

Reporting and Benchmarking Indices for Power Quality Surveys

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Abstract:

The amount of data retrieved from power quality surveys is very large (in the order of Gigabytes per year) and innovative methods of reporting are necessary to provide useful insights into power quality management. The University of Wollongong has developed, and implemented in a recent Australian survey of several utilities, a series of indices and reporting techniques which greatly simplify the analysis of large amounts of power quality data. This paper outlines the primary indices developed. A Utility Scorecard is proposed as a method of reporting the overall power quality performance of a utility for comparisons with other utilities and for benchmarking purposes.

1. INTRODUCTION

The interest of regulators and the gradual rise in awareness of the effect of power quality disturbances on equipment by customers has led to many utilities beginning to take a much more pro-active stance toward the measurement of power quality levels on their networks. Combined with the continual connection of modern power electronics equipment which produces and/or is susceptible to power quality disturbances, routine power quality monitoring is becoming increasingly important for utilities in order to plan for and maintain acceptable power quality levels on their networks.

At this point in time, financial and logistical expenses make it impossible to monitor power quality at every substation or busbar in all but the smallest of networks. Effective routine power quality monitoring requires as many power quality monitors as possible be scattered strategically throughout a network to provide an overall indication of power quality levels. The amount of data retrieved from only a few power quality monitors over a year is substantial and with such large amounts of data methods of reporting are of paramount importance so that useful insight may be obtained. The authors of this paper have managed The Long Term National Power quality Survey, a routine power quality survey involving several distribution companies covering the majority of the eastern seaboard and almost all of NSW. As a result of this survey, the reporting methods discussed in this paper were developed.

When considering how to report power quality it is important to be mindful of what the utility is interested in or needs to know. Some key objectives in power quality reporting are:

(i) Summarise the level of power quality disturbances at a site

(ii) Clearly show problem sites and disturbances so that remedial action may be undertaken.

(iii) Indicate overall utility performance, possibly against standards as well as other utilities.

Objectives (i) and (ii) may be satisfied by the primary indices calculated for each site as described in Section 2.

It is assumed that at a management level, the overall performance of the utility compared to standards and compared to other utilities will be of most interest, followed by the performance of the various sites. Thus it is essential to provide a method of indicating the overall performance of the utility's sites as well as the performance of the utility compared to the other utilities involved in the survey. In addition, with regulatory authorities now beginning to enforce limits for power quality, it is essential that utilities have access to real data from their networks as well as global levels which shows realistic achievable levels or benchmarks. These benchmarks are extremely useful in that they show the overall realistic levels achievable by the utility and by utilities globally, information that can be taken to regulators for negotiating purposes. Of course confidentiality is an important issue when reporting data from multiple utilities and it is important that the methods used to compare utilities do not disclose confidential information. Objective (iii) may be satisfied by the Utility Scorecard proposal for overall utility indices outlined in Section 3. This Utility Scorecard is a newly developed method and is incorporated into the Long Term National Power Quality Survey compiled by the University of Wollongong.

2. PRIMARY INDICES

Power quality disturbances may be classified into two distinct types requiring different analysis and reporting methods.

1. Variations or Continuous Disturbances: these are present in every cycle of the waveform and may be observed by a handheld meter. Examples of continuous disturbances are voltage level, unbalance, harmonics and flicker. Continuous disturbance levels are often defined by standards using statistical parameters.

2. Events or discrete disturbances: Discrete disturbances such as sags, swells and transients usually occur as isolated disturbances over 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.

There are currently no generally accepted standards dealing with discrete disturbances

The disturbances analysed in the Long Term National Power Quality Survey are voltage, voltage unbalance, voltage harmonics and voltage sags. Before any attempts can be made to provide an overall performance indicator or utility benchmark or indeed calculate primary indices it is essential that consistent measurement practices are adopted across utilities sites may be compared across utilities and utilities benchmarked against each other. For continuous power quality disturbances, [1] is accepted as the established guide on the measurement of power quality disturbances. [1] states that variations should be measured in 10-cycle windows, further averaged to give short term values. Further averaging of these short term values results in 10 minute values which have been accepted in several standards [2, 3] as the most suitable reporting period for power quality disturbances.

Once consistent measurement techniques have been defined, it is natural to look for a statistical method to reduce the data to a form that provides a good degree of detail about the operation of a site, without being overly complicated or ambiguous.

For continuous disturbances, if the quantity is to be characterised by a single number, a statistical measure such as average or maximum, as shown in Fig. 1, might be used. However, in practice, the average can be too optimistic since the waveform is larger than this for a considerable amount of the time and the maximum has been found to be too pessimistic as it occurs only very briefly and may not be repeated for an extended period of time. Primary indices utilise the 95% value, (sometimes called the 95th percentile cumulative probability level) the value which is not exceeded for 95% of the time. Figure 1 shows an example of the various statistical parameters.

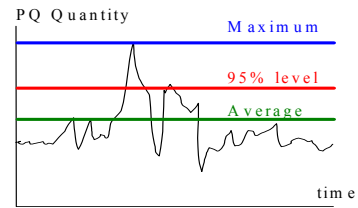


Fig.1: Example of Statistical Parameters

Although the use of the 95% value is suitable for primary indices, 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. Secondary indices, not discussed here, have been developed to account for periods of extreme behaviour.

Once a statistical measure has been decided upon, the question then remains, over what period should the statistical measure be applied? Many standards often call for weekly values calculated from all the data collected over 1 week. However, the use of a weekly value determined from all the data collected over one week fails to address the possibility that in one weeks worth of data sampled at 10 minute intervals, there could be a continuous 8.4 hours worth of data that is significantly higher than the 95% level. To address this, it is recommended that a more suitable measure for a weekly value is the maximum of the daily 95% levels over a week. Where survey durations are greater than one week, the index for each week can be determined and the maximum of these values retained as the index.

For discrete disturbances, statistical analysis is impossible due the fact these disturbances are 'events' and only occur during abnormal operating conditions. The occurrence of a discrete disturbance 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 a discrete disturbance can be said to have occurred? The level which would have to be significant is called the threshold and is often adjustable on power quality monitors. Once the event threshold has been exceeded, the power quality disturbance type needs to be recognised, its parameters determined and stored together with the time and date stamp, a process called event capture.

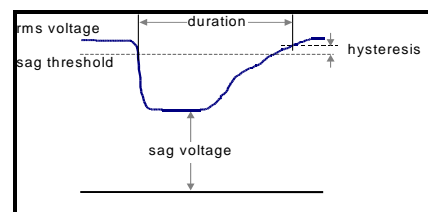


Fig. 2: Sag Threshold and Duration Example

Primary indices provide the basis for the overall indices proposed in Section 3. In most cases, primary indices are calculated using well defined measurement methodology such as that outlined in [1] and

correspond to industry accepted, well defined limits and ranges drawn from various standards. Explanation of the primary indices for voltage, unbalance, harmonics and sags is detailed below.

2.1 Voltage (AVD)

Voltage level is not technically a disturbance and is the only primary power quality quantity for which the optimum measurement should not ideally be zero (for example the optimum result for disturbances such as voltage unbalance or total harmonic distortion is zero). Thus a method of voltage reporting is required that creates a condition whereby zero is the optimum result and increasing values indicate increasing levels of disturbance.

A method of calculating a voltage index that describes the absolute deviation of voltage levels around the centre of the voltage range has been developed. More succinctly, this method calculates the absolute difference between the measured voltage and the voltage in the middle of the desired range. This index is known as the Absolute Voltage Deviation (AVD).

Thus, AVD is a measure of the spread of voltage around a specified range, and can be conveniently expressed as a percentage of the site nominal. The 95th percentile level of AVD can be calculated for each phase, and the maximum of these values retained as the primary voltage index.

2.2 Voltage Unbalance

There are two definitions of voltage unbalance factor (VUF), the international IEC definition and a USA IEEE definition. The IEC definition is becoming widely adopted and is given here. If a three phase set of voltages has positive and negative sequence components V_P and V_N ,

$$VUF = V_N/V_P \quad (1)$$

This takes no account of zero sequence because it has no adverse effect on loads and is often absent at MV levels anyway. Perhaps a better name for VUF is "negative sequence unbalance factor". It can be calculated from simple line-line readings [4]

$$\beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2} \quad (2)$$

$$VUF = \frac{\sqrt{1 - \sqrt{3 - 6\beta}}}{\sqrt{1 + \sqrt{3 - 6\beta}}} \quad (3)$$

Where instruments are able to directly measure and calculate unbalance, according to [1] the voltages used to calculate unbalance should be the fundamental component of the RMS voltage input signal measured over a 10-cycle time interval. Included in [1] is a note

stating that the effects of harmonics shall be minimized by the use of a filter or by using a DFT algorithm. These 10-cycle values may then be RMS averaged to a larger time period with 10 minutes being internationally accepted.

Caution is required when dealing with the measurement of unbalance. Directly measured unbalance should be determined from 10-cycle voltages RMS averaged to a 10 minute time interval. Different power quality monitors may use different methods to calculate unbalance and it is important to ensure that unbalance is being calculated correctly. Failure to sample correctly for unbalance calculation may lead to the loss of high frequency unbalance data and unbalance calculated in this manner has been observed to be up to 30% lower than correctly calculated unbalance [5].

Where directly measured unbalance is unavailable, unbalance may be calculated using the three corresponding voltages and time periods by way of the IEC formula. Again there is the problem of sampling periods and this should be taken into account when unbalance values are examined. In addition the IEC formula requires line-to-line voltages. Where line-to-line voltages are not available, line-to-neutral voltages may be used in the calculation. The use of line-to-neutral voltage in this calculation can result in additional zero sequence components, but these are usually small when 10 minute values are used [2].

The primary index for unbalance is then simply the 95th percentile level of VUF.

2.3 Voltage Harmonics

The measurement of voltage harmonics involves sampling of the voltage waveform many times a second, depending on how many harmonics are required to be determined. The FFT (Fast Fourier Transform) is then applied to find the fundamental component V_1 and harmonics V_2 etc, usually to the 40th order. These values are averaged over 10 minute intervals. The voltage THD is determined at the same time. It is recommended that any harmonic reported as a percentage of the time-varying fundamental voltage be modified to be reported as a percentage of the site nominal voltage, providing a consistent base for comparisons across sites. The use of the actual fundamental voltage is often recommended, but this varies from site to site and from time to time making comparisons awkward.

Sometimes it is useful to determine harmonic phase as well. This enables the harmonic power to be determined. Its direction can be useful in identifying the location of high harmonic sources.

In Australia it is common to concentrate only on the THD and 5th harmonic. Thus the THD becomes an indicator of the overall harmonic state of a site. The 95th percentile level of THD can then be determined for each phase, and the primary harmonic index is the maximum of these values.

2.4 Voltage Sags

From the RMS value of each cycle, the voltage envelope can be determined. PQ monitors generally have adjustable sag or dip threshold settings. The sag start and finish are determined as the instants at which the RMS voltage falls below and then increases above the threshold respectively, allowing the sag duration to be determined. The sag voltage is the magnitude of the retained voltage (often given as a percentage of the nominal voltage) during the sag.

The above description relates to a single phase sag. It becomes more difficult to characterise sags in a 3 phase system as a single number when there are different voltage envelopes on the phases. The solution to this problem is time and phase aggregation. Phase aggregation involves aggregating sags occurring at a common time stamp down to one sag voltage and duration. Time aggregation involves aggregating all sags occurring within one minute of each other into one sag, this prevents sags which occur due to the initial fault such as recloser operations being reported as multiple sags.

Other than reporting each sag individually (large amounts of data), there is no universally accepted method of reporting sags. A primary index called the Sag Index, fully detailed in [6] has been developed to address this problem.

The Sag Index is 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 incorporates a scaling factor so that sags of long duration near the threshold do not appear to be as bad as deeper sags of shorter time. The current method of time and phase aggregation currently employed is as follows - For sags occurring at the same time stamp across multiple phases, the Sag Index of the sag on each phase is calculated and the primary index is the average of these Sag Indices. For Sags occurring within one minute of each other the one with the largest Sag Index is reported and the others discarded.

3. Overall Indices

A method of calculating and presenting meaningful overall indices to provide a utility with an overview of performance has been developed. The overall utility report consists of several sections and is known as the Utility Scorecard. The Utility Scorecard uses overall disturbance indices directly derived from the primary indices discussed in Section II. The Long Term National Power Quality Survey includes many sites from different voltage levels. For ease of reporting, sites have been broken down into low voltage (230V sites) and medium/high voltage (11kV, 22kV, 33kV, 66kV and 132kV) due to the fact that each has different standards and reporting methodologies.

The Utility Scorecard consists of two tables, namely, the Utility Indices Table and the Worst Served Customers Table and series of graphics for benchmarking purposes all of which are described in detail.

3.1 Utility Indices Table

The first table in the Utility Scorecard is the Utility Indices table. The purpose of the Utility Indices Table is to provide some information about the levels of the various disturbances throughout the utility as well as to provide an indication of the performance of the utility with respect to global levels and the levels achieved by the other utilities participating in the survey. In order to do this effectively, two proposed methods of calculating an overall utility index and rank are presented.

The development of overall utility disturbance indices and a method of ranking utilities based on all the primary indices reported in a routine survey is not a trivial task. For long term surveys over several years it was important to develop methods that would allow long term benchmarking. The primary indices cannot be used to calculate some type of statistical measure due to the fact that the units are not consistent and a relative weighting scheme has to be chosen. Normalisation by the maximum acceptable values as given in standards is not possible at this stage because no widely accepted standards exist for voltage unbalance or voltage sags. Two methods of calculating overall utility disturbance indices have been developed and will be compared. For the purposes of this paper we shall call these 2 methods Method A and Method B.

To compare Method A with Method B, an example consisting of four simulated utilities using typical values for each disturbance has been developed. Table 1 shows the disturbance indices obtained for the four simulated utilities A, B, C and D along with the Global Utility Average value for each disturbance.

Table I: Sample Utility RMS values

Utility	Utility RMS Value			
	Voltage (AVD)	Unbalance	Harmonics (THD)	Sags (SI)
A	5.3%	1.4%	5.8%	342
B	3.6%	0.7%	7.2%	745
C	6.7%	2.1%	5.7%	253
D	4.8%	1.0%	4.9%	238
Global Utility Average	5.10	1.30	5.90	394.50

3.1.1 Method A

Using the information in Table 2, Method A assigns a rank to the utility for each disturbance relative to the other utilities. That is the utility with the lowest (best) value for each index is given a rank of 1 and so on. For instance, Utility A has position 3 for voltage, 3 for unbalance, 2 for harmonics and 3 for sags. The overall utility rank is then calculated by first averaging the four disturbance ranks. These averages can then be used to determine the order of the utilities. Table 3 shows the ranking of the utilities in Table 2 using Method A.

Table II: Ranking using Method A

Utility	Utility Position				Average of Positions	Rank
	Voltage (AVD)	Unbalance	Harmonics (THD)	Sags (SI)		
A	3	3	2	3	2.75	3
B	1	1	4	4	2.5	2
C	4	4	1	2	2.75	3
D	2	2	4	1	2.25	1

3.1.2 Method B

Method B utilises a method of normalising the primary indices involving division of the utility RMS values by the global utility average. The choice of the global average as the quantity to divide by was not straightforward. The maximum of the utility RMS values could have been used, giving Normalised utility Index values between 1 and 0. However, the maximum values may often vary considerably from year to year, especially during years with unusual climatic conditions. The maximum may also be more heavily weighted by utilities submitting only a few poor sites and will not be reflective of the levels obtained by most utilities. These factors make comparisons across years difficult and possibly irrelevant.

Values from standards or proposed standard levels based on past surveys could also have been used, but without accepted standards for unbalance and sags, this would not have been practical. Some standards are also derived from overseas values and may not be applicable to Australia.

The average was employed due to the fact that this quantity should not change markedly year to year allowing long term comparisons of indices. Use of the average also ensures that comparisons are being made with actual achievable levels and not levels derived from standards which may be found to be not applicable to Australian networks. Use of the average is also superior to use of the maximum in that it provides a good indication of where the utility lies with respect to the average which is deemed more important than the maximum. A Utility disturbance index greater than 1 shows that the utility is above average in a disturbance while utility disturbance indices less than 1 shows that it is below average.

Once the Normalised Utility Averages have been calculated for each disturbance, calculation of an overall global index is simplified by the fact that each of the overall utility disturbance indices is dimensionless. Thus an overall Utility Index may be calculated by simply averaging the four Utility indices. The overall utility Index is then displayed graphically in the same fashion as the Utility Disturbance indices, giving the utility an indication of how it performed in relation to the other participants.

Table 3 shows the normalised indices and rank for each utility using Method B

Table III: Ranking using Method B

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

3.1.3 Comparison of Method A and Method B

Table 2 (Method A) shows that Utility A finishes equal last in spite of not finishing last for any disturbance and recording Utility RMS Values that are around average, while Utility B which shows good Utility RMS Values for voltage and unbalance and poor values for harmonics and sags finishes second. This then begs the question - is Utility B, which has good results for voltage and unbalance but very poor results for harmonics and sags, a better utility than Utility A, which shows average results across the board? Intuitively and comparatively, the answer must be no and this highlights how ranking using just utility positions and no other information, as is the case for Method A, can create misleading results and can greatly disadvantage some utilities while helping others.

As can be seen from Table 3 Method B using normalised indices places Utility A second, which is intuitively closer to the overall performance of the utility than the rank of fourth obtained using past methods. On the other hand, Utility B is now ranked third, again closer to what the performance of Utility B seems to be intuitively.

Thus Method B is seen to be superior to Method A and has been adopted as the preferred ranking method for the Utility Indices Table. The Table shows the Utility RMS Value, known as the Utility Average, of the primary indices for each disturbance. The global average of the RMS values (Global Utility Average) achieved by all utilities is provided for comparison. The Global Utility Average is the average of the Utility Averages for each disturbance from all participating utilities. A Normalised Utility Average is then calculated by dividing the Utility Average by the Global Utility Average. An example of the Utility Indices Table is shown in Table 4 (note that these are typical values and not the results of a particular survey).

Table IV: Utility Indices Table

Indices	Utility Average		Global Utility Average		Normalised Utility Average	
	LV	MV	LV	MV	LV	MV
Voltage (AVDI)	5.30%	2.12%	5.10%	2.50%	1.04	0.85
Unbalance (VUFI)	1.40%	6.30%	1.29%	1.02%	1.09	6.18
Harmonics (THDI)	5.80%	3.98%	5.90%	2.70%	0.98	1.47
Sags (SI)	342	98.7	394.5	165.2	0.87	0.60

This table is conditionally formatted to display Normalised Utility Average Index values greater than 1 shaded red, values between 0.8 and 1 yellow and values less than 0.8 green. This conditional formatting quickly identifies problem disturbances.

3.1.4 Graphical Representation of Utility Ranking

To compliment the Utility Indices Table, the Normalised Utility Averages are also illustrated

graphically, so that the utility can easily visualise where its disturbance levels lie with respect to the other utilities participating in the survey. There are four graphs, one for each disturbance, at each voltage level. Figure 3 shows an example of how the Utility Disturbance Indices are presented. The Utility which is being reported has its value in black. This graphical method has the advantage that it quickly allows a utility to determine where it stands in comparison to the other participating utilities without divulging any confidential details.

In addition to the Normalised Utility Averages graphics, the overall utility indexed, which is not shown in the Utility Indices Table, is also shown graphically in order to indicate where a utility finished with respect to other participating utilities. An example of this may be seen in Figure 4

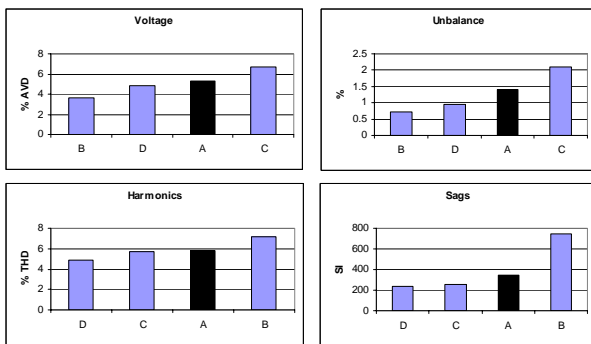


Fig. 3: Example of Utility Normalised Averages Graphics showing the reported Utility (A) in black

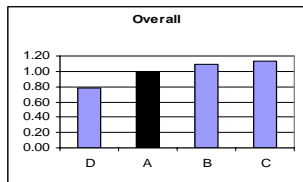


Fig 4: Graphical Representation of overall Rank

3.2 Worst Served Customers Table

The Worst Served Customers Table shows the 95th percentile levels achieved by all sites of all utilities involved in the survey. This means that the worst served 5% of customers will experience disturbance levels at least as high as those reported in this table. This information can be useful when approaching regulators with regard to the levels achievable both locally and globally. For each disturbance this table shows the primary index levels achieved by 95% of the Utility's sites (Utility 95% Site Level) as well as the primary index levels achieved by 95% of sites in the survey (i.e. globally across all utilities) (Global 95% Site Level). In the third section of the table, comparisons to global values are drawn by showing a ratio of utility values to global values. A ratio less than 1 shows that 95% of the utilities sites can meet what is being achieved by 95% of sites across the survey. Utilities which have ratios greater than 1 have more

than 5% of sites which are above the levels being achieved by the worst 5% of sites across the survey. Table 5 shows an example of the Worst Served Customers Table. This table is also conditionally formatted to display Normalised Utility 95% Site Level values greater than 1 shaded red, values between 0.8 and 1 yellow and values less than 0.8 green. This again allows quick identification of problem disturbances.

Table V: Worst Served Customers Table

Indices	Utility 95% Site Level		Global 95% Site Level		Normalised Utility 95% Site Level	
	LV	MV	LV	MV	LV	MV
Voltage (AVDI)	6.20%	2.50%	7.23%	3.26%	0.86	0.77
Unbalance (VUFI)	1.50%	0.86%	2.55%	1.45%	0.59	0.59
Harmonics (THDI)	6.10%	4.12%	4.98%	4.53%	1.22	0.91
Sags (SI)	623	595.8	722.69	662.9	0.86	0.90

4. Conclusions

Reduction of the large amounts of data obtained from routine power quality surveys to easily comprehensible indices is not a trivial task. The University of Wollongong has developed a series of primary indices that give a direct indication of the performance of a site. For variations or continuous disturbances, 95% values are used, while for sags a new approach has been developed due to the fact that there are no applicable sag standards.

A proposal for further reducing data to give an overall report which provides an overview of power quality levels across the entire network and would be of special interest to management has been developed. This proposal known as the Utility Scorecard reduces data to a single number for each disturbance based on primary indices and allows for quick indication of where the utility stands with regard to average and 95th percentile levels globally. In addition, a method of showing a utility's performance compared to other utilities without divulging any confidential information has also been developed.

5. References

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- [2] IEC Standard for Electromagnetic Compatibility (EMC) – part 3: Limits – Section 6: Assessment of Emission Limits for Distorting Loads in MV and HV power Systems, IEC 61000-3-6:1996.
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[6] V.J. Gosbell, D. Robinson, S. Perera, "*The Analysis of Utility Voltage Sag Data*", International Power Quality Conference Proceedings, Oct 2002, Singapore, pp. 479-490.