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The Australian long term power quality monitoring project

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The Australian Long Term Power Quality Monitoring Project

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Abstract**-- The Australian Long Term Power Quality Monitoring Project now involves over 500 sites over 5 years and is one of the largest and longest running in the world. The project necessitated the development of a monitoring strategy, including choosing the number of sites, the type of disturbances to monitor and a means of collecting information from a variety of instruments. The presentation of such a large amount of data must consider a variety of needs from the wide view of the network manager to the needs of area managers for details on specific sites. A key feature of the survey is the ability of different distributors to compare themselves with others. New indices have been developed, particularly for voltage sags.**

Index Terms**— Harmonics, power quality data analysis, power quality monitoring, unbalance, voltage, voltage sags**

I. INTRODUCTION

MANAGEMENT of power quality (PQ) levels on electricity networks is fast becoming a basic day to day activity for electricity distributors. With the proliferation of modern electronic equipment that create and in turn are affected by PQ disturbances, utilities now have to have robust PQ management and planning processes in order to maintain acceptable PQ levels on their networks. Proactive PQ monitoring provides the essential feedback into the PQ management and planning process. Consequently many utilities are installing system wide PQ monitoring schemes such as those described in [1], [2] and [3].

Proactive PQ monitoring projects began at the University of Wollongong in 2000. This pilot project was the first proactive PQ monitoring project undertaken in Australia and aimed to report and benchmark PQ levels across the nation and to give utilities experience in survey methodology. In this first instance 11 utilities across the nation were involved in the project and 8 sites were chosen for monitoring from each utility by the University. Each of these sites was monitored for one week and a report generated.

Following encouraging results from this initial survey, The Long Term National Power Quality Survey (LTNPQS) was initiated. The LTNPQS project is quite different to the original pilot project which only involved monitoring a few sites for a limited period using instrumentation supplied by the University. The LTNPQS project involves year round monitoring with each participant involved selecting the sites and instrumentation for monitoring and supplying the data. Continuous measurements are taken of voltage variation, unbalance, harmonics and sags. After 5 years of operation, the survey has evolved to include some 500 plus sites from across the Australian eastern seaboard, making it one of the largest and longest running survey of its type in the world.

The deregulation of electricity distribution in the majority of Australian states has resulted in different situations in each state, with single state-owned utilities in some and several privately owned utilities in others. Thus, as opposed to the surveys detailed in [1], [2] and [3], the LTNPQS is a multi-utility project along the lines of those described in [4] and [5]. However, while the LTNPQS is similar to these projects there are some important differences. For the LTNPQS, there is no centralised control over the data submitted nor is there any control over the instrumentation used. As opposed to the surveys described in [4] and [5] which utilise the same type of instrument at all sites, LTNPQS participants are free to choose the instrumentation to be used and submit data ad-hoc. Consequently data is received from a variety of instruments ranging from modern PQ monitors through to smart tariff meters (STMs) with some PQ functionality.

This paper details the development of the LTNPQS project including the growth of the survey, limitations and difficulties in performing such a survey, developments in reporting techniques and a basic outline of the results achieved to date.

II. EVOLUTION OF THE LTNPQS

There has been significant evolution of the LTNPQS project since the first PQ survey instigated by the University of Wollongong in 2000. The first LTNPQS in 2002/2003 included some 213 sites, comprised of 51 low voltage (LV) sites and 162 medium voltage (MV) sites. The current LTNPQS survey includes some 593 sites comprised of 408 LV sites and 185 MV sites from 8 utilities across Australia, making it one of the largest PQ surveys in the world. Fig. 1 shows the growth in site numbers for the LTNPQS since its inception in 2002. It can be seen that there has been much stronger growth in the number of LV sites compared to MV sites. This may be due to the fact that while many utilities have had instrumentation available at the MV level either to ensure acceptable PQ levels across the bulk of the network or due to regulatory requirements, the increased interest in PQ levels across the wider network has lead to the installation of many more instruments at LV. Another reason for the increase in LV sites has been the development of affordable STMs with

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some PQ functionality. These devices are being extensively used where it would once have been cost prohibitive to install PQ monitoring equipment.

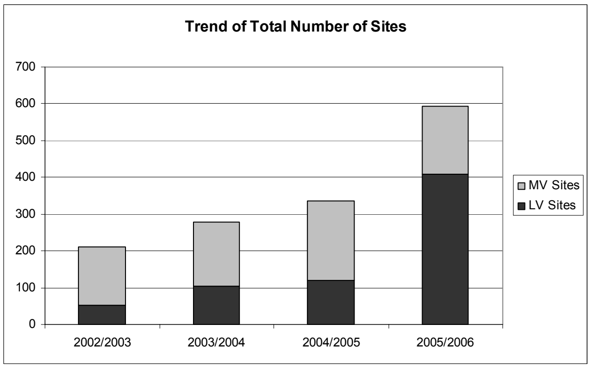

Fig 1: Growth in LTNPQS Site Numbers

Commensurate with a project of this size has been a need to continuously develop methods of reporting that allow large amounts of data to be reduced to a meaningful form without the loss of important detail. Consequently, indices and reporting techniques such as those described in [6] and [7] have been specially developed to suit the project and are under continuous review.

III. DISTURBANCES MONITORED

The disturbances measured for the LTNPQS and a brief rationale for each is as follows:-

Voltage Variation: This is a basic PQ parameter and important for the operation of equipment. Overvoltages may cause equipment damage while undervoltages may cause equipment to maloperate or overheat.

Voltage Unbalance: High levels of voltage unbalance can cause additional heating in three phase motors. There is some debate in Australia at present as to the appropriate limits to apply to unbalance.

Voltage Harmonics: THD or Total Harmonic Distortion is the key harmonic parameter reported in the LTNPQS. Harmonic distortion is an important PQ parameter as it known to cause the maloperation of some equipment, causes additional losses in motors due to counter-rotating magnetic fields and may destroy improperly installed power factor correction capacitors. Changes in technology may have a major impact on harmonic emissions, and it is thought prudent that its trend should be followed even if it is not a problem at present.

Voltage Sags: These very short (<1 minute) duration changes in voltage magnitude are due to system faults and direct connection of large loads and may be the most costly of all PQ disturbances to customers. Depending on the severity of the voltage sag, digital and control equipment may trip out resulting in significant economic loss for commercial and industrial customers [8]. These losses can be especially large for continuous production processes such as petrochemical plants, dairy plants, paper plants and plastic extrusion plants etc.

Current measurement is generally more difficult than voltage measurement and most useful for investigation of specific problems as opposed to routine monitoring. As the survey is based on proactive measurement in order to determine overall PQ levels, only voltage disturbances are measured as these provide indication of overall utility PQ levels and are those seen by the customer.

IV. PRACTICAL LIMITATIONS

In practice it is not possible to fulfil some requirements that would be necessary for a completely rigorous PQ monitoring exercise. For best assessment of PQ levels, PQ surveys should be conducted on a large number of sites with characteristics representing the full spectrum of sites supplied by the utility. As the LTNPQS relies on sites selected by and monitored by the participant the makeup of sites is at the discretion of the utility and may not necessarily be ideal. In practice it is very rare to have monitoring of weak sites due to the fact that most fixed installation PQ or smart revenue meters are installed at zone substations or at large customer installations. In the case of MV it is difficult to find suitable transducers for measurement away from substations. A similar problem exists in obtaining sites with different load characteristics; most utilities install instrumentation at industrial or commercial premises resulting in a dearth of sites from residential, rural or remote locations. Consequently, although the number of sites submitted to the survey has continued to grow, the characteristics of most sites are similar and the LTNPQS is dominated by strong sites with similar load and network type characteristics.

Ideally, all PQ monitoring would be performed by specialised, PQ monitoring equipment compliant with relevant PQ standards. In practice this equipment is expensive to buy and in the past it has difficult for utilities to justify the purchase of such devices. Data for the LTNPQS comes from a variety of instruments with a variety of capabilities.

Another practical limitation has been the loss of valuable PQ data. If data is not collected at regular intervals from PQ instruments it can be lost due to PQ monitor memory being overwritten. The current average survey availability is 65% of the year for LV sites and 75% of the year for MV sites.

Even when data coverage is high, analysis of the data can present specific difficulties. A dedicated PQ database system has been developed for the LTNPQS as described in [9]. This database contains all of the received data transformed into a standardised form. Data submitted by participants can be received in many different formats and transforming data from a wide range of instruments presents significant challenges.

V. LTNPQS REPORTING TECHNIQUES

Any long term PQ survey consisting of hundreds of sites will produce large volumes of data even if only a handful of disturbances are measured. The challenge in reporting this data is to reduce it to a useable form without losing important detail. This is the chief aim of all reporting in the LTNPQS. The current LTNPQS report contains a three- tiered hierarchical reporting structure which has been gradually developed since the inception of the project. This structure endeavours to make the LTNPQS accessible and useful at all levels of the participant organisation from senior management through to dedicated power quality engineer.

The first and lowest tier of this hierarchical reporting structure is a detailed site report outlining the performance of each site. The next tier is the network report which uses several indices to describe the performance of each site in the utility. The final tier is a high level overview suitable for review by senior management. Each tier of the report is described in detail below.

LV and MV sites are reported separately due to the vastly different characteristics of these sites. MV sites give a good indication of the PQ levels seen by large MV customers. One MV monitoring site can provide indicative performance over a wide area of LV customers but provides limited information on LV voltage variation, LV unbalance and LV harmonics. LV sites are very important because the bulk of customers are connected to the LV network and this is where PQ disturbances are generally at their worst.

A. Site Report

Site level reporting consists of very detailed information for each site for each disturbance type. The site report contains all of the data collected for a particular site shown graphically. For continuous disturbances or variations (voltage variation, voltage unbalance, and voltage THD) the site report consists of a histogram of disturbance levels overlayed by a site cumulative probability curve. The global cumulative probability curve, generated from all disturbance data included in the survey, is included to give an indication of the performance of the site with respect to all other sites in the survey.

A typical voltage variation histogram is shown in Fig. 2. It can be seen that there are several lines plotted on the site histogram. These lines are useful in accessing the performance of the site and indicate important site characteristics such as disturbance limits as well as statistical indicators. When site readings are outside limits, this histogram is useful for identifying possible causes and mitigation methods. Taking voltage as an example, a histogram which shows a tight grouping of columns shifted above or below the limits may indicate a voltage tap problem, while a histogram with a long tail may indicate a heavy load or site capacity problem.

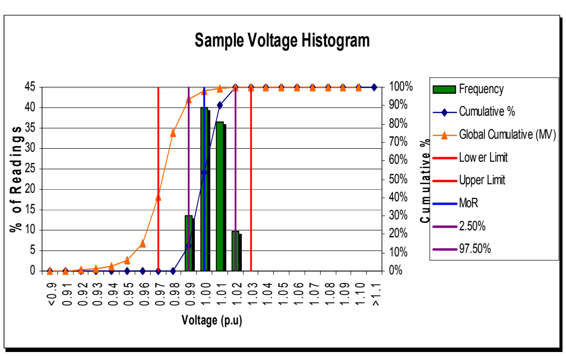

Fig 2: Sample Voltage Histogram

For voltage sag reporting, which is the only discrete disturbance included in the LTNPQS, the site report consists of a sag scattergraph showing the sag voltage (remaining voltage) and duration of each sag plotted on a depth-duration graph. The graph is overlayed by the CBEMA curve [10] as well as the protection curve [11] developed by the University of Wollongong. Fig. 3 shows a typical sag scattergraph. The CBEMA curve is shown to indicate the potential effect of each sag on equipment, but is not highly useful to the utility as it has been shown in [11] that the utility can not hope to meet the requirements of the CBEMA curve. The protection curve, which shows the longest duration to be expected for reflected faults under typical Australian overcurrent protection setting practices, is a more useful method of assessing the performance of the site. Sags to the right of the protection curve which are due to reflected faults indicate that there may be a protection issue at that site.

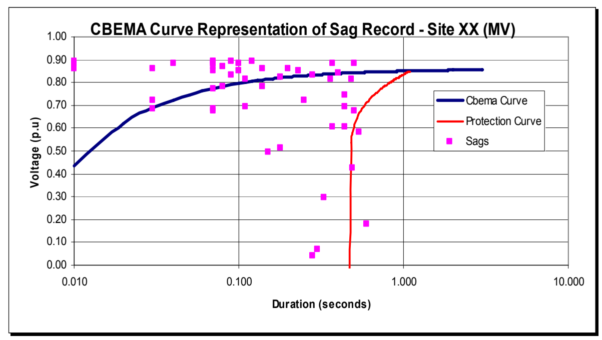

Fig 3: Example Sag Scattergraph

At the network level, a range of indices are calculated for each site to indicate the level of each PQ disturbance. There are two types of indices calculated for each site, primary indices, which have a direct relationship to limits, and secondary indices, as defined in [7], which provide more detailed information about site performance.

B. Network Report

At the network level, in order to reduce the time-varying data to a useful form, 95th percentile levels are used to indicate PQ performance for variations. The 95th percentile value is the value which will not be exceeded for 95% of the time. The 95th percentile is used in preference to other statistical indicators, such as the maximum or 99th percentile, as it is less susceptible to very rare, atypical events. The use of these statistical indicators is consistent with the assessment of limits given in international standards such as IEC61000-3-6 [12].

For voltage sags, the primary index is the Sag Index which has been developed by the University of Wollongong. The method of calculating this Sag Index is outlined in [13]. It is a weighted sum of the number of sags, with longer or deeper sags receiving a greater weight.

A method of ranking sites based on their performance over the four measured disturbances in the LTNPQS has been developed. This method, called the Customer Severity Index (CSI), is based on estimating the total impact on a customer due to the combination of the four disturbances. The CSI aims to show how a site performs relative to others with respect to the overall PQ effect on the customer. The CSI uses a process which weights disturbances based on potential impacts to equipment and employs normalisation of disturbance levels by limits to transform disturbance levels into common units so that they may be combined into a single index. Presentation of the data in this format allows a utility to get a good understanding of which sites are performing poorly, since it allows easy identification of outlying sites which may need attention. Fig. 4 shows an example CSI graph in which site UOW018 of fictitious utility UOW is clearly seen as on outlier.

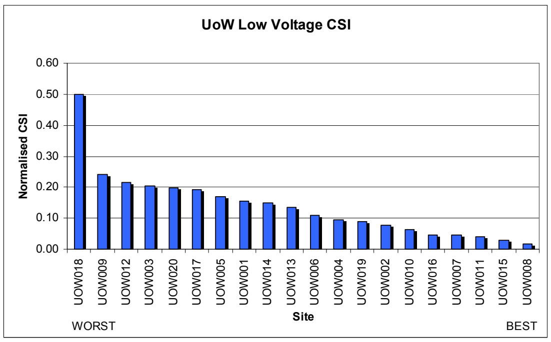

Fig 4: Example CSI graph

C. Utility Report

At the utility level it is important to give an overview of the PQ performance of the whole utility that is not overly complicated but provides sufficient information to draw conclusions about overall performance. For this purpose reporting methods have been developed to indicate overall utility performance with benchmarking against other utilities.

In order to report the overall performance of the utility, utility averages of site indices are calculated. There are two different overall utility indices calculated for each disturbance, namely an RMS value of site indices and a 95^{th} percentile value of the site indices. The first represents the average performance of the utility while the second is a measure of the PQ levels experienced by the worst-served customers.

Once overall utility averages have been determined it is possible to use these values to benchmark the utilities. Benchmarking is displayed through the use of bar graphs such as the ones shown in Fig. 5 which show the utility averages for each disturbance with the bar for the utility being assessed coloured differently. This provides a utility with insights as to how it performs relative to its peers and at the same time maintains confidentiality.

The trend of disturbances over the years is another important indicator of utility PQ performance. The utility averages may be used to generate year by year trends as shown in Fig. 6 which can alert a utility that disturbance levels are increasing and limits may soon be exceeded.

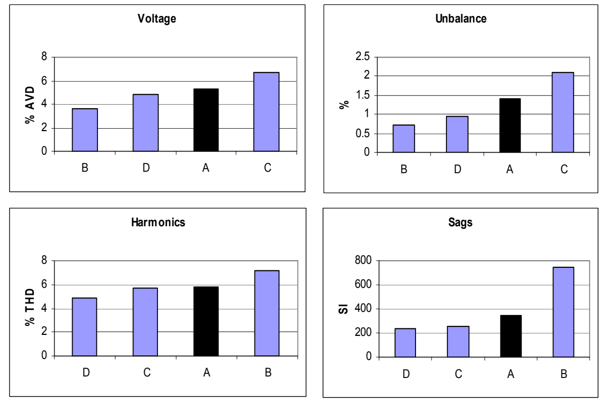

Fig 5: Example Utility Benchmarking Graph where the black bar shows the specific utility under study

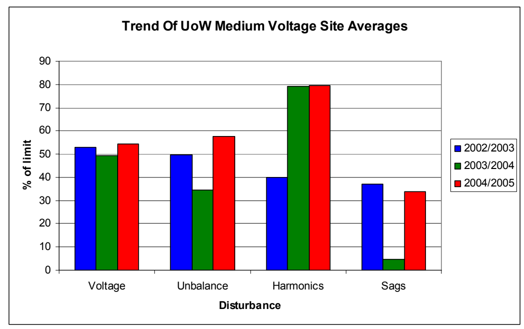

Fig 6: Example Disturbance Trend Graph

Trending of monthly variation of disturbances, useful for analysis of seasonal variations, can also be achieved and an example of this is shown in Fig. 8. This data gives insights as to when short term measurements at a site might give atypically high or low values.

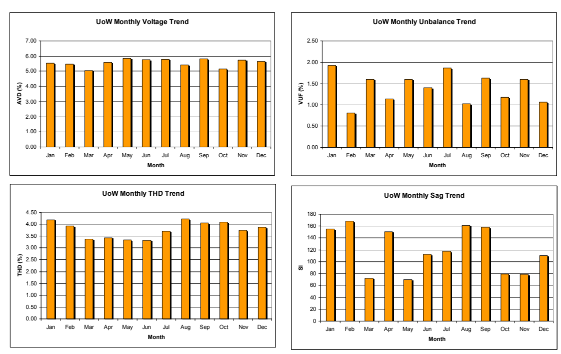

Fig 8: Example Monthly Trend Graphs

VI. INDICATIVE RESULTS SO FAR

A. Overall Results

After 4 years of the LTNPQS project some strong conclusions can be made regarding the state of PQ on Australian distribution networks.

In general, PQ levels in Australia are within limits for most disturbances. The PQ disturbance of most concern on Australian distribution networks appears to be LV voltage levels. Survey results show that these voltage levels are too high with a significant proportion of sites exceeding the nominal LV supply limits.

The next disturbance of most concern appears to be MV unbalance levels due to the fact that many utilities are required to comply with a 1% limit. The data gathered so far indicates that a 1% limit cannot be met at many sites. In fact, results from the most recent survey show that 20% of sites cannot meet a 1% unbalance limit. Not withstanding the equipment problems caused by unbalance, it is possible that a revision may be necessary for this limit. A more achievable limit may be 2% which was exceeded by only 4% of sites.

For sags, analysis has also shown that it is not possible for the electricity network to meet the requirements of the CBEMA curve due to the limitations of protection systems. The protection curve [11] has been shown to be much more indicative of the capabilities of the electricity network in terms of controlling the depth and duration of sags.

B. Disturbance Trends

The fact that the LTNPQS annual project has continued for a number of years has allowed interesting observations to be made regarding disturbance trends. This is one of the principal benefits of maintaining a long term survey.

Two issues at the forefront of long term measurements of PQ have been the observation of a consistent rise in harmonic levels over time in Europe [14] and the amount of time required for monitoring in order to obtain sag data which is typical of the long term sag data at a site. With 4 LTNPQS reports now issued comments can be made on the Australian experience for these issues. Fig. 9 and Fig. 10 show the trend of 95th percentile THD levels over time for LV and MV sites respectively. The information in these graphs has been normalised against the reading for the first year presented (2002/2003).

It can be seen that there has been a modest increase in LV levels over the four years that the LTNPQS has been in operation. For MV there has been a considerably more marked rise in levels over time, such that the latest levels are almost twice the levels recorded in 2002/2003. Some of this increase may be attributed to the growth in the number of sites in the LTNPQS which will lead to some variation in THD levels, however, the trend is too consistent and the change in MV site number too small to be attributed to changes in site numbers alone. Current trends in harmonics show a rise of 0.1% per year for LV sites and 0.3% per year for MV sites.

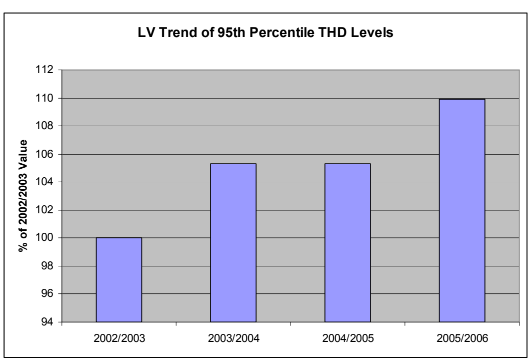

Fig 9: LV THD Trend

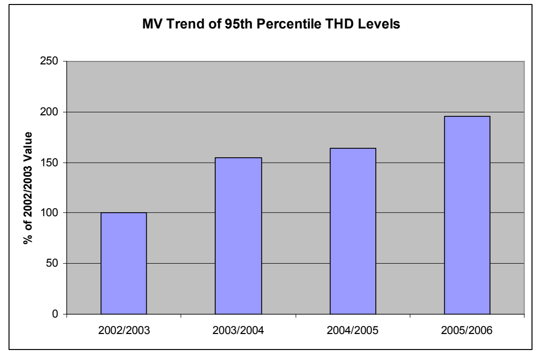

Fig 10: MV THD Trend

Fig. 11 and Fig. 12 show the trend of Sag Index levels over the four year for which the LTNPQS has been operating for LV and MV sites respectively. Sag Index levels have been normalised against the value for 2002/2003. Once again, increases in site numbers may result in some doubt as to the reliability of the trend values, however, it can clearly be seen that there is no apparent trend in Sag Index over the first four years of the LTNPQS. This is inline with other studies [15] which indicate that many years worth of data is required to characterise sag behaviour.

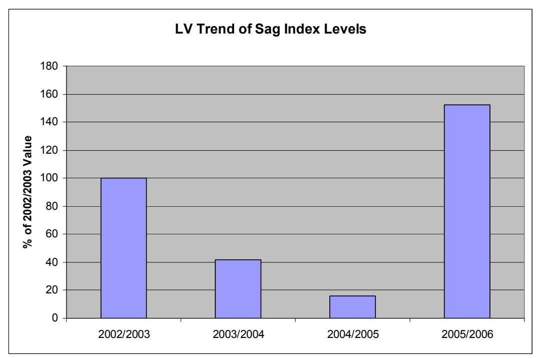

Fig 11: LV Sag Index Trend

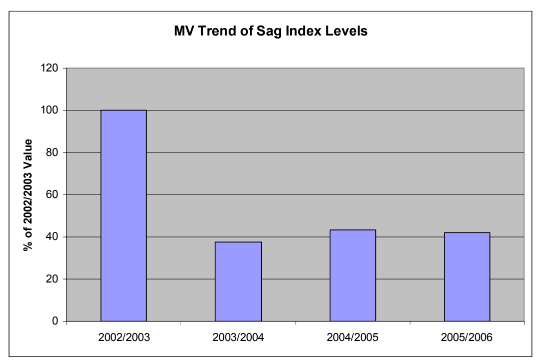

Fig 12: MV Sag Index Trend

VII. CONCLUSIONS

After 5 years of continuous development, the LTNPQS project has grown to become one of the largest and longest running PQ monitoring surveys in the world. This paper has described the development of the LTNPQS project from the first pilot study conducted by the University of Wollongong through to the large annual survey conducted today.

Many of the theoretical and practical aspects that need to be considered in conducting such a survey are detailed, including instrumentation, site selection and data transformation and storage. The innovative and unique reporting methods which have been developed over the course of the project have been outlined. Chief amongst these is the three-tiered reporting structure aimed at reducing large amounts of data to a useful form without the loss of important detail. In this structure, the reports are divided into site, network and utility sections. The site section gives the most detailed information about PQ at each site, the network section shows PQ levels across the network and the utility section provides an overview of the utility performance and provides benchmarking against other utilities.

The development of indices for reporting PQ levels at each site and the development of novel sag reporting methods, related to both the CBEMA curve as well as a practical protection curve, are also unique developments of the LTNPQS.

After 5 years of operation and with some 500 sites included in the survey some strong conclusions can be made regarding the state of PQ on Australian distribution networks. Reports to date have found that voltage at LV levels appears to be the disturbance of most concern and is generally higher than expected. Harmonic levels have been found to be lower than expected but are steadily increasing in line with trends seen internationally. It has been found that there will be many sites which cannot meet the 1% MV unbalance limit set by regulators in some Australian states. Sag levels are well outside the CBEMA curve and a theoretical model has been developed to show why this must be so. It is hoped that work in this area will lead to better understanding of the specification of equipment sag immunity levels.

Utilities are now finding that the LTNPQS is integral to their PQ monitoring and planning activities and many utilities now use the LTNPQS in discussion with regulators and as a method of determining and rectifying sites with poor PQ performance. In the future it is hoped that the LTNPQS project will continue to grow allowing further development of PQ reporting techniques and better understanding of PQ levels in Australia.

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IX. BIOGRAPHIES

Sean Elphick graduated from the University of Wollongong with a BE (Elec) degree in 2002. He commenced employment with the Integral Energy Power Quality Centre in 2003. Initially employed to work on a Strategic Partnerships with Industry - Research and Training Scheme (SPIRT) project dealing with power quality monitoring and reporting techniques. His current activities include delivery of the Long Term National Power Quality Survey, a first of its type in Australia as well as various other power quality related research and consulting projects.

Vic Gosbell obtained his BSc, BE and PhD degrees from the University of Sydney. He has held academic positions at the University of Sydney and the University of Wollongong where he became the foundation Professor of Power Engineering. He is now an Honorary Professorial Fellow and Technical Advisor to the Integral Energy Power Quality and Reliability Centre. He is currently working on harmonic management, power quality monitoring and standards. He is a member of Australian standards and CIGRE sub-committees and is a Fellow of the Institution of Engineers, Australia.

Robert Barr is a consulting engineer and director of his company Electric Power Consulting Pty Ltd. Robert holds an Honours degree in Electrical Engineering from Sydney University, a Master of Engineering degree from the University of NSW and a PhD in electrical engineering from the University of Wollongong. Robert has over 34 years experience in the field of electricity distribution and is a fellow of the Institution of Engineers Australia, a member of the Association of Consulting Engineers Australia and National President of the Electric Energy Society of Australia.