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## Abstract

The Australian Long Term Power Quality Survey (LTNPQS) now covers 2,000 sites with a range of different characteristics including strength (related to fault level), line construction and dominant load type. This paper details the latest outcomes of the LTNPQS project in terms of both disturbance levels and reporting methods. A comparison of the differences between voltage, unbalance and harmonic THD levels at strong (close to transformer) and weak (towards the end of LV feeders) sites has been performed and significant differences have been found. A multivariable linear regression study has been undertaken in order to investigate the correlation between site characteristics and PQ disturbance levels. Unexpectedly, little correlation could be identified. If true, this would mean that the overall PQ disturbance levels achieved by a utility may be estimated from a smaller set of sites than has been previously assumed. © 2012 IEEE.



## Keywords

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# Characteristics of Power Quality Disturbance Levels in Australia

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***Index Terms* – Power Quality, Power Quality Monitoring, Power Quality Survey**

## I. INTRODUCTION

Management of power quality (PQ) levels on electricity networks is a basic day-to-day activity for electricity utilities. It is necessary to fulfil regulator requirements, meet customer expectation, ensure correct operation of equipment connected to the network and to make best use of network assets. With the proliferation of modern electronic equipment that emit and in turn are affected by PQ disturbances, utilities now need to have robust PQ management and planning processes in order to maintain acceptable PQ levels on their networks. The introduction of large numbers of distributed generation systems, especially on low voltage networks, also presents PQ challenges which must be addressed by electricity utilities. The main PQ issues related to distributed generation are voltage control and harmonic distortion. However, unbalance due to uneven distribution of generation may also be a concern.

Proactive PQ monitoring provides the essential feedback into the PQ management and planning process required to address the challenges of operating a modern electricity distribution network. Consequently many utilities are installing network wide PQ monitoring systems.

Proactive PQ monitoring initiatives 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 electricity utilities their first 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 in 2002. The LTNPQS project is quite different to the original pilot which only involved monitoring a few sites for a limited period using instrumentation supplied by the University. The LTNPQS project involves year round monitoring, using the Australian financial year (1 July – 30 June), with each participant involved selecting the sites and instrumentation for monitoring. Continuous measurements are taken and the data supplied to the university. After 9 years of operation, the survey has evolved to include some 2000 sites from across the Australian continent, making it one of the largest and longest running surveys of its type in the world. The disturbances measured for the LTNPQS are as follows:

- **Steady State Voltage Variation:** The most basic PQ parameter and important for the operation of equipment.
- **Voltage Unbalance:** High levels of voltage unbalance can cause additional heating in three phase motors.
- **Voltage Harmonics:** THD or Total Harmonic Distortion is the key harmonic parameter reported.
- **Voltage Sags (Dips):** These very short (< 1 minute) duration changes in voltage magnitude are due to system faults and direct connection of large loads. Sags may be the most costly of all PQ disturbances to customers.

Measurement of current is generally more difficult than voltage measurement and most useful for investigation of specific problems as opposed to routine monitoring. As the survey is designed for proactive measurement in order to determine overall PQ levels, only voltage disturbances

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are measured as these provide indication of overall utility PQ levels and are those seen by the customer.

Much like standards, the LTNPQS has been a 'living' project. PQ indices and reporting methods have evolved over time for a range of reasons. These include developments in reporting and analysis gained through research, changes in the requirements of industry and changes to regulations and standards. There have been many publications related to proactive power quality surveying initiatives undertaken by the University of Wollongong in conjunction with Australian electricity distribution industry bodies such as [1], [2] and [3].

The first sections of this paper outline recent developments in the LTNPQS project including developments in reporting indices, key findings and future directions. Subsequent sections of the paper investigate the impact of the characteristics of a site (site strength, network construction type and load type) on the PQ performance at the site. A number of analysis techniques are utilised including multivariable linear regression.

### *A. The LTNPQS Today*

The 2010/2011 LTNPQS reports, which are being processed at the time of writing, contain data from over 2000 sites. Of these sites, approximately 1500 are low voltage (LV) sites and the remainder are medium voltage (MV) sites. Seven utilities from across Australia have provided data. Data has been received from 5 of the 6 Australian states. It is estimated that the utilities involved supply power to at least 80% of the population of Australia. In previous years, data has been obtained from all Australian states. As such, in terms of site numbers, geographic extent and longevity, the LTNPQS has grown to be one of the largest PQ monitoring projects in the world.

## II. Recent Development of Power Quality Indices

At the commencement of the survey, the development of power quality indices was very much in its infancy. Many of the indices included in the LTNPQS today are unique and have been developed and fine-tuned using the experience gained through operation of the survey over time.

### *A. Sag Indices*

Reporting of sags is one of the most complex and least defined areas of power quality surveying. Other than reporting each sag individually (large amounts of data), there is still no universally accepted method of reporting sags. All of the sag indices included in the LTNPQS project have been developed specifically for the project.

Reporting of sags is complicated by the fact that sags can occur on multiple phases, or even start on one phase and become multiple phase, and events occurring at multiple timestamps may be due to the same incident. Current best practice in power quality reporting as described in IEC61000-4-30 [4] is that sags should be aggregated so that events due to a single root cause are not reported multiple times. This aggregation process is known as phase and time aggregation and is implemented in the LTNPQS. The current method of phase and time aggregation is as follows:

- For sags occurring at the same time stamp across multiple phases, the sag index for the sag on each phase is calculated and the retained value is the average of these indices. This is phase aggregation

- Time aggregation is achieved by way of an arbitrary five minute window which commences at the timestamp of the first sag. Phase aggregation is performed on all sags occurring within this window. The reported sag is then the maximum of the phase aggregated values.

The first primary sag index developed by the University of Wollongong is detailed in [5]. This index was a measure of sag severity in terms of both depth and duration. It is based on an estimation of the complaint rate or the proportion of customers exposed to a sag from the site that are adversely affected by it.

The sag index which is currently implemented in the LTNPQS is termed the Sag SAIFI Index. This index attempts to relate sag activity to the reliability measure SAIFI. The main feature of the Sag SAIFI Index concept is that it provides a single number measurement of the voltage sag performance at a site or across a network. Sag severity levels are calculated by log/linear interpolation between the ITI Curve [6] (0 severity) and a point on the voltage sag retained voltage-duration plane that is known to cause disruption to most items of sensitive equipment. These points relate to the sag immunity of equipment and may change over time as new generations of equipment are developed. A full description of the Sag SAIFI Index is presented in [1].

## III. Key LTNPQS Findings to Date

### *A. Steady State Voltage Levels at LV Sites*

Possibly the key finding of the survey to date is that steady state voltage levels can be too high at strong sites under light load. Overall, approximately 30% of strong low voltage sites record voltage levels outside of the 230V + 10% (253 V) limit. Fig. 1. shows a typical voltage histogram. The limits are shown as red lines on the graph. It can be seen that there are a significant number of readings above the upper limit line. These readings correspond to periods of light network loading.

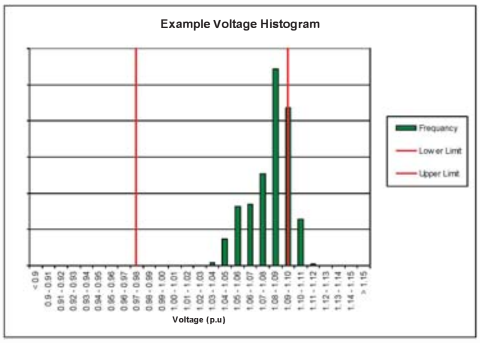


Fig. 1. Typical Voltage Histogram

Examination of the data shown in Fig. 1. in isolation indicates that a simple adjustment of the tap position on the distribution transformer may bring sites back into compliance. However, this strategy ignores the impact of this adjustment on the far end of the low voltage feeder. Australia traditionally has long LV feeder runs by world standards and it is this fact that has led to the high voltage issue at the sending end of the feeder as transformer taps have traditionally been set at a high voltage level to compensate for voltage drop along the feeder. This assumption of voltage drop is partially validated by a study of 152 sites classified as weak or remote from the sending end of the feeder. This study showed that approximately 10% of sites recorded 1$^{st}$ percentile voltage levels below the lower voltage limit used in the survey (230 V – 2%). These results suggest that adjustment of tap position at the sending end of the feeder may result in some low voltage issues at the remote end of some feeders. However given the prevalence of high light load voltage levels some action must be taken and the relatively low number of potential low voltage issues could be rectified on a case by case basis.

This understanding of voltage levels gained in the LTNPQS is of particular importance as Australia is working toward a power quality type standard, similar in function to AS61000.3.6 [7], which include limits and assessment methodology for steady state voltage. Results from the LTNPQS indicate that if the current voltage limits in AS60038 are adopted into this new voltage standard there would be a serious compliance issue. Further complicating development of this standard is the rapid take-up of distributed generation connected at LV, particularly solar PV systems. One Australian distribution utility is presently accepting nearly 1000 applications per week to connect solar PV systems to low voltage networks. High penetration of these systems has been observed to lead to localised voltage rise in the LV network. Peak power export of these systems will occur during the day when load is light further exacerbating the high voltage issue under light load.

### *B. Sag Trends*

Sag levels have been found to be highly variable compared to continuous disturbance levels and strongly dependant on climatic conditions. There are now 7 years of sag levels available, and there still does not appear to be any strong trend observed for sag levels. Fig. 2. and Fig. 3. show 95$^{th}$ percentile sag trends for LV and MV sites. In these graphs, sag levels are presented as a percentage of the provisional sag SAIFI limit which has been developed by the University of Wollongong.

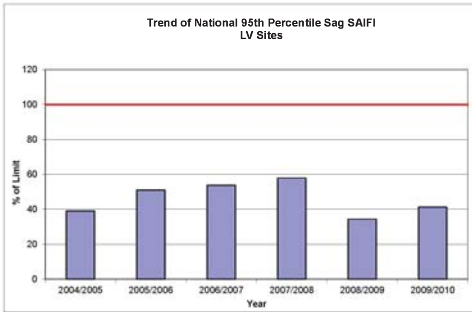


Fig. 2. Trend of LV 95$^{th}$ Percentile Sag Levels

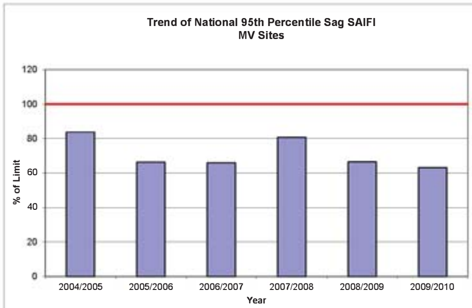


Fig. 3. Trend of MV 95$^{th}$ Percentile Sag Levels

Fig. 2. and Fig. 3. clearly show the variation in sag levels throughout the duration of the LTNPQS for LV and MV respectively. It can be seen that LV sag levels show no particular trend with values increasing and decreasing on a year-by-year basis. Although not shown in the graphs, sag levels were particularly high in 2002/2003. This was due to severe windstorms experienced across the Australian eastern seaboard. These windstorms also created a spike in reliability indices illustrating the strong link between sags and reliability due to extreme weather events. Sag levels of this magnitude have not been observed since.

## IV. FUTURE DIRECTIONS FOR THE LTNPQS

### *A. Impact of Smart Metering Technologies*

The implementation of smart metering technologies has the potential to exponentially increase the number of sites from which PQ data may be available. Data from these sites may be included in the LTNPQS further strengthening the project.

Smart metering projects are currently being installed in many countries around the world. Ostensibly these systems are designed to simplify metering, provide additional data on network operation, rapidly identify outages and to assist in demand side integration strategies. In the most basic form, smart meters will simply replace traditional electronic or induction disc energy consumption meters and perform a similar function albeit

with additional capabilities. However, distribution utilities have a once-in-a-generation opportunity to specify metering instrumentation that is not only useful for measuring energy consumption data but may also fulfil other network monitoring needs such as PQ. However, the main limitation of including PQ functionality in smart meters is that while the cost to include PQ functionality on a per instrument basis may be relatively small, when multiplied by the thousands or millions of smart meters to be installed, the cost is not negligible. As such, it is unlikely that every smart meter would have PQ functionality. In fact PQ functionality on every instrument would not be useful or practical as the data obtained from meters in similar location will likely be similar. As such, the data burden, i.e. communications cost along with storage and backup, would increase significantly while the usefulness of the data would only increase incrementally.

In order for distribution utilities to make best use of the smart metering rollout, the utility should develop a targeted approach to meter placement. Under this targeted approach a number of locations would be selected for installation of upgraded metering which includes PQ functionality. This strategy would offset the need to include PQ functionality in all instruments, a cost saving, but could lead to many additional sites supplying data.

Any strategy determining placement of upgraded metering would need to be developed such that all important points of the network are monitored and that statistical confidence in reported data can be achieved. Most key points on MV and HV networks now have dedicated power quality monitoring and, as such, most locations to be affected by smart meter rollouts will be on LV networks. The key points on these networks would be the distribution transformer, the end of the feeder and possibly the middle of the feeder. The site selection methodology would need to take into account the network characteristics such as construction type (e.g. underground, overhead), physical characteristics such as topography and geography along with the types of load connected (e.g. rural, residential, commercial, industrial).

## V. PQ Levels Based on Site Characteristics

The framework of the LTNPQS allows for submission of a range of information which details the characteristics of each site to be provided by participants. These characteristics include the strength of the site, the construction of the network and the predominant load type supplied by the site. For site strength, two characteristics are available; strong or weak. The distinction between strong and weak sites is that a site is deemed strong if it is located closer to the supply than the point on the MV distributor or LV feeder where the supply fault level is halved. At MV this distance may be several kilometres while for LV this distance is approximately 30 m. The network construction categories are as follows: -

- City – Predominantly short underground feeders and distributors. Ring systems. Strong networks.
- Suburban – Predominantly short overhead MV feeders (up to approximately 5 km) and relatively short LV distributors (up to several hundred metres) but including some underground feeders and distributors.
- Short Rural – Predominately longer overhead feeders and distributors.
- Long Rural – Long to very long overhead feeders and distributors to remote locations.

The predominant load categories are as follows: -

- Industrial
- Commercial
- Residential
- Mixed

Full site characteristic data was available for 1171 LV sites. Using this data, this section of the paper investigates the effect that site characteristics has on overall PQ levels.

### *A. Comparisons of PQ levels at Strong and Weak LV Sites*

The Australian electricity distribution network is a 230 V 50 Hz system. As such, LV feeders can be up to several hundred metres long. It would be expected that PQ levels at the remote ends of LV feeders would be somewhat different to levels observed at the distribution transformer terminals. The 2010/2011 LTNPQS reports represent the first time that a significant number of LV sites remote from the distribution transformer, or weak sites, have been included in the survey. The inclusion of these sites has allowed better understanding of power quality levels throughout the distribution network. As most customers are connected at LV this information is extremely useful not only for understanding PQ levels across the network but also in framing standards whose limits reflect the capabilities of the distribution network. Data collected as part of the LTNPQS project has directly aided the development of the new Australian Standard for steady state voltage, AS 61000.3.100 [8]. Analysis of this nature may also aid in PQ state estimation. If sufficient data to ensure statistical confidence could be collected from a number of both strong and weak sites, comparisons of this data could provide factors that may be applicable at all sites. The advantage of this would be that monitoring would only be required at one position on the feeder. The strong/weak comparison factor could then be applied to estimate the PQ level at any point on the LV feeder. Results of comparison data from strong and weak LV sites have revealed some interesting outcomes which are discussed below. It should be noted that the weak sites are not necessarily connected downstream from the strong sites.

*1. Results for Steady State Voltage*

Three voltage indices are of use when comparing the performance of strong and weak sites. These are the 99$^{th}$ percentile value of voltage, the 1$^{st}$ percentile value of voltage and the voltage spread which is calculated by subtracting the 1$^{st}$ percentile voltage from the 99$^{th}$ percentile voltage. According to AS 61000.3.100 [8], the limits for 1$^{st}$ percentile and 99$^{th}$ percentile voltage are as follows:

- 1$^{st}$ percentile voltage 216 V or 0.94 pu (on 230 V base).
- 99$^{th}$ percentile voltage 253 V or 1.1 pu (on 230 V base).

Based on the above limits the limit for voltage spread is 16%.

For 99$^{th}$ percentile voltages, the performance of weak and strong sites is similar as would be expected intuitively. For 1$^{st}$ percentile voltages, which represent heavy load conditions, it would be expected that voltage levels at weak sites would be lower than those at strong sites and this is found to be the case. For the 50$^{th}$ percentile site, the 1$^{st}$ percentile voltage at weak sites is found to be 99% of the voltage at strong sites. For the 95$^{th}$ percentile site, voltage levels at weak sites are 98% of voltage levels at strong sites. The fact that the 1$^{st}$ percentile voltage level at weak sites are relatively close to the 1$^{st}$ percentile voltage levels at strong site provides an indication that the high light load voltage levels described in Section III.Acould be corrected by adjustment of distribution transformer tap settings.

Fig. 4 shows cumulative probability curves for voltage spread at strong and weak sites. It can be seen that, as would be expected, the voltage spread at weak sites is considerably higher than that observed at strong sites. The ratio between voltage spread at strong and weak sites is approximately 1.45 for both the 50$^{th}$ percentile and the 95$^{th}$ percentile site.

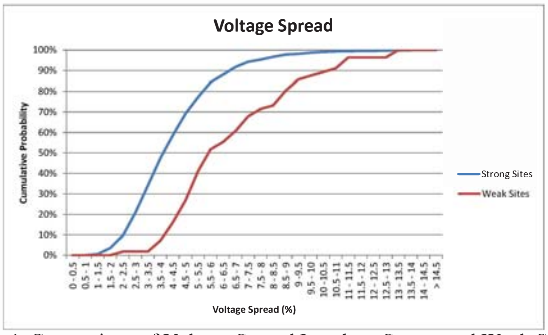


Fig. 4. Comparison of Voltage Spread Levels at Strong and Weak Sites

*2. Results for Voltage Unbalance*

Data for voltage unbalance at LV sites showed the largest discrepancy between the values obtained at strong and weak sites. Values of unbalance at weak sites were found to be significantly higher than those observed at strong sites. Fig. 5. shows the cumulative probability curves for unbalance levels at strong and weak sites.

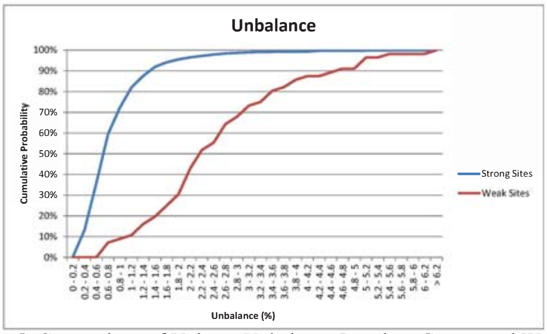


Fig. 5. Comparison of Voltage Unbalance Levels at Strong and Weak Sites

Further analysis of the data presented in Fig. 5. shows that 4.5% of strong LV sites were found to exceed the 2% limit for unbalance compared to 70% for weak sites. For the 50$^{th}$ percentile site, the ratio between the unbalance level at strong and weak sites is 3.21. For the 95$^{th}$ percentile value, the ratio is fairly consistent at 2.63. Based on the data analysed it can be expected that unbalance levels at the end of LV feeders will be approximately 3 times the level measured at the distribution transformer terminals.

*3. Results for Voltage THD*

Voltage THD levels were found to be higher at weak sites than at strong sites. Fig. 6. shows cumulative probability curves for voltage THD at strong and weak sites.

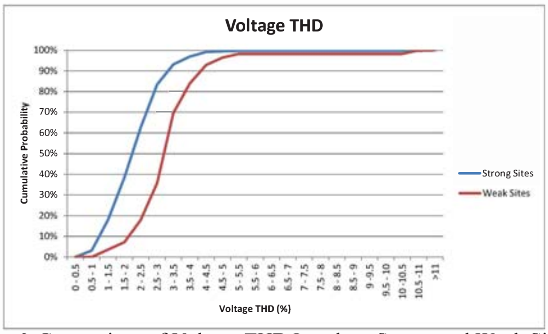


Fig. 6. Comparison of Voltage THD Levels at Strong and Weak Sites

For the 50$^{th}$ percentile site, voltage THD levels at weak sites are 145% of the strong site value. For the 95$^{th}$ percentile site, voltage THD values are 125% higher for weak sites than for strong sites.

*B. Impact of other Site Characteristics on PQ performance*

Categorical multivariable non-linear regression has been applied to data from the 1171 available LV sites in order to attempt to determine the most important site characteristics with regard to PQ performance. For the purposes of this study, the theory of categorical

multivariable linear regression assumes that any index may be expressed in the form:

$$H = C + k_1(x_{i1}) + k_2(x_{i2}) + k_3(x_{i3}) + \ldots \quad (1)$$

Where:

H is the value of the PQ disturbance index at the site
C is a constant
$x_{i1}, x_{i2}, x_{i3}, \ldots$ are independent variables
$k_1, k_2, k_3, \ldots$ are constants associated with the relevant independent variables

In this case, the independent variables are the characteristics of the site. The linear regression model takes the index of the site and calculates constants that provide a best fit for the index value. As such for this study, equation (1) may be re-expressed as:

H = C + $k_1$(strength (strong or weak)) + $k_2$(network construction (city, suburban, short rural, long rural)) + $k_3$(load type (industrial, commercial, residential, mixed)) (2)

The regression model shown in (2) was applied to data for voltage spread, voltage unbalance and voltage THD.

### *1. Results of Regression Model*

The results of the regression model yielded an unexpected outcome. Overall, the model was unable to give a fit with an error lower than approximately 20% (in most cases the error was significantly higher). This indicates that there is no particular site characteristic which heavily influences PQ performance at a site. For all disturbances, strength was the most important site characteristic when determining site performance, as would be expected given the analysis results shown in Section V.A. All other characteristics appeared to have second order impacts on PQ performance.

The weak relationship between site characteristics and PQ disturbance index values may aid in the selection of sites to be monitored. There appears to be no strong necessity to select sites with a range of characteristics in order to understand PQ levels throughout the network.

## VI. Conclusions

The Australian Long Term PQ Survey now covers 2,000 sites with a range of different characteristics including strength (related to fault level), line construction and dominant load type. Annual sag results for a site are reported by a single index related to SAIFI. Overall sag performance is not showing any consistent trend over the ten years of the survey because of the variation in annual weather patterns. Voltage has been found to be sometimes too high at some strong LV sites and this has caused the tripping out of some solar PV units. This has stimulated the development of an Australian PQ type voltage standard.

A comparison of voltage, unbalance and harmonic THD is given for strong and weak sites and significant differences have been found. Multivariable linear regression of site PQ disturbance indices has so far failed to find any significant dependence on other site characteristics. If true, this would means that the overall PQ levels achieved by a utility may be estimated from a smaller set of sites than has been previously assumed.

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## VIII. Biographies

**Sean Elphick (M'2011)** graduated from the University of Wollongong with a BE (Elec)(Hons) 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 Smith** graduated from the NSW Institute of Technology in 1979. In 1981, he studied for his MSc degree at the University of Manchester Institute of Science and Technology (UMIST), UK. In 1995, Dr Smith received his PhD from Sydney University. Dr

Smith joined the Integral Energy Power Quality Centre at the University of Wollongong in 1997. He has an interest in measurement and reporting of power quality disturbances, network transient phenomena and their control, and power quality aspects of distributed generation.

**Vic Gosbell (M' 1975)** 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 Emeritus Professor and Technical Advisor to the Endeavour 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.

**Dr Robert Barr** is a consulting engineer and director of his company Electric Power Consulting Pty Ltd. He holds a PhD in electrical engineering from the University of Wollongong. Robert has over 40 years experience in the field of electricity distribution and is a fellow of the Institution of Engineers Australia and a member of the Association of Consulting Engineers Australia. Dr Barr is an Honorary Professional Fellow at the University of Wollongong and has been named Australian National Professional Electrical Engineer of the year for 2012 by the Electrical College Board of Engineers Australia.