APQRC

AUSTRALIAN POWER QUALITY AND RELIABILITY CENTRE

Australian Power Quality and Reliability Centre

Power Quality Monitoring and Disturbance Investigations

Characterisation of Power Quality Disturbances and Investigation Methodology

Technical Note 19
September 2021

UNIVERSITY OF WOLLONGONG

Table of Contents

1. Introduction

Power quality monitoring is the measurement and assessment of power quality levels or disturbances on an electricity network or within an installation. In [1] a power quality disturbance is defined as “Any power problem manifested in voltage, current or frequency deviations that results in failure or misoperation of customer equipment”. Power quality monitoring is implemented through the use of specialised instrumentation designed to measure the various power quality disturbances. Power Quality instrumentation will be dealt with in Technical Note 20.

The monitoring, assessment and limitation of power quality disturbance emission levels comes under the umbrella of Electromagnetic Compatibility (EMC). A Compatibility Level (CL) is specified for each power quality disturbance and varies depending on the nominal voltage of the network considered. Disturbance levels must remain below this level. To ensure that this occurs most of the time, Planning Levels (PL) are specified by the Network Service Provider (NSP) that are generally lower than or equal to the CL and are used for the purpose of determining emission limits. These concepts are illustrated in Figure 1.1 which shows probability density distributions for disturbance levels and equipment immunity levels.

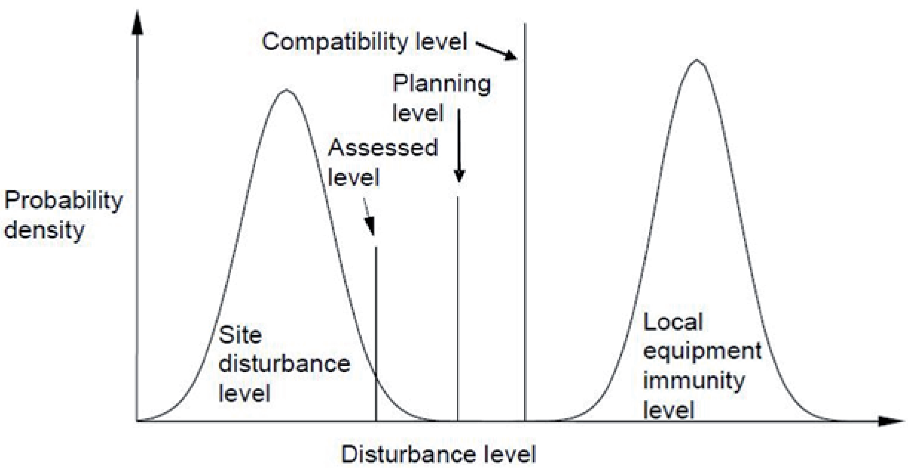

Figure 1.1: Basic power quality concepts with time statistics relevant to one site within the whole system [11].

The different power quality disturbances affect equipment connected to the electricity network in different ways [12] and can have significant detrimental impacts on such equipment, including domestic, commercial and industrial devices. This inevitably leads to an economic impact. For example, it is estimated that power quality problems cost industry and commerce in the European Union about 10 billion Euros per annum [2].

Consequently, power quality monitoring is primarily driven by economic considerations, whether initiated by the electricity distributor (for regulatory or planning purposes) or by the customer (to determine why equipment is failing or maloperating, or process operations are being disrupted).

There are two distinct power quality monitoring rationales; reactive and proactive monitoring. The reasons for, and methodology of, conducting monitoring for each rationale can differ markedly.

Reactive monitoring is undertaken in response to a known abnormal operation of the electricity system often arising from either a customer complaint (in the case of the electricity distributor) or maloperation or failure of equipment.

Proactive monitoring refers to routine monitoring and is usually performed by NSPs. Proactive monitoring can be used for a variety of reasons including regulatory requirements and for planning and asset management purposes.

This Technical Note will focus on power quality monitoring in relation to plant investigations (i.e. reactive monitoring) rather than monitoring as part of a regulatory compliance survey.

2. Characterisation of Power Quality Disturbances

Power quality disturbances are generally categorised into two broad types, namely either Variations (always present to some degree i.e. steady state voltage, unbalance, fluctuations/flicker, harmonics) or Events (random or semi-random occurrences i.e. interruptions, sags, swells, transients). The different characteristics of variations and events necessitates different requirements for each type of disturbance for monitoring, reporting and setting of limits.

2.1 Characterisation and Measurement of Variations

Variation type disturbances such as steady state voltage level are described by constant values under steady state conditions (e.g. under laboratory conditions). In this situation they can be read using simple handheld meters with no data-logging capability. Under field conditions there is likely to be time variation because of disturbing effects. When the variation is fast, handheld meters may be ineffective and it is preferable to continuously log the quantity. The quantity may then be represented by a trend graph as shown in Figure 2.1.1, a plot of the value measured at regular intervals over time. Typically, a 10-minute interval is used.

If the quantity is to be characterised by a single number over time, a statistical measure such as average or maximum, also shown in Figure 2.1.1, might be used. In practice, the average can be too optimistic since the waveform is larger than this for 50% of the time, often by a factor of two or more. However, the maximum may be too pessimistic as it occurs only very briefly. An intermediate approach is to use the 95% value, (sometimes called the 95% cumulative probability level or 95th percentile) the value which is not exceeded for 95% of the time.

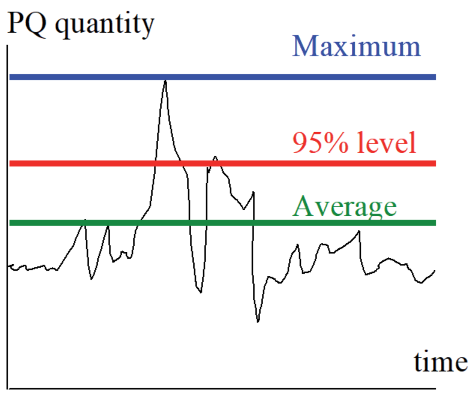

Figure 2.1.1: Trend graph example

Although the use of the 95% value is generally satisfactory, it will be exceeded for 8.4 hours in a week. Use of the 95% value assumes that the behaviour in the remaining 5% of the week is not too extreme. If a situation arises where this is not so, some other statistic may have to be considered, for example, the 99% value.

2.2 Characterisation and Measurement of Events

Event disturbances such as voltage sags or transients usually occur as isolated disturbances with duration of a few cycles with a long interval before they are repeated. The concept of “steady state” is not applicable to these disturbances since, if the term was to mean anything, it would be that they are absent. They cannot be examined by handheld meters without logging capability.

The occurrence of an event is recognised by a monitoring instrument by the presence of a cycle which is different to the cycle before it. However, if measurements were made with a small enough resolution, no two cycles would be the same. Hence the question arises as to how different a cycle has to be before an event disturbance can be said to have occurred? The level which would have to be significant is called the threshold and is often adjustable on PQ monitors. Some PQ monitors have preselected thresholds that can be used as a starting point. As a guide, the threshold for a voltage sag could be set to 15% of nominal voltage, a voltage swell +15% of nominal voltage, and a voltage transient +20% of the nominal voltage. Once the event threshold has been exceeded, the PQ disturbance type needs to be recognised, its parameters determined and stored together with the time and date stamp, a process called event capture.

For example, consider the occurrence of a voltage sag on 5-5-2020 at time 3.31.06 pm as shown in Figure 2.2.1. Suppose the sag is a voltage reduction of 35% (i.e. to 65% retained voltage) for two cycles (0.04 secs). Depending on the instrument design, it may record “Sag 2020:05:05:15:31.06 35 0.04”. A list of such events and their parameters gives an event log.

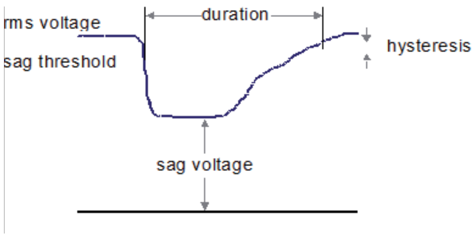

Figure 2.2.1: Characterising an event disturbance

2.3 Interaction Between Power Quality Disturbances and Equipment

Power quality disturbances are coupled into electrical equipment via three main mechanisms:

i. Conduction through the connected mains power cable;
ii. Induction into the mains power cable and any control circuits from adjacent power cables or nearby transient overvoltage activity;
iii. Capacitive coupling from nearby high frequency events.

This Technical Note will focus on the monitoring of power quality disturbances on the mains power cable of affected equipment.

3. Investigation Methodology

The protection of MV and LV systems is a well-studied concept and usually, protection coordination can be suitably maintained with conventional protective devices such as over current (O/C) relays and fuses. Although microgrids are mostly connected at these voltage levels, microgrid protection presents different challenges. Present microgrid deployments mainly rely on traditional protection methods in both islanded and grid-connected modes. Various studies have proposed novel microgrid protection schemes; however, these have not led to a commercially available protection system for microgrid applications.

The basic objectives of power quality surveys are as follows [3]:

i. Determine the soundness of the premises wiring and earthing system supplying the equipment;
ii. Determine the quality of the AC voltage supplying the equipment;
iii. Determine the sources and impact of power quality disturbances on equipment performance;
iv. Analyse the survey data to identify cost-effective improvements or corrections, both immediate and future.

3.1 Where to Monitor

The location of power quality monitors within the plant being investigated will depend on where the affected equipment is located and the availability of access points for voltage and current connections. This is particularly an issue with medium voltage (MV) installations where voltage and current transducers (generally voltage transformers (VT) and current transformers (CT)) must be used.

If possible, power quality measurements should be made at multiple locations simultaneously. The data obtained in this way is most useful for determining the nature of the power quality problem and its possible source. If simultaneous monitoring cannot be undertaken, each location can be monitored individually, taking care to ensure similar operating conditions at each location to allow direct comparison of measured data. The number of monitoring points will depend on the nature of the problem and the nature of the affected equipment. As a minimal starting point, monitoring should be undertaken at the affected equipment (or at the distribution board directly supplying it), then upstream at the nearest point of common coupling to other plant equipment, and also at the main switchboard (to assess the performance of the incoming supply) [4]. Figure 3.1.1 shows a typical power quality monitor installation connected for monitoring both voltage and current.

Figure 3.1.1: Example of power quality monitoring of voltage and current.

3.2 What to Monitor and Monitoring Period

In general, it is advisable to measure as wide a range of disturbances as possible even if a particular disturbance is suspected of causing the particular problem. It is important to collect as much data as possible to properly analyse the problem. Modern power quality monitors can be readily configured to measure most types of disturbance (both variation and event types) simultaneously.

For assessing the cause of problems in an industrial plant, both voltage and current should be measured. Voltage measurements provide information about the voltage quality delivered to the plant and within the plant, and characterise transients and voltage sags which may affect connected equipment. Current measurements correlated to voltage disturbances give much information about the cause and potential impact of these disturbances, and are essential if harmonics are a concern since current can characterise the harmonic injection from the plant into the power system [1].

The duration of monitoring will depend on the monitoring objectives. If the impact on the plant of voltage sags and transients on the distribution network are being assessed, monitoring may be required for a significant length of time since these events can be rare. For the assessment of most other disturbances, monitoring should be performed for at least one business cycle (usually one week minimum) to understand how load changes and system variations affect the levels of these disturbances [1].

3.3 Assessment Procedure

The basic methodology of power quality fault-finding is outlined in the flow chart shown in Figure 3.3.1 below:

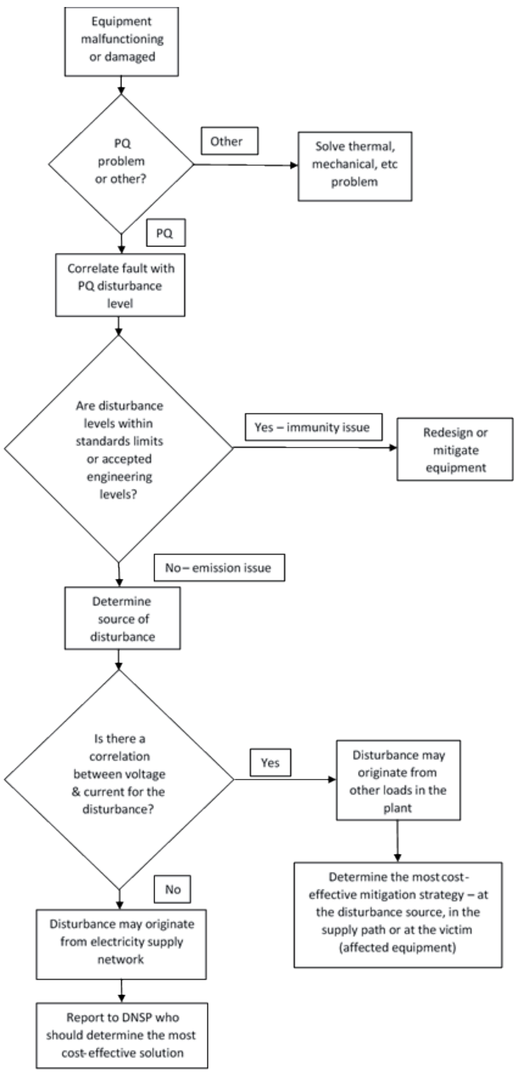

Figure 3.3.1: Power quality fault-finding methodology.

With regard to the fault-finding process, the following useful comments can be made:

i. General - Customer disturbance reports (logs) are essential in providing information such as the nature of the problem, time of occurrence, any coincident problems or known operations (which may cause disturbances), and environmental conditions. It is also helpful to know what power conditioning equipment is being used (if any), and if there have been any recent changes to the premises wiring distribution system or to the electricity distribution network supplying the plant [3]. In addition, an early assessment of the condition of the premises wiring and earthing system is important in order to eliminate this as a cause of the problem. Issues with plant wiring and earthing account for a large proportion of reported plant power quality problems [3].
ii. Disturbance identification - A power quality monitor should be installed for a long enough period for the fault to appear several times. The times of fault occurrence should be checked against recorded power quality levels. It is not sufficient to only check against event disturbances. Variation trends should also be checked since they might have high peaks at certain times. It may also be necessary to check other quantities since some power quality problems might only occur when there is a combination of high levels with high temperatures.
iii. Allowable limits - It is necessary to decide whether the problem is an emission problem (too high a level on the supply) or an immunity one (equipment tolerance is too low). This is relatively easy to discern where standards are well defined, e.g. for voltage levels, unbalance, harmonics and fluctuation, but requires some engineering judgement otherwise. In this regard, guidance is given in Australian Standards AS/NZS 61000.2.4 [5] and TR IEC 61000.2.6 [6] for industrial plants for allowable emission levels and assessment procedures.
iv. Mitigation - If both source and victim occur in your installation, cost comparisons will reveal where modifications need to be made. To take one extreme, if a cheap item of equipment is affecting many expensive items, the fix should be made at the source or possibly in the path (e.g. by filtering). There are other situations where the source is expensive, and the only problem is one piece of equipment needing a relatively small capacitor to be replaced by something larger – for example where sags affect a small power supply. That is why it is important to determine what part of the affected equipment is likely to be the “weak link” and what are the part’s critical sensitivities to power quality disturbances e.g. harmonics or sags.

3.3.1 Voltage standards

Supply voltage is governed by a number of Australian standards which deal with variation type power quality disturbances such as voltage levels, unbalance, harmonics and fluctuations. These quantities are mainly controlled by proper plant design. However, similar standards do not exist for event type disturbances which tend to be controlled by protective devices e.g. Dynamic Voltage Restorers (DVR), Uninterruptable Power Supplies (UPS), filters, Surge Protection Devices (SPD), etc.

Two Australian standards deal with the preferred voltage range on distribution networks. AS 60038 [7] specifies standard voltages that should be used for the preferred nominal voltages of the electricity network, and as reference values for equipment and system design. AS 61000.3.100 [8] describes how to monitor the electricity network and apply the limits specified in AS 60038. For low voltage customers, these limits are 230 V line to neutral +10% to -6% (i.e. 253V to 216V) at the connection point to the supply network. These limits apply to 10-minute root mean square (RMS) voltages and are 99th and 1st percentile limits, measured over a period of at least seven days and disregarding periods of supply interruption.

AS 60038 [7] further defines a utilisation voltage range to allow for voltage drops within the customer’s installation due to the operation of connected electrical equipment. AS/NZS 3000 [9] limits this voltage drop to 5% so the utilisation voltage range is +10%, - 11% i.e. 253 V to 205 V for 230 V nominal low voltage circuits.

For the other variation disturbances mentioned above, guidance on appropriate emission levels and assessment procedures on the public network and within industrial plants is given in the standards specified in Table 3.3.1.1 below.

DISTURBANCE	COMPATIBILITY		COMPLIANCE	
	Public Network	Industrial Plant	Public Network	Industrial Plant
Steady State Voltage	AS60038 [7]	AS61000.2.4 (LV & MV) [5]	AS61000.3.100 [8]	
Unbalance	AS61000.2.2 (LV) [13] AS61000.2.12 (MV) [14]	AS61000.2.4 (LV & MV) [5]	AS6AS61000.2.12 (MV) [14] 1000.3.14 (LV) [17] AS61000.3.13 (MV) [16]	TR IEC 61000.2.6 (LV & MV) [6]
Harmonics	AS61000.2.2 (LV) [13] AS61000.2.12 (MV) [14]	AS61000.2.4 (LV & MV) [5]	AS61000.3.14 (LV) [17] AS61000.3.6 (MV) [11]	TR IEC 61000.2.6 (LV & MV) [6]
Flicker / Fluctuations	AS61000.2.2 (LV) [13] AS61000.2.12 (MV) [14]	AS61000.2.4 (LV & MV) [5]	AS61000.3.14 (LV) [17] AS61000.3.7 (MV) [15]	TR IEC 61000.2.6 (LV & MV) [6]

For voltage sags and transient overvoltages, due to their stochastic nature and magnitude range, there are no standards which give compatibility levels. However, there are standards which give typical values, describe their impact and give guidance on how to deal with them e.g. AS/NZS 61000.2.4 [5] for industrial plants, and for public networks, AS/NZS IEC/TR 61000.2.8 [18] (voltage sags) and AS/NZS IEC/TR 61000.2.14 [19] (transient overvoltages).

3.3.2 Power quality data assessment software

A power quality monitoring campaign often produces a large amount of captured data. This data must be analysed and collated to assess the power quality of the industrial plant. Modern power quality instruments are usually supplied with dedicated analysis software for this purpose. The key functions of such software are [1]:

i. Viewing of individual disturbance events.
ii. RMS variation analysis including tabulations of voltage sags and swells, magnitude-duration scatter plots, and calculation of a wide range of RMS indices e.g. SARFI (System Average RMS Variation Frequency Index).
iii. Steady-state analysis including trends of RMS voltages, RMS currents, and negative- and zero-sequence unbalances. Also, statistical analysis can often be performed to provide, for example, various averages and cumulative probability levels.
iv. Harmonic analysis to produce voltage and current harmonic spectra, statistical analysis of various harmonic indices, and trending over time.
v. Transient analysis including statistical analysis of maximum voltage, transient durations, and transient frequency.
vi. Standardised power quality reports (e.g. daily and weekly reports, statistical performance reports, executive summaries, customer power quality summaries).
vii. Analysis of protective device operation.
viii. Analysis of energy use.
ix. Correlation of power quality levels or energy use with specific parameters.
x. Equipment performance as a function of power quality levels (equipment sensitivity reports).

3.3.3 Guidance for power quality problem analysis

General guidance for power quality problem diagnosis can be found in previous Technical Notes prepared by the Australian Power Quality and Reliability Centre (APQRC). These can be found on the APQRC website under Publications and give possible causes of some typical equipment problems related to power quality issues.

3.3.4 Practical considerations

The following are some practical guidelines involved in conducting a typical site analysis based on frequently found disturbances and their characteristics [10]:

i. Initially, examine the site for those issues that don't seem to correspond to identifiable power quality disturbances e.g. wiring and earthing problems (especially missing, improper or poor-quality connections, or neutral-earth bond issues), high speed transients and common-mode electrical noise.
ii. Look for power quality issues related to the distribution network inside and outside plant. These may be repetitive or cyclical in nature, and line to line e.g. voltage sags and momentary interruptions.
iii. Look for possible harmonic distortion sources (e.g. variable speed drives) and their consequences e.g. harmonic currents.
iv. Correlate any captured disturbance waveforms with possible causes in order to establish a category for the cause to aid identification [1]. In general:
    a. High-frequency voltage variations will be limited to locations close to the source of the disturbance (low-voltage wiring often damps out high-frequency components very quickly due to circuit resistance).
    b. Power interruptions close to the monitoring location will cause an abrupt change in voltage while those remote from the monitor will result in a decaying voltage due to stored energy in motors and capacitors.
    c. The highest harmonic voltage distortion levels will occur close to capacitors that are causing resonance problems (a single frequency will usually dominate the voltage harmonic spectrum).

Other methods such as the total harmonic distortion measurement, travelling wave-based methods, and wide-area protection using phasor measurement units (PMUs) are proposed, each offering several advantages and disadvantages.

In addition to the above, the use of physical devices for adjusting the current levels have been examined in the literature. The utilisation of energy storage units to increase fault current levels and the use of fault current limiters (FCLs) to limit the fault magnitude from the grid side or SG units are among such proposals [12] [21]. Increased costs, as well as the need for proper control and operation, are among the challenges of using such devices.

4. Summary

This Technical Note has described power quality monitoring and disturbance assessment particularly in relation to plant investigations (i.e. reactive monitoring) rather than monitoring as part of a regulatory compliance survey.

The purpose of power quality monitoring and assessment was introduced then the impact of power quality disturbances on plant equipment was described via the different categories of disturbance, namely, Variations and Events, including how they are characterised.

Investigation methodology was outlined including objectives, where to monitor, what to monitor, and suggested monitoring period. Assessment procedure was detailed together with relevant standards, description of assessment software, a problem analysis guide and some practical considerations.

Simulation studies and practical experiments have investigated the effects of communication network problems such as packet loss, latency, and jitter on microgrid operation [9]. It has been shown that these issues can have a very negative impact on the system operation in terms of voltage, frequency and power losses.

In addition to the aforementioned characteristics, the communication system must ensure interoperability among various IEDs, communication technologies, and protocols. Furthermore, it should be flexible enough to cope with the frequent changes that happen in microgrids by adding or removing devices. Cybersecurity issues are another major concern as the number of interconnected devices grows continuously.

6. References

[1] Dugan, R., McGranaghan, M., Santoso, S., Beaty, H., Electrical Power Systems Quality, Third Edition, McGraw-Hill 2012.

[2] Chapman, D., The Cost of Poor Power Quality, Copper Development Association, 2001.

[3] IEEE Std 1100-2005, IEEE Recommended Practice for Powering and Grounding Electronic Equipment, 2005.

[4] IEEE Std 1159-2019, IEEE Recommended Practice for Monitoring Electric Power Quality, 2019.

[5] AS/NZS 61000.2.4:2009, Electromagnetic compatibility (EMC) Part 2.4: Environment–Compatibility levels in industrial plants for low-frequency conducted disturbances, Standards Australia, 2009.

[6] TR IEC 61000.2.6:2012, Electromagnetic compatibility (EMC) Part 2.6: Environment–Assessment of the emission levels in the power supply of industrial plants as regards low-frequency conducted disturbances, Technical Report, Standards Australia, 2012.

[7] AS 60038–2012, Standard voltages, Standards Australia, 2012.

[8] AS 61000.3.100–2011, Electromagnetic compatibility (EMC) Part 3.100: Limits–Steady state voltage limits in public electricity systems, Standards Australia, 2011.

[9] AS/NZS 3000:2018, Electrical Installations (Wiring Rules), Standards Australia, 2018.

[10] Waggoner, R. M. (Editor), Practical guide to quality power for sensitive electronic equipment, 2nd Edition, EC&M Books, Intertec Publishing Corp., Kansas USA, 1997.

[11] TR IEC 61000.3.6:2012, Electromagnetic compatibility (EMC) Part 3.6: Limits–Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems, Standards Australia, 2012.

[12] Australian Power Quality and Reliability Centre, Technical Note No. 1 – Understanding Power Quality, June 1998.

[13] AS/NZS 61000.2.2:2003, Electromagnetic compatibility (EMC) Part 2.2: Environment–Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems, Standards Australia, 2003.

[14] AS/NZS 61000.2.12:2003, Electromagnetic compatibility (EMC) Part 2.12: Environment–Compatibility levels for low-frequency conducted disturbances and signalling in public medium-voltage power supply systems, Standards Australia, 2003.

[15] TR IEC 61000.3.7:2012, Electromagnetic compatibility (EMC) Part 3.7: Limits–Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems, Standards Australia, 2012.

[16] TR IEC 61000.3.13:2012, Electromagnetic compatibility (EMC) Part 3.13: Limits–Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems, Standards Australia, 2012.

[17] SA/SNZ TR IEC 61000.3.14:2013, Electromagnetic compatibility (EMC) Part 3.14: Limits–Assessment of emission limits for harmonics, interharmonics, voltage fluctuations and unbalance for the connection of disturbing installations to LV power systems, Standards Australia, 2013.

[18] AS/NZS IEC/TR 61000.2.8:2009, Electromagnetic compatibility (EMC) Part 2.8: Environment−Voltage dips and short interruptions on public electric power supply systems with statistical measurement results, Standards Australia, 2009.

[19] AS/NZS IEC/TR 61000.2.14:2009, Electromagnetic compatibility (EMC) Part 2.14: Environment−Overvoltages on public electricity distribution networks, Standards Australia, 2009.

AUSTRALIAN POWER QUALITY AND RELIABILITY CENTRE

APQRC

For more information please contact:

Sean Elphick
Australian Energy Power Quality and Reliability Centre
University of Wollongong
Northfields Avenue
Wollongong NSW 2522
Australia

Phone: +61 2 42214737
Fax: +61 2 42213236

Email: elpho@uow.edu.au
Web: https://eisweb.adeis.uow.edu.au/apqrc/

UNIVERSITY OF WOLLONGONG