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Assessing network compliance for power quality performance

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Assessing Network Compliance for Power Quality Performance

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***Abstract* - IEC standards suggest that a network is compliant if 95% of the sites are compliant. In many cases it is only practical to measure the PQ parameters of some of the sites in a network and to use statistical analysis. The paper examines the minimum number of monitored sites needed to demonstrate compliance with a prescribed degree of confidence - e.g. at the 95% confidence level. Analysis is made of samples extracted randomly from sites included in the Australian Long Term National PQ Survey. The required number of sites is found to vary with the PQ disturbance of concern and is largest with voltage unbalance. In all cases the number exceeds that proposed in CEER guidelines.**

***Index Terms*—Power Quality Indices, Power Quality Monitoring**

I. INTRODUCTION

Large scale power quality monitoring systems using permanently installed monitoring instruments are becoming much more common. A survey conducted by CIGRE/CIRED joint working group C4.112, summarised in [1], indicates that 82% of utilities have permanent monitoring systems installed. 60% of these utilities have more than 20 instruments. The necessity to demonstrate compliance with local or international regulations at individual sites is stated to be the motivation for installation of power quality monitoring systems for 66% of survey respondents.

The aforementioned survey indicated that power quality compliance of individual sites is important to utilities. With more and more large power quality monitoring systems being installed and with regulators taking greater interest in power quality, it can be reasonably assumed that in addition to compliance at each site, compliance of the entire network will also be of interest. This then raises the question of how can a utility prove overall network compliance. The solution at high voltage (HV) or even medium voltage (MV) where the number of sites is relatively small might be simply to install an instrument at each site. However, this methodology is not applicable at low voltage (LV) where sites numbers can be very large. The key question then becomes what proportion or number of sites at LV is appropriate to monitor across a network in order to verify whole of network compliance. Secondary considerations include is this number of sites feasible and what will the monitoring protocol be?

IEC documents such as [2] favour an approach which involves 95% compliance in time and space. Put more simply, this means that 95% of sites should comply 95% of the time. However, 95% of available LV sites is an impractically large number of sites to directly monitor. This means a sample of the population of LV sites should be selected and results analysed using statistical estimation techniques. While there is very limited literature available which gives guidance as to the sample size required to prove network compliance at LV sites, the Council of European Energy Regulators (CEER) Guidelines of Good Practice on the Implementation and Use of Voltage Quality Monitoring Systems for Regulatory Purposes [3] recommends the following site numbers for various statistical indicators of overall network performance:

- 20 sites if averages over all locations will be reported
- 200 sites if 95^{th} percentile values over all locations will be reported
- 1000 sites if 99^{th} percentile values over all locations will be reported

While the CEER guidelines do give specific site numbers, no reference is made as to how these were obtained. This paper investigates the number of sites required in order to prove network compliance using the mean or average site, the 95^{th} percentile site and the 99^{th} percentile site. Of these three statistical indicators, the 95^{th} percentile value is seen as the most important as it is the most commonly cited value both in standards and in theoretical statistics. The mean has been investigated here as there are well defined statistical methods that can be used to determine sample sizes and these can be used as a first step toward determining the site numbers required for other statistical indicators. The 99^{th} percentile values are examined in order to assess how many additional sites would be required to determine if 99% of sites are compliant since it is possible that compliance requirements might be tightened at some future time.

While there are well accepted statistical methods to determine the number of sites required to calculate a mean value for the whole network, such methods to determine the number of sites required for 95th percentile and 99th percentile values are less well known, are more complex and use order statistic theory. Instead, an empirical study has been undertaken to determine required site numbers using data from the Long Term National Power Quality Survey (LTNPQS), a long running large scale power quality survey conducted in Australia.

II. LTNPQS Data and Disturbance Indices

A. *Introduction to the LTNPQS*

Proactive monitoring of power quality across Australia has been undertaken since 2002 through the Australian Long Term National Power Quality Survey (LTNPQS) as described in [4] and [5]. Since inception, the database of power quality data associated with this project, which is housed at the University of Wollongong, has grown to include data from over 3300 sites provided by 12 of the 16 Australian electricity distribution utilities. These sites include a mix of low (230 V) and medium/high (6.6 kV – 132 kV) voltage sites. Utilities that currently participate or have participated in the LTNPQS project supply electricity to at least 90% of the population of Australia.

B. *Data Utilised in this Study*

For the purposes of this paper a specific data set has been selected from the LTNPQS database. This data set comprises of the LV site data for the 2009 – 2010 and 2010 – 2011 Australian financial years (1 July – 30 June). Data was available for voltage variation, voltage unbalance and voltage THD. In order to be included in the data set, the site must have been monitored for a least half (50%) of each financial year. Table I shows the number of sites available for the study. It can be seen in the table that the site numbers have been categorised as either strong or weak. A strong LV site is one which is very close to the supply transformer terminals while a weak site is one which is remote. The distinction has been made between strong and weak sites due to the fact that it was shown in [6] that weak sites can have considerably different power quality performance to strong sites. As such, the site numbers required to assess the performance for strong and weak sites can reasonably be assumed to also differ considerably.

TABLE I: LTNPQS Site Numbers Available for Study

	2009 - 2010			2010 - 2011		
Disturbance	**Strong Sites**	**Weak Sites**	**Total**	**Strong Sites**	**Weak Sites**	**Total**
Voltage	1620	72	1692	1174	71	1245
Unbalance	1100	71	1171	1172	70	1242
Harmonics	1613	62	1675	1168	71	1239

It should be noted that there are some limitations related to the data that has been used for this study which must be taken into account when an estimation of site numbers is made:

- The data used in the study is heavily biased toward strong sites. It has been shown in [6] that there can be significant differences between power quality levels at strong and weak sites. The impact of this limitation is that the study will most likely underestimate the actual site numbers required for estimation of the population value.
- The data used for unbalance may have accuracy limitations related to unbalance being calculated from line-neutral rms voltage values. This is due to the fact that few of the instruments used have the ability to measure true negative sequence unbalance.

C. *LTNPQS Reporting Indices*

A range of site reporting indices have been developed especially for the LTNPQS. These site indices form the basis for the analysis presented in this paper. The following are the indices used for assessment of each disturbance in this paper:

- **Voltage Variation** – the index used for voltage is Absolute Voltage Deviation (AVD). AVD is a measure of the spread of voltage around the middle of the nominal voltage range. The limit for AVD is 8%. Further details of AVD are given in [7].
- **Voltage Unbalance** – the 95th percentile level of the negative sequence voltage unbalance at a site is the reported index. The limit for voltage unbalance used in the LTNPQS is 2%.
- **Voltage Harmonics** – The Total Harmonic Distortion (THD) is used to define voltage harmonics. The 95th percentile level of the voltage THD at a site is the reported index. The limit for voltage THD used in the LTNPQS is taken from the Standards Australia handbook HB264 [8] and is 7.7%.

III. Methods to Determine Site Numbers

A. *Method to Determine Number of Sites Required for Mean*

There are well defined statistical methods which can be used to calculate the number of sites (i.e. sample size) which are required to estimate the mean of the population for a given confidence and allowable error. When the standard deviation of a population is known, the population mean can be described as shown in (1) and (2) [9].

$$\mu = \bar{x} \pm E \quad (1)$$

and

$$E = Z_{crit} \times \frac{\sigma}{\sqrt{n}} \quad (2)$$

where:

- E is the acceptable error value,
- n is the number of sites,

- Z_{crit} is the Z critical value for the required confidence level (1.96 for 95% confidence, 2.58 for 99% confidence) based on a normal distribution,
- σ is the population standard deviation and
- $\bar{x}$ is the sample mean.

Rearranging (2), the equation to determine the number of sites required to give an estimate of the overall population mean to within an acceptable error for a given confidence level is given in (3).

$$n = \left(\frac{Z_{crit} \times \sigma}{E}\right)^2 \qquad (3)$$

The only variable which is not known in (3) is σ. However, if some data is available σ can be approximated by the sample standard deviation if the sample size is large enough. It can clearly be seen that the number of sites is sensitive to the acceptable error value which is user defined and the sample standard deviation which is related to the variability in disturbance levels across sites.

B. *Method to Determine the Number of Sites Required to Assess Compliance for 95% and 99% of Sites*

While statistical methods exist to determine the number of sites required in a sample to achieve a good estimation of the population mean, theoretical methods to determine the number of sites to give a good estimation of the population 95th or 99th percentile levels are less well defined. As such, in order to investigate this problem an empirical study has been undertaken using the data for all sites for the 2009-2010 financial year as described in Section II.B. The methodology for the empirical study was as follows:

- Samples of differing size (*n*) were selected at random from the available data. For the purposes of this study *n* is was chosen as 20, 50, 100, 200 and 500.
- The 95th or 99th percentile value is calculated for each sample.
- This process is repeated 1000 times for each value of *n*. This leads to 1000 values for each sample size, e.g. for *n* of 20 there are 1000 95th percentile values.
- The distribution of the 1000 values for each *n* is then compared to the actual 95th or 99th percentile value of the population used for this study.

IV. Determination of Site Numbers

A. *Site Numbers Required to Calculate Population Mean*

The number of sites required to estimate the population mean can be calculated using (3). However, an acceptable error value and a sample standard deviation is required. For the purposes of this paper, the acceptable error has been specified to be ±5% of the disturbance limit. Based on this requirement, the required error for each disturbance is shown in Table II.

TABLE II: Required Error for Each Disturbance

Disturbance	Limit (%)	Error (%)
Voltage	8	0.40
Unbalance	2	0.10
Harmonics	7.7	0.39

The standard deviation calculated from the data described in Section II.B is shown in Table III.

TABLE III: Standard Deviation Values for Study Data

	2009 - 2010			2010 - 2011		
Disturbance	**Strong Sites**	**Weak Sites**	**All Sites**	**Strong Sites**	**Weak Sites**	**All Sites**
Voltage (%)	1.83	1.23	1.81	1.81	1.43	1.79
Unbalance (%)	0.65	1.58	0.83	0.61	1.34	0.76
Harmonics (%)	0.97	1.38	1.00	0.95	1.23	0.99

Based on the error values shown in Table II and the standard deviation values shown in Table III, Table IV shows the site numbers required for 95% confidence. Table V shows the same information based on a 99% confidence level. In order to explain the significance of the data it is best to choose an example. Take voltage at strong sites for 2009 – 2010 where the required number of sites is 81. This value is interpreted as follows: for voltage at strong LV sites if a sample of 81 sites is taken from the population 100 times, the sample mean value will be within ±0.4 (the required error for voltage) of the population mean 95 out of 100 times.

TABLE IV: Site Numbers Required for Estimation of Population Mean with 95% Confidence

	2009 - 2010			2010 - 2011		
Disturbance	**Strong Sites**	**Weak Sites**	**All Sites**	**Strong Sites**	**Weak Sites**	**All Sites**
Voltage	81	36	79	78	49	77
Unbalance	163	958	265	141	694	220
Harmonics	24	48	25	23	38	25

TABLE V: Site Numbers Required for Estimation of Population Mean with 99% Confidence

	2009 - 2010			2010 - 2011		
Disturbance	**Strong Sites**	**Weak Sites**	**All Sites**	**Strong Sites**	**Weak Sites**	**All Sites**
Voltage	139	63	136	135	85	132
Unbalance	281	1654	457	244	1199	380
Harmonics	41	83	43	39	66	42

The tables above indicate that approximately 100 - 150 sites are sufficient to get a good estimate of the population mean for voltage variation and voltage harmonics. Significantly more sites are required for voltage unbalance.

An empirical study was also carried out using the method described in Section III.B. Based on the criteria of the distribution of sample 5th and 95th percentile values being within ±10% of the actual values, it was found that 50 sites were required for voltage variation and harmonics and 200 sites were required for unbalance. This result tallies well with the site numbers specified in Table IV.

B. Site Numbers Required to Estimate Population 95th Percentile Value

The method as described in Section III.B has been used to determine the number of sites required to estimate the population 95th percentile value. In the first instance the distribution of the 1000 values for each sample size *n* is described by the maximum and minimum value. This provides the worst case scenario and is the upper limit for site numbers. For the purposes of this study, the number of sites required is considered sufficient if the sample distribution is within ±10% of the true population value. To better explain this, take the example of Figure 1 which shows the distribution of sample values for *n* = 20 sites. For Voltage Variation, the actual value is 8.25% as shown by the solid line on the graph. The ±10% values are 7.43% and 9.08% which are shown as the dashed lines on the graph. In order for *n* = 20 to give a good estimate of the population value, based on a distribution described by the minimum and maximum value, all of the bars on the chart should fall between the two dashed lines. For this graph this is clearly not the case, as such, a sample size greater than 20 sites is required to give a good estimate of the population value.

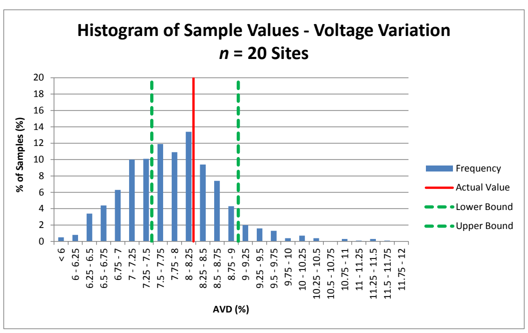

Figure 1. Example Graph Showing Distribution of Sample Values

1) Voltage Variation

Figure 2 shows the percentage difference between the distribution of the sample maximum and minimum values and the population value for each sample size. Dashed lines have been added to the graph to indicate the ±10% values. It can be seen from the figure that almost the entire distribution of sample values is within ±10% for an *n* of 200 sites. The distribution of the sample values is well within the ±10% constraint for *n* = 500 sites. As such, it could be said that between 200 and 500 sites are required to give a good estimation of the population 95th percentile value for the voltage variation index used in this study.

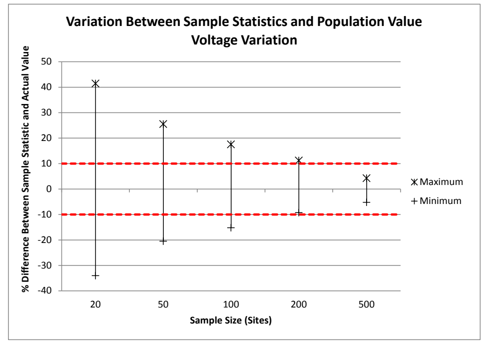

Figure 2. Variation between Sample Distribution and Population Value for Voltage Variation

2) Voltage Unbalance

Figure 3 shows the number of sites required to give an estimate of the population value for voltage unbalance. It can be seen that even with *n* = 500 sites, the distribution of sample values is still greater than ±10% from the population value.

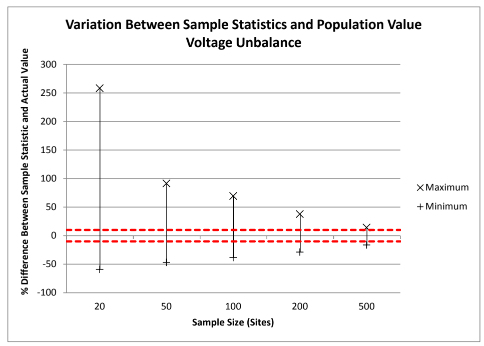

Figure 3. Variation between Sample Distribution and Population Value for Voltage Unbalance

3) Voltage Harmonics

Figure 4 shows the number of sites required to give an estimate of the population value for voltage harmonics (THD). It can be seen that for *n* = 200 sites, the distribution of sample values is almost within ±10% of the population value.

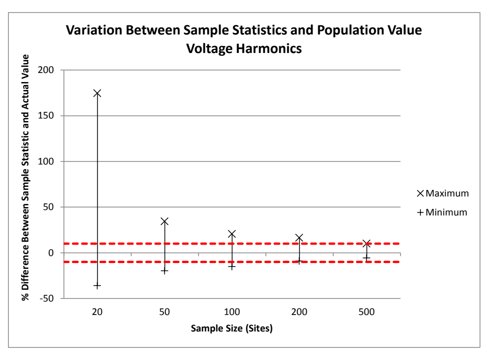

Figure 4. Variation between Sample Distribution and Population Value for Voltage Harmonics

4) Discussion

The empirical study performed in this paper indicates that at least 200 sites are required to gain a reasonable estimation of a population 95th percentile value for voltage variation and voltage harmonics. For voltage unbalance, it has been shown that not even 500 sites will give a good estimation of the population 95th percentile value. This indicates that there is very large variability in the underlying population for these disturbances. For voltage unbalance, some of the diversity can be attributed to the impact of weak sites where the voltage unbalance levels tend to be significantly different from those at strong sites as discussed in [10].

In order to remove the high variability usually associated with maximum and minimum values, if the distribution of the sample values is described by the 99th and 1st percentile values as opposed to the maximum and minimum (effectively changing the confidence level), the new site numbers required for the sample distribution to be within ±10% of the population value are given in Table VI. It can be seen that 500 sites will give a good estimate of the population value for voltage variation, voltage unbalance and voltage harmonics.

TABLE VI: Site Numbers Required to Estimate Population 95th Percentile Value for Sample Distribution Described by 99th and 1st Percentile Values

Disturbance	Number of Sites
Voltage Variation	100
Voltage Unbalance	~500
Voltage Harmonics	~200

C. *Site Numbers Required to Estimate Population 99th Percentile Value*

Using the same methods applied in Section IV.B, the number of sites required to estimate the population 99th percentile to within ±10% of the actual value is greater than 500 for all disturbances regardless of whether sample distributions are based on maximum and minimum or 99th percentile and 1st percentile values.

V. Conclusions

This study has presented a statistical methodology which can be used to determine the number of sites required to calculate PQ levels across entire networks. While there are well accepted statistical methods to determine the number of sites required to estimate a mean value for the whole network, such methods to determine the number of sites required for 95th percentile and 99th percentile values are less well defined. Instead, an empirical study has been performed in order to determine site numbers for these statistical parameters.

Overall, it has been found that the site numbers required to estimate the population value vary considerably based on the disturbance type and the position of monitoring. Similar site numbers are required to estimate population values for voltage variation and voltage harmonics. However, many more sites are required to estimate population values for voltage unbalance.

Comparing the results of this study with site numbers published in the CEER Guidelines of good practice on the implementation and use of voltage quality monitoring systems for regulatory purposes shows that the CEER recommended value of 20 sites for calculating an overall network average (mean) value is not sufficient. The values of 200 and 1000 sites for estimating 95th and 99th percentile values respectively are acceptable for voltage variation and harmonics but are likely not sufficient for voltage unbalance.

The data utilised in this study is heavily strong site biased, that is it comes mostly from sites close to distribution transformer terminals. It has been shown that there is more variation in power quality levels for weak sites (those remote from transformer terminals). Given that the statistical analysis in this study is heavily impact by the standard deviation of the sample, this indicates that even more sites than specified in this study may be required if weak sites are taken into account. The impact of weak sites on the required number of sites in order to determine overall network performance is an area of ongoing work.

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