

Table 6-10 again shows a relationship between load type and length of feeder. There is no evidence of a linear relationship between any of the physical characteristics and the annual Voltage Unbalance Index.

2. Multivariate linear regression analysis between the physical characteristics and Voltage Unbalance Index. The results of this analysis are given in Table 6-11:

Table 6-11: Results of multi-variate linear regression of site physical characteristics and Voltage Unbalance Index.

Variable	Coefficient	P Value
Constant	-3.1886	0.2273
Load type	0.2844	0.0483
Max. demand	-0.1221	0.1744
Max.demand/fault level	22.094	0.1746
Ave. load current	5.71E-05	0.7630
Length of feeder	0.0002	0.8387
% Overhead	-0.5091	0.1361
Significance F	0.169	
Adjusted R	0.461	

There is no clear evidence of a linear relationship between site physical characteristics and Voltage Unbalance index. The Significance F statistic of 0.169 indicates that none of the individual characteristics are essential in the model. The P-Value for load type indicates that this has the most influence on site unbalance index. This is to be expected, considering that residential load will mostly consist of small single phase installations where it is much harder to balance the loading across the three phases, compared to larger commercial or industrial installations that typically have a three phase supply.

The percentage of overhead lines, and the ratio of maximum demand to fault level have no apparent effect on voltage unbalance. Looking at site voltage unbalance indices across the different load types, commercial is best, followed by industrial, and residential is worst.

6.4.3 Harmonics Index:

1. Correlation analysis between each of the physical characteristics and the corresponding Harmonics Index for each site. The results are given in Table 6-12 below:

Table 6-12: Results of multi-variate linear regression of site physical characteristics and Harmonics Index.

	Load Type	*Fault Level (MVA)*	*Max Demand*	*Max Dem/Fault Level*	*Ave. Load Current*	*Length of Feeder*	*% O/Head Lines*
Load Type	1						
Fault Level (MVA)	0.4912	1					
Max Demand	0.2414	0.7986	1				
Max Dem./Fault Level	-0.0323	0.4540	0.8969	1			
Ave. Load Current	-0.1522	0.1343	0.0472	-0.0244	1		
Length of Feeder	0.8369	0.4011	0.2012	-0.0277	-0.2304	1	
% O/Head Lines	0.4693	-0.0880	-0.4836	-0.6735	-0.2528	0.432	1
Annual HI Index	0.4688	0.0505	-0.0697	-0.1701	0.5701	0.367	0.1746

From Table 6-12, there is no evidence of any linear relationship between any one of the site physical characteristics and the site Harmonics Index.

2. Multivariate linear regression analysis between the site physical characteristics and Harmonics Index. Initial analysis indicated that there is no relationship between site annual Harmonics Index and length of feeder or percentage of overhead lines. These two factors were eliminated from the analysis, leaving load type, maximum demand (MVA), maximum demand/fault level, and average load current as the input factors. The results of this analysis are given in Table 6-13.

Table 6-13: Results of multi-variable linear regression considering site physical characteristics and Harmonics Index.

Variable	Coefficient	P Value
Constant	6.787	0.522
Load type	1.088	0.018
Fault level	-0.048	0.4139
Max. demand	0.200	0.571
Max.demand/fault level	-33.068	0.599
Average load current	0.003	0.004
Significance F	0.021	
Adjusted R	0.658	

Based on the P-values for each of the parameters, the above results suggest that load type and average load current have a significant influence on the Harmonics Index for a site. Average load current shows the strongest evidence of influence on site Harmonics Index, followed by load category.

The analysis was repeated, this time using only the three load categories (commercial, industrial and residential) as the inputs for the regression analysis. For this analysis, the constant term was set to zero so that relative coefficients and valid P-values could be obtained for each of the categorical variables. Results are given in Table 6-14.

Table 6-14: Results of multi-variable linear regression considering site load type and Harmonics Index.

Variable	Coefficient	P Value
Commercial	1.6245	0.025
Residential	3.007	0.0001
Industrial	2.533	9.164×10^{-6}
Significance F	2.21×10^{-5}	
Adjusted R	0.800	

Industrial load type shows the strongest evidence of a relationship with Harmonics Index. The Adjusted R value indicates that variation in load type explains 80% of the variation in site Harmonics Index. Based on the coefficients, commercial sites would be expected to have the lowest Harmonics Index, followed by industrial sites. Residential sites would have the highest Harmonics Index. This initially seems a surprising result. It might be expected that industrial sites that would typically have a significant proportion of distorting loads (variable speed drives, d.c. supplies, computers etc.) would have higher Harmonics Indices than residential sites. However, it has been found that voltage THD tends to be highest during times of low linear loading, typically at night and during the early morning hours on residential feeders [26].

Comparing the results of Table 6-14 with those of Table 6-13, it appears that while load type has a large influence on Harmonics Index, a significant amount of variation in the Harmonics Index is also explained by the value of average load current at the site.

6.4.4 Summary of analysis of relationship between site physical characteristics and individual PQ Indices (Voltage Index, Voltage Unbalance Index, Harmonics Index):

1. For each of the individual PQ indices (VoltageIndex, Voltage Unbalance index, Harmonics Index) that are components of the overall PQ index of a site, the relationship between the indices and specified physical characteristics was analysed. The site physical characteristics under consideration were load

category, maximum demand, maximum demand/fault level, average load current, length of feeder, and percentage of overhead lines.

2. Load category (commercial, industrial, residential) is the only physical parameter that appears to have any significant influence on determining the Voltage Index of a site.
3. There is no clear relationship between site Voltage Unbalance index and any of the site physical characteristics under consideration. Neither correlation nor multivariate linear regression analysis produce any evidence that the measured level of voltage unbalance at a site is affected by the physical characteristics considered.
4. Correlation analysis of site harmonics indices showed no linear relationship between any one of the physical characteristics and the harmonics index. The results of the multi-variate linear regression analysis indicated that load category and average load current are the main physical characteristics that influence the site Harmonics Index.

6.5 Conclusions from factor analysis of PQ data.

1. Of the three component indices (Voltage Index, Voltage Unbalance Index, and Harmonics Index) that combine to give the overall site PQ index, harmonics index is the most influential in discriminating between sites having a high or low overall PQ index. Where a site had a higher (worse) overall PQ index, it was usually due to that site having a high Harmonics Index.
2. There is no evidence of correlation between the component indices. For example, if a site has a high Voltage Index, it does not imply that it will also have poor voltage unbalance or harmonics levels.
3. Load type and load ratio (maximum demand/fault level) are the most influential physical characteristics in determining the overall site PQ Index. 61.4% of the variation in overall site PQ index over the 13 sites can be explained by the load type and load ratio. Of the three load categories (commercial, industrial, residential), commercial typically has the lowest PQ index, followed by industrial, with residential sites being worst.

4. The conclusions of this study are based on a small sample of sites with instances of missing data. Expanding the number of sites in the survey and having a more complete data sample could change the results of the analysis significantly.

Chapter 7: Thesis Conclusions and Future Work

7.1 Conclusions from research

This research project started out with two main research questions:

1. What are the best methods for analysing and reporting data from a power quality survey?
2. What can we find out by analysing power quality data from the Vector network?

With no prior knowledge of the power quality levels on the Vector network and in the absence of any particular power quality problems to investigate, the approach taken was to start with a preliminary study of the data and attempt to identify any significant trends or abnormalities in the data that might warrant further investigation.

A literature review on the topic of power quality for electricity utilities was conducted to identify current best practice in the implementation, analysis and reporting of power quality surveys. The purpose of the literature review was also to determine whether existing methods of power quality data analysis and reporting meet the needs of Vector Ltd. The review included national and international power quality standards and regulations documents. The main points that were highlighted from this literature review were:

- While there is no standard practice in the implementation of utility routine power quality surveys, there is a common philosophy of monitor site location choice so as to achieve results representative of the network as a whole.
- Current methods of power quality data analysis and reporting do not fully meet the needs of Vector Ltd. Indices in common use do not adequately represent the customer impact of supply disturbances. The lack of standardisation in reporting methods means that network disturbance levels cannot be easily compared between utilities.
- Results of utility power quality surveys are not widely available in the public domain. This is probably due to the commercial sensitivity of the material. The results of some surveys are available at significant cost.
- Well-established international standards exist that specify limit values for all types of power quality phenomena. However, there is some variation in the

values specified in the different standards, and this has led to some confusion by utilities as to which standard they should be conforming to, and the exact requirements of the standards. There is considerable debate regarding the suitability of some of the standards and the measurement and analysis techniques that are described therein. A number of alternative indices have been proposed. It is unlikely that any of these alternatives will become widely used unless they are incorporated into international standards.

- There is currently little standardisation in the reporting of the results of power quality surveys. Such standardisation is necessary to facilitate benchmarking of results between different utilities.
- A US national power quality survey identified annual trends in harmonic distortion levels that support the findings of the Vector survey. The finding of the Vector study that harmonic distortion has the most influence on overall PQ levels is also supported by a number of research papers.

International and national power quality standards have been investigated and discussed in Chapter 3. While New Zealand has adopted the IEC 61000 series EMC standards, maximum disturbance levels for some power quality phenomena are also specified in the New Zealand Electricity Regulations and the Electricity Governance Rules. There are some inconsistencies in the performance requirements specified in these documents. The levels of voltage variation, voltage unbalance and THD at the monitored sites on the Vector network have been assessed against the relevant limit values. All sites conformed to the AS/NZS 61000 standard requirements. The maximum limit levels quoted in the NZ Electricity Regulations apply to the customer PCC at a nominal voltage of 230/400V, and so cannot be applied to the MV distribution system. It should also be noted that the NZ regulations do not explicitly state any allowance for levels during conditions beyond the control of the network operator (unlike the AS/NZS standards that only require measured levels to be within the specified limits for 95% of the time).

Methodologies for carrying a routine power quality have been described in more detail in Chapter 4 – Power Quality Monitoring and Instrumentation. The methodology used by Vector has been assessed against the requirements of the relevant standards, including instrumentation requirements. It was found that the monitoring instruments being used by Vector are adequate for a statistical survey, but do not have the required accuracy to establish conformance with standards. There is also a problem with missing data. Some sites do not have any (or incomplete) data for significant parts of the survey duration, and this does compromise the validity (or at least the robustness) of the results of the data analysis.

The monthly summary report that is produced for each site currently includes logged entries of discrete PQ events, and displays these events overlaid on a plot of the ITIC electrical equipment immunity reference curve. Trend lines of measurements are also plotted against time. It is recommended that the monthly summary report should include calculation of 95% cumulative probability values for continuous disturbances, so that these can be assessed against limit values specified in standards documents.

Chapter 5 describes the analysis techniques used to summarise the large amount of raw data that was acquired during the survey period. Early in the project it was decided to limit the scope of the project to the continuous disturbance types of voltage variation, voltage unbalance and harmonic distortion. The analysis techniques used are based on those developed by the Integral Energy Power Quality & Reliability Centre at the University of Wollongong. These techniques are based upon the requirements of the IEC 61000 EMC standards, which have been adopted by Australia and New Zealand (cloned as the AS/NZS 61000 series standards). For each site, monthly indices for voltage, voltage unbalance and harmonic distortion have been calculated. A proposal for calculation of seasonal and annual site indices has been proposed and trialled in this study. A universal index which represents the overall PQ performance of a site has also been proposed and applied to the Vector data. The indices have been used to rank the 13 monitored sites on the Vector network relative to the overall PQ level.

The use of secondary indices (as proposed by the Integral Energy Power Quality & Reliability Centre) was also trialled. The purpose of these secondary indices is to give a measure of the excessiveness of the extreme values that fall outside specified planning levels. It was found that for all disturbance types that deviations beyond the suggested levels were insignificant. This suggests that urban sites on the Vector network that were the subject of this study are all relatively ‘strong’ and experience relatively low levels of continuous voltage variation. While the use of secondary indices has the potential to yield useful information, further refinement of the planning levels will be required if the process is to be applied to data from the Vector network. Alternatively, the use of secondary indices may prove to be more useful if applied to less dense suburban and rural parts of the network where there are typically higher levels of voltage variation.

Shortcomings in the voltage index were identified and an alternative index has been proposed which is based on both the magnitude and duration of voltage disturbance beyond specified planning levels. Application of this index to the Vector data indicates that the principle is sound but further refinement of the planning levels is required to produce a meaningful index.

Factor analysis has been applied to the Vector data in chapter 6. The aim of the factor analysis was to answer two questions:

1. Of the three continuous PQ disturbance types included in this study (voltage variation, voltage unbalance, harmonic distortion), which one has the most influence in determining the overall PQ performance of a site?
2. Which of the known physical characteristics of a site has the most influence in determining the overall PQ performance of a site?

Correlation and multi-variable linear regression methods were applied to attempt to answer these two questions.

It was found that harmonic distortion levels show the strongest correlation with the overall PQ index of sites. Where a site had a higher (worse) overall PQ index, it was mainly due to that site having a high harmonics index. There is no evidence of correlation between the component indices for voltage, voltage unbalance and harmonics, indicating that if a site has high levels of one type of disturbance, it will not necessarily have high levels of the other disturbance types.

With regard to the physical characteristics of a site, load type and load ratio were found to be the most influential factors in determining the overall PQ index of a site. Of the three load categories (commercial, industrial and residential), commercial typically has the lowest (best) PQ index, followed by industrial, with residential sites being worst. It should however be noted that these conclusions are based on a small sample of sites, some of which have incomplete data. Expanding the survey to a larger number of sites and analysing data over a longer time period could change the results of this analysis.

This project has successfully demonstrated that information of considerable use can be obtained by the analysis of continuous PQ phenomena data. Effective methods for summarising and reporting of continuous disturbance levels have been demonstrated. Continuous disturbance levels can be assessed against relevant standards and regulations. Site indices can be used to rank sites across a network to assist in the prioritising of remedial work. Site indices for voltage, voltage unbalance and harmonics can be combined to give a relative measure of overall PQ performance at a site. This combined index can likewise be used to rank sites across a network. Statistical techniques have been applied to determine the influence of individual disturbance types on the overall PQ performance of a site, and the relative influence of the known physical characteristics on PQ performance has been determined.

7.2 Future Work

While this study has provided answers to the research questions defined in this thesis, it has raised a number of other questions. There is also a need for further research to determine whether some of the findings of this study hold true over a longer period of analysis.

A number of inconsistencies and deficiencies have been identified in existing PQ standards and regulations. There is potential for the results of on-going PQ data analysis to be used to influence the development and implementation of PQ standards in New Zealand and internationally.

Analysing power quality data in the manner used in this study is a very time-consuming activity. Automation of the data analysis procedures employed in this study would enable Vector to produce meaningful reports that quantify the levels of continuous PQ disturbances on the network. This would enable easy assessment of the disturbance levels against limits specified in standards. It would also enable the easy tracking of trends in PQ levels over time.

The Vector Distribution Code makes reference to applicable New Zealand standards and regulations. While there is no explicit reference to Vector-specific internal planning levels, it is implied that the planning levels recommended in the relevant standards and regulations are applied by Vector. These planning levels may or may not be suitable for the Vector network. Establishing appropriate planning levels will give Vector clear PQ objectives beyond simply conforming to the standards (given that the limit values given in standards are compatibility levels, and as such represent a worst-case situation). Application of internal planning levels could be via the secondary index values described in this thesis. The secondary index limit values applied in this study were clearly not appropriate for the Vector network. Further work is required to determine appropriate limit values for these secondary indices. Clearly defined internal planning levels could also be applied in the implementation of the alternative voltage index (Voltage Deviation Index) as proposed in this thesis. A similar algorithm could be applied in the development and implementation of an alternative harmonic distortion index.

There is the possibility that the PQ survey analysis and reporting methodology used in this study could be extended to include other electricity utilities in New Zealand. Provided that there is consistency in measurement, analysis and reporting methods, this would enable the benchmarking of typical disturbance levels on New Zealand electricity distribution networks. This information can then be fed back to the regulatory body to ensure that realistic and achievable PQ performance standards can be developed.

It would be worthwhile to extend this study of PQ data from the Vector network over a longer time period. The data used in this study covered one full year. This may or may not have been a typical year in terms of power quality performance. Extending the study over a longer time period would enable the identification of longer-term trends, and can establish whether the results obtained from the 2003-2004 study are typical. This study suffered from numerous examples of missing or incomplete data from some sites. Extending the study over a longer time period will increase the total amount of data being analysed and will help to reduce the likelihood of missing, incomplete or abnormal data skewing the analysis. A study that extends over several years will enable the network manager to track network PQ levels over a longer period of time. The effects of changes in the network (network improvements, changes in loading levels, increase in proportion of non-linear load) can be assessed and tracked over time.

A significant aspect of the Vector power quality survey is that monitoring is taking place at the MV level. It has yet to be determined whether PQ disturbance levels measured at the MV level are representative of disturbance levels for customers connected at LV. Connection of PQ monitors at LV downstream of existing MV monitors would enable comparison of disturbance levels between MV and LV. While there has been some research into the propagation of disturbance levels through distribution networks, it is still not possible to quantify LV disturbance levels based on measurements made at MV.

This scope of this study has been restricted to continuous power quality disturbances. Given that both utilities and their customers tend to be more concerned about discrete disturbances (voltage sags/swells, transients), it would be worthwhile carrying out in-depth analysis of discrete disturbance data from the Vector network.

It is to be hoped that Vector's commitment to the monitoring of power quality will continue. As more monitoring sites are included and more data is amassed over time, a more complete picture of network power quality performance will become obtainable. The increase in non-linear loads and the increased susceptibility of customer equipment to supply disturbances ensures that the study of power quality for electricity networks will continue to be an essential part of their operation in future.

Bibliography

[1] Martzloff F., Power Quality Work at the IEC, Proceedings of PQA'97 Europe, Stockholm 1997

[2] Dugan R., McGranaghan M., Beaty H., Electrical Power Systems Quality, McGraw Hill, New York, ISBN 0-07-018031-8

[3] Smith V., Gosbell V., Introduction to Power Quality Issues, Integral Energy Power Quality Centre, University of Wollongong, EEA Quality of Electrical Supply training course, June 2004 Christchurch New Zealand

[4] Brooks D., Dugan R., Waclawiak M., Sundaram A., Indices for Assessing Utility Distribution System RMS Variation Performance, IEEE Transactions on Power Delivery, Vol.13, No.1, January 1998

[5] Rauch G., Sabin D., McGranaghan M., Sundaram A., Implementing System-Wide Power Quality Monitoring Plans, IEEE Transmission & Distribution Conference Proceedings 1996 pp37-44

[6] Sabin D., Grebe T., Sundaram A., RMS Voltage Variation Statistical Analysis for a Survey of Distribution System Power Quality Analysis, IEEE 1998

[7] Gosbell V., Smith V., Barr R., Perera B. S. P., A Methodology for a National Power Quality Survey of Distribution Networks, Journal of Electrical & Electronic Engineering, Australia, 2002, Vol.21, No.3, pp.181-188

[8] Roman T.G.S., Ubeda J., Power Quality Regulation in Argentina: Flicker and harmonics, IEEE Transactions on Power Delivery, Vol.13, No.3, July 1998, pp.895-901

[9] Eassa N., Prediction of Electrical Power Quality Disturbances Using State Estimation Techniques, CIRED 2005 – Round Table on Lightning Protection of MV and LV Lines, Torino, June 2005

[10] Gosbell V., Robinson D., A study of Continuous PQ Disturbance Levels in MV/LV Distribution Systems, CIRED 17th International Conference on Electricity Distribution, Barcelona May 2003

[11] Sabin D., Advantages and Drawbacks of Permanent PQ Monitoring, CIRED 2005 – Proceedings of Session 2 – Power Quality & EMC Q9.1, Torino June 2005

[12] Kandil M., Farghal S., Elmitwally A., Refined Power Quality Indices, IEEE Proceedings on Generation & Transmission, Vol.148, No.6, November 2001

[13] Baran M., Kim J., Hart D., Lubkeman D., Lampley C., Newell W., Voltage Variation Analysis for Site-Level PQ Assessment, IEEE Transactions on Power Delivery, Vol.19, No.4, October 2004

[14] Lin T., Domijan A., On Power Quality Indices and Real Time Measurement, IEEE Transactions on Power Delivery, Vol.20, No.4, October 2005

[15] Terzija V., Stanojevic V., Power Quality Indices Estimation Using Robust Estimation Approach, Electrical Engineering Journal (2005) 87: 173 - 179

[16] Bingham R., Kreiss D., Santoso S., Advances in Data Reduction Techniques for Power Quality Instrumentation, http://www.dranetz-bmi.com/pdf/datareduction.pdf

[17] Anbalagan P., Vasantharathna S., Ashok A., Web Based Power Quality Monitoring and Control, IEEMA Journal, September 2004

[18] Abdel-Galil T., Saadany E., Yousef A., Salama M., Disturbance Classification using Hidden Markov Models and Vector Quantisation, IEEE Transactions on Power Delivery Vol.20, No.3, July 2005

[19] Joint Working Group Cigre C4.07/Cired, Power Quality Indices and Objectives – Final WG Report January 2004

[20] Styvaktakis E., Bollen M., Gu I., Expert System for Classification and Analysis of Power System Events, IEEE Transactions on Power Delivery, Vol.17, No.2, April 2002

[21] Gosbell V., Robinson D., Perera S., The Analysis of Utility Voltage Sag Data, Proc. International Power Quality Conference, October 2002, Singapore pp. 479-490

[22] Brooks D., Dugan R., Waclawiak M., Sundaram A., Indices for assessing utility distribution system rms variation performance, IEEE Transactions on Power Delivery 1998

[23] IEC Standard for Electromagnetic Compatibility (EMC) – part 4-30: Testing and Measurement Techniques – Power Quality Measurement Methods, IEC 61000-4-30: 2003

[24] Gosbell V., Perera S., Barr R., Baitch A., Primary and Secondary Indices for Power Quality (PQ) Survey Reporting, Proc. ICHQP 2004, September 2004, Lake Placid USA, Paper 93

[25] AS/NZS Standard for Electromagnetic Compatibility (EMC) – part 4-7: Testing and Measurement Techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto, AS/NZS 61000.4.7:1999

[26] Sabin D., Brooks D., Sundaram A., Indices for Assessing Harmonic Distortion from Power Quality Measurements: Definitions and Benchmark Data, IEEE Transactions on Power Delivery, 1999 (on-line version accessed: http://www.ccu2.org/harmind.pdf)

[27] Overview of the EPRI Distribution System Power Quality Project: www.electrotek.com/projects/dpq/dpq.htm

[28] Heydt G., Jewell W., Pitfalls of Electric Power Quality Indices, IEEE Transactions on Power Delivery, Vol.13, No.2, April 1998

[29] Farghal S., Kandil M., Elmitwally A., Quantifying electric power quality via fuzzy modelling and analytic hierarchy processing, IEEE Proceedings on Transmission and Distribution, Vol.149, No.1, January 2002

[30] Gosbell V., Perera B.S.P., Herath H., Unified Power Quality Index (UPQI) for Continuous Disturbances, Proceedings ICHQP 2002

[31] Gosbell V., Robinson D., Barr R., Smith V., How Should Power Quality be Reported, Proc.EESA Annual Conference, Electricity 2002, August 2002, Canberra Australia

[32] Elphick S., Gosbell V., Barr R., Reporting and Benchmarking for Power Quality Surveys

[33] Institute of Electrical and Electronic Engineers (IEEE, U.S): www.standards.ieee.org

[34] IEC (International Electrotechnical Commission): www.iec.ch

[35] CENELEC – European Committee for Electrotechnical Standardisation: www.cenelec.org

[36] EURELECTRIC/UNIPEDE: www.unesco.org/uati/associations/associationseng/unipedeng.htm

[37] CIRED: www.cired.be

[38] CIGRE: www.cigre.org. Study committee C4: www.cigre-c4.org

[39] ANSI (American National Standards Institute): www.ansi.org

[40] EPRI (Electric Power Research Institute): www.epri.com

[41] NEMA (National Electrical Manufacturers Association): www.nema.org/stds

[42] ITIC (Information Technology Industry Council: www.itic.org and INCITS (International Committee for Information Technology Standards): www.incits.org

[43] Bollen, M. J. Understanding Power Quality Problems, IEEE Press Series 2000, ISBN 0-7-803-4713-7

[44] New Zealand Electricity Governance Rules, www.electricitycommission.govt.nz/pdfs/rulesandregs/rules/rulespdf/partC-19-May-05.pdf

[45] New Zealand Electricity Regulations 1997, www.ess.govt.nz/rules/pdf/electricity_regulations_1997.pdf

[46] New Zealand Electrical Codes of Practice NZECP36 (1993), www.ess.govt.nz/rules/pdf/nzecp36_1993.pdf

[47] AS/NZS 61000.2.2:2003: Environment – compatibility levels for low-frequency conducted disturbances and signalling in public low voltage power supply systems

[48] AS/NZS 61000.3.6: Limits – Assessment of emission limits for distorting loads in MV and HV power systems.

[49] AS/NZS 61000.3.7: Limits – Assessment of emission limits for fluctuating loads in MV and HV power systems

[50] Vector Distribution Code (no source or URL available)

[51] Gosbell V., Mannix D., Robinson D. & Perera S., Harmonic Survey of an MV Distribution System, Proceedings of Australasian Universities Power Engineering Conference, Perth, September 2001

[52] Power Measurement Ltd website: www.pwrm.com/products/IONEEM/applications

[53] Data sheet for ION 7700 Energy and Power Quality Meter, Power Measurement Ltd, January 2002 (Product and Application Guide CD)

[54] Australian National Power Quality Benchmarking Survey, conducted by the Integral Energy Power Quality & Reliability Centre, University of Wollongong

[55] Integral Energy Power Quality & Reliability Centre Technical Note 6: Voltage Unbalance, http://www.elec.uow.edu.au/iepqrc/files/technote6.pdf

[56] Integral Energy Power Quality & Reliability Centre website: www.elec.uow.edu.au/iepqrc

[57] Wild C., Seber G., Chance Encounters – A first course in data analysis and inference. University of Auckland. John Wiley & Sons, Inc., 2000
ISBN 0-471-32936-3

Appendix A: Additional Power Quality Standards

Table 1: IEEE 1159-1995 Standard

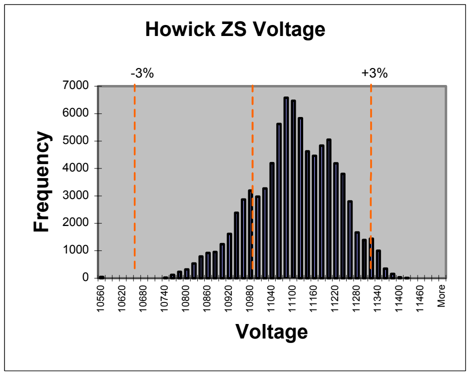
Categories	Typical duration	Typical voltage magnitude
Transients Impulsive Oscillatory	 50 ns< duration <1ms 3ms< duration < 5µs	 0-8 pu
Short duration variations: Instantaneous Sag Swell Momentary Interruption Sag Swell Temporary Interruption Sag Swell	 0.5 – 30 cycles 0.5 – 30 cycles 0.5 cycles – 3 sec 30 cycles – 3 sec 30 cycles – 3 sec 3 sec – 1 min 3 sec - 1 min 3 sec – 1 min	 0.1 – 0.9 pu 1.1 – 1.8 pu Less than 0.1 pu 0.1 – 0.9 pu 0.2 1.1 – 1.4 pu Less than 0.1 pu 0.1 – 0.9 pu 1.1 – 1.4 pu
Long duration Variations Sustained Interruption Undervoltage Overvoltage	 Longer than 1 min Longer than 1 min Longer than 1 min	 0.0 pu 0.8 – 0.9 pu 1.1 – 1.2 pu
Voltage unbalance	Steady-state	0.5 – 2%
Waveform distortion DC offset Harmonics Inter-harmonics Notching Noise	 Steady-state Steady-state Steady-state Steady-state Steady-state	 0.0 – 0.1% 0.0 – 20% 0.0 – 2.0% 0.0 – 1.0%
Voltage fluctuations	Intermittent	0.1 – 7%
Power frequency variations	Less than 10 sec	

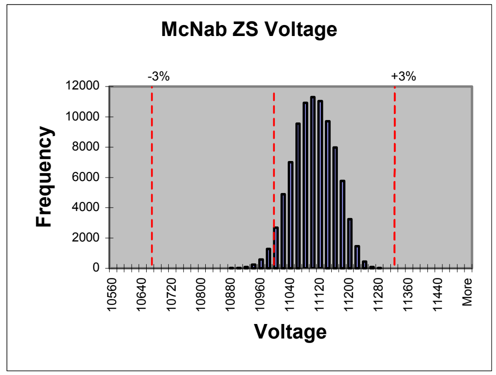
Table 2: Summary of CENELEC EN 50160.

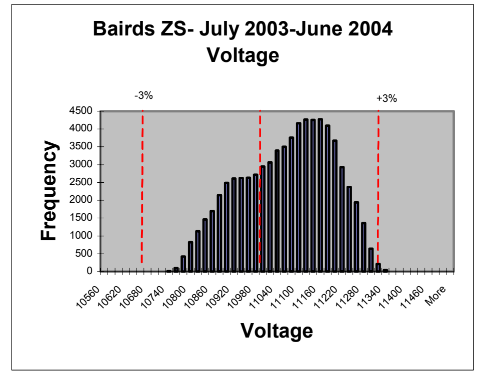
Disturbance type	Limit
Frequency	±1% for 99% of the year; ±6% for 1% of the year
Voltage	Within ±10% from nominal for 95% of any 10 minute mean
Unbalance	20 min rms value no more than 2% for 95% of a 24 hour period
Harmonics · Triplen harmonics · Odd non-triplen harmonics · Even harmonics · THD	95% of the 10 minute mean values to be within the values in Table 1 of the CENELEC document 5-0.5% for 3rd harmonic and greater 6% - 1.5% for 5th –23rd harmonics 2-0.5% for 2nd harmonic and greater 8%
Voltage fluctuations	$P_{lt} \leq 1$ for 95% of a week
Voltage sags	Frequency 10's –1000/year; most will have a depth of less than 60% and a duration of less than 0.5 sec
Short term interruptions Long term interruptions	10's –100's /year; 70% will have a duration of less than 1 sec frequency 10 – 50 /year
Transient overvoltage Live conductor/earth	Transients with rise times of µs – ms with a peak not exceeding 6kV

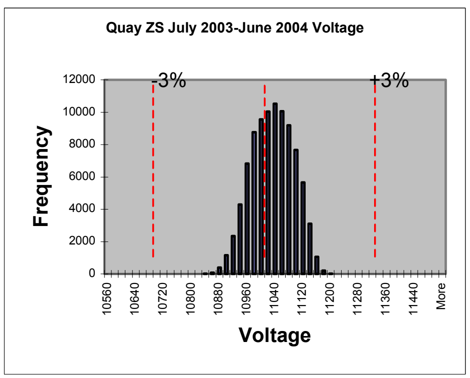
Appendix B:

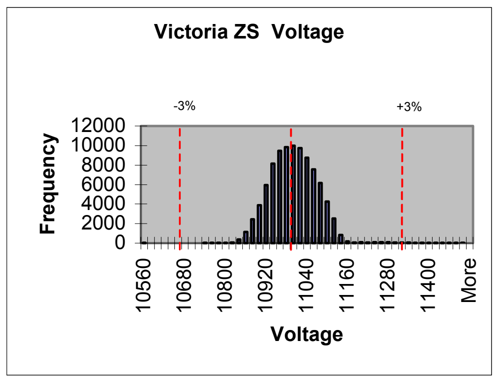
Voltage distribution histograms for monitored zone substations on the Vector network. Dotted lines indicate the nominal (target) value of voltage and proposed planning level variation limits of ± 3%.

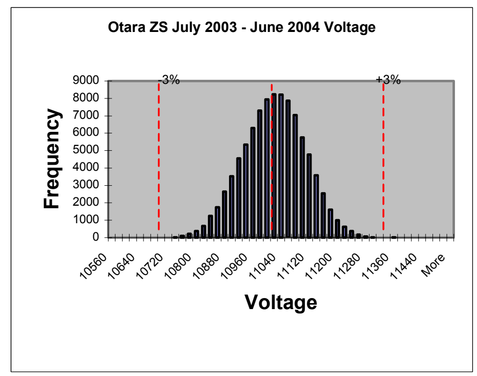


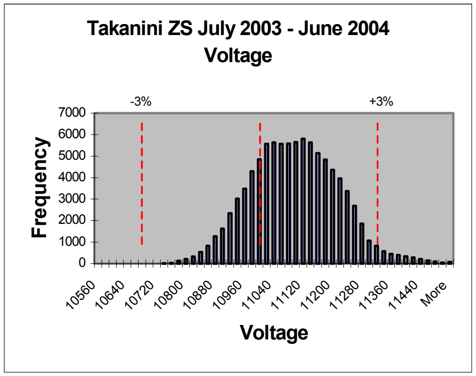


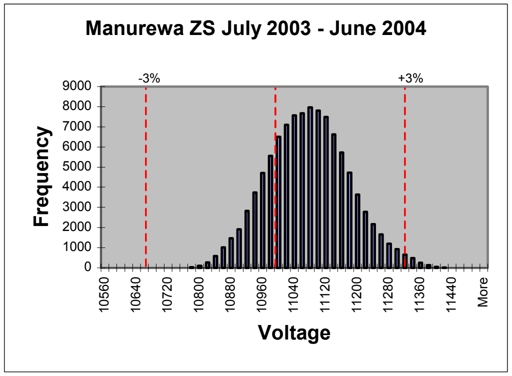


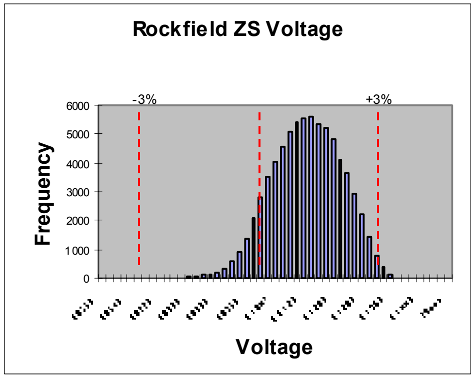


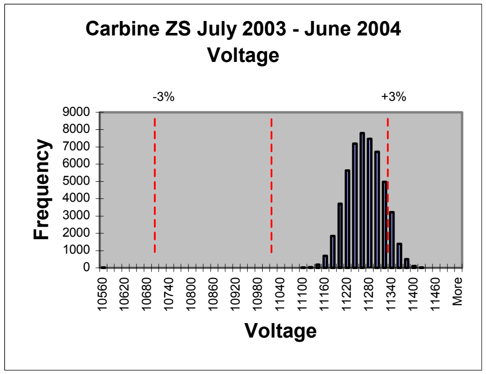


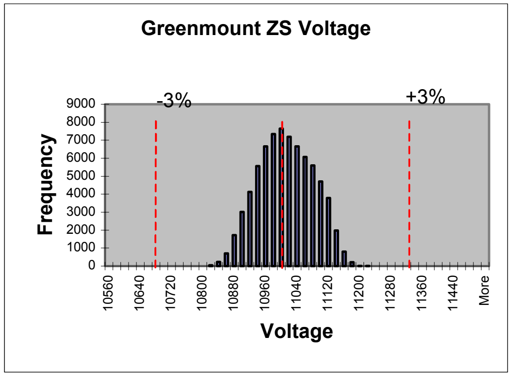


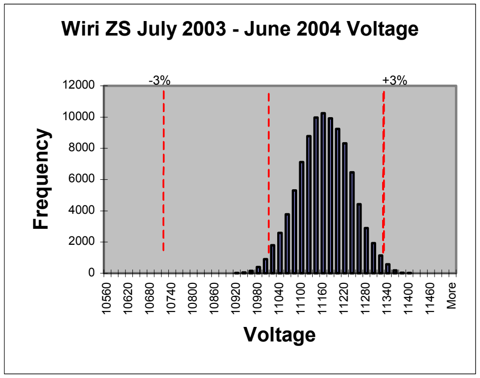

Takanini ZS July 2003 - June 2004 Voltage
Frequency
Voltage
-3%
+3%

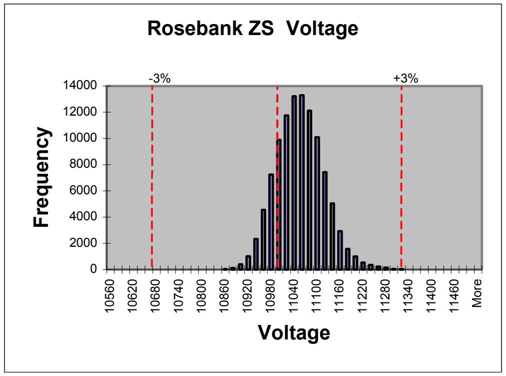

Manurewa ZS July 2003 - June 2004
Frequency
Voltage
-3%
+3%


Rockfield ZS Voltage
Frequency
Voltage
-3%
+3%

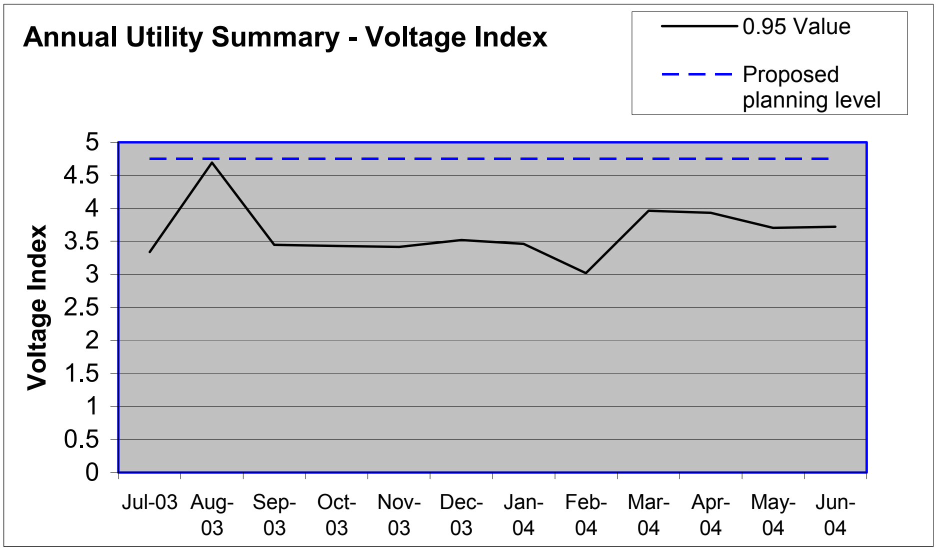

Carbine ZS July 2003 - June 2004 Voltage
Frequency
Voltage
-3%
+3%


Greenmount ZS Voltage
Frequency
Voltage
-3%
+3%


Wiri ZS July 2003 - June 2004 Voltage
Frequency
Voltage
-3%
+3%


Rosebank ZS Voltage
Frequency
Voltage
-3%
+3%
14000
12000
10000
8000
6000
4000
2000
0
10560
10620
10680
10740
10800
10860
10920
10980
11040
11100
11160
11220
11280
11340
11400
11460
More

Appendix C: Annual Trend of Utility Voltage Index



Explanatory notes:

- Site Voltage Index $VI = \frac{|V - V_{float}|}{V_{float}} \times 100\%$
- Monthly Utility Voltage Index is the 95th percentile value of the individual site VIs.
- Ideal value for both site and utility voltage index is zero (if measured voltage is always exactly equal to float voltage).
- There is no existing limit value for a utility index in the standards or regulations.
- Suggested planning level given is 4.75%. This is based on the NZ Electricity Regulations requirement that voltage supply at a voltage other than the standard low voltage values of 230/400V be within ±5% of the agreed voltage. The NZ regulations do not quote 95% values, so the ±5% limit has been taken as the maximum variation. Taking a 95% value of 5% gives a planning level of 4.75%.