

# NEW FRAMEWORK FOR UTILITY POWER QUALITY (PQ) DATA ANALYSIS

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## Abstract

Power quality monitoring of many sites of a utility produces an enormous amount of data. The analysis of this data can take place in many different ways at many different levels. This paper provides a conceptual framework for describing the data analysis process. It can be represented graphically in the form of a triangle with data flow from the bottom upwards and enables consistency in PQ analysis and helps identify where there are deficiencies in present analysis practices.

## 1. INTRODUCTION

The electric power industry is continuing to evolve into a competitive market as deregulation takes place. Together with this and the increasing number of sensitive loads that are being connected to the electricity network, customer expectations are also increasing. Regulatory bodies are also beginning to demand that electricity suppliers set and meet benchmark objectives, treating electricity to be like any other product [1]. There is greater emphasis by regulators on regular monitoring of power quality [2] to demonstrate that PQ objectives have been met.

One problem associated with regular monitoring is that a large volume of unstructured data covering the various types of power quality disturbances is produced. The collected data is not in a suitable form to give insights to the general long term PQ condition of a particular site or a particular area within the network. Although there has been a considerable amount of work on the characterisation of individual types of power quality disturbances and particular indices [3, 4], there exists no framework that allows one to examine the overall power quality. The development of Power Quality Indices (PQI) using many levels of structured data analysis will be the solution to the above requirement. Such PQI can be used to

1. Meet regulator requirements.
2. Provide customer information, so that they can design plant to be reliable.
3. Give network planners information as to whether PQ objectives are being met.
4. Allow prioritisation of network upgrades to improve power quality.
5. Allow comparison with other utilities to establish best practice.
6. Provide a basis for customer PQ contracts and premium power.

The development of a framework for power quality data analysis aimed at the establishing PQIs is the main theme of this paper. For this purpose, the already existing concepts behind disturbance characterisation and disturbance indices are revisited. The disturbances covered include long term rms voltage variations, voltage unbalance, flicker and harmonics, voltage sags, swells and transients, both oscillatory and impulsive. Rapid changes in voltages (as mentioned in the voltage fluctuation standards), interharmonics and notching have not been considered for brevity.

## 2. PROPOSED FRAMEWORK FOR PQ DATA ANALYSIS

### 2.1 The PQ Analysis Triangle (PQAT)

The information flow from one monitored site can be enormous. Neglecting transients, which impose an even large data flow requirement, the sample rate for PQ monitoring is set by the Australian standards on harmonics which includes harmonics up to the 40<sup>th</sup>. Assuming that three phase voltages are monitored with a minimum sample rate of 4kHz, a sampling accuracy of 12 bits gives about 10GB of data per week from one site.

This information flow will be overwhelming unless it is structured suitably. The Power Quality Analysis Triangle given in Figure 1 has been developed to show the different data formats and their relationships. The original sampled data is shown as Block 1 at the base of the triangle. Broadly the different disturbance types need to be identified and a single index determined for each covering a standard period, usually a year. There are several steps in achieving this as indicated. At each step the data is reduced, a process we call "time compression". This ultimately leads to a single PQI for

the monitored site at Block 9. Succeeding steps are different in that the data for larger and larger areas are brought together, a process we call "space compression". This diagram provides a consistent conceptual framework for identifying the function of individual PQ data analysis approaches in the overall data analysis procedure.

The processes within the "time compression" stages are best explained by making the distinction between "continuous" and "discrete" disturbance types. Continuous disturbances are present in every cycle to a greater or lesser degree. Thus for the types to be considered in this paper, voltage level, unbalance, flicker and harmonics, it is possible to calculate a measure every cycle. The discrete types appear as isolated and independent events. This difference can be seen in the different approaches to reporting. Continuous events can be shown as a trend graph giving the disturbance magnitude as a function of time. Discrete events can be given as a series of diary entries, where

for each date and time-stamped event a captured waveform (rms in the case of sags, instantaneous in the case of transients) is given.

There are differences in the way the two types of disturbances affect equipment and so they require different approaches to the specification of maximum acceptable levels. Except for flicker, the effect of continuous disturbances on equipment is mainly thermal. The value for one cycle has little direct relationship with equipment damage. It is normal to measure the influence of a continuous disturbance by some longer term statistical average. Each discrete event can have a significant impact on equipment operation. However, once the event has passed, there is in general no long term memory effect, and the equipment will respond to the succeeding events independently. Thus the acceptable levels of discrete disturbances tend to be expressed as the number of events exceeding a certain level of severity.

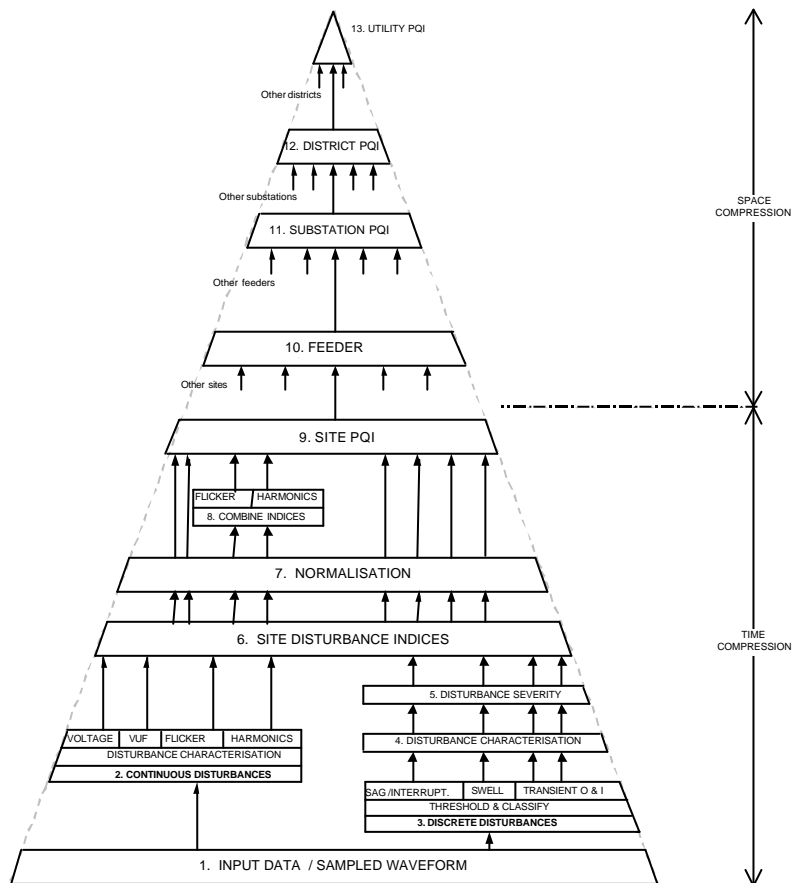


Figure 1: PQ Analysis Triangle

Note that only the functions of the various blocks are given in general with specific algorithms to be discussed later where they have been developed.

## 2.2 Time Compression

At the base of the triangle is Block 1, the raw data from the sampled points of the voltage at particular site. *Disturbance characterisation* is the determination of appropriate parameters for each disturbance type. For continuous disturbances, this process is relatively straight-forward, resulting in parameters being calculated for each sampled cycle (Block 2). There is one parameter for each of voltage, unbalance and flicker (flicker sensation level) and many for harmonics ( $V_2$ - $V_{40}$  and VTHD).

The procedure for the discrete disturbances is considerably more complex. Each set of data needs to be compared with a threshold to determine which discrete events are present (Block 3). Block 4 then processes each identified disturbance according to its type and ascribes appropriate parameters, for example depth and duration in the case of a sag. There is no simple method of combining all these parameters directly into one overall index for the survey period. We postulate that the next logical stage is to determine a single number for each event to give a measure of its *Disturbance severity*, represented by Block 5. This might be a simple 0 or 1 depending on whether the event lies inside or outside some region such as the CBEMA curve.

Block 6 calculates a *Disturbance index* for each disturbance type to give a measure of levels over the survey period. For continuous disturbances, the 95% cumulative probability level is used in many standards such as flicker and harmonics, and a similar approach can be applied to voltage and unbalance. Little has been done on how a single index can be determined for the discrete disturbances. One approach is a summation of the disturbance severities. Continuing the example of sags in the previous paragraph, one could simply add the severity values giving the number of sags which lie outside the CBEMA curve.

A *Site PQI* is a single PQ index measuring the overall level of PQ disturbances and is accomplished in Block 9 from the individual disturbance indices. This cannot be simply done on the output of Block 6 as there are more than one number to describe flicker and harmonics. Two intermediate stages shown as Blocks 7 and 8 are required to reduce this to one each and this is treated in more detail in Section 5.

## 2.3 Space compression

Further data compression is possible to give indices to show the level of PQ over areas of more than one site. It would be useful if this aggregation could be done in a number of stages. A *Feeder PQI* represents the average PQ along the feeder using the Site PQIs from all monitored sites. Weighting could be applied according to the number of customers or the maximum demand of customers. Feeder PQIs can be lumped in to substation indices, then district indices, and finally a single index for the utility. The benefit of this multi-level approach is that useful information is available to network planners regarding benchmarking with other utilities, and comparisons can be made between districts having different maintenance, protection or operation practices to enable beneficial procedures to be identified. Space compression will not be treated further in this paper.

## 3. DISTURBANCE CHARACTERISATION

### 3.1 Continuous PQ disturbances

#### Overview

This subsection concerns Block 2. Although values for the continuous disturbances can be calculated each cycle, the standards generally recommend that they are combined by averaging over each 10 minute interval. For example the instantaneous flicker sensation level  $P(t)$  is processed by statistical means to give the short term flicker severity index  $P_{st}$ .

It would not be useful to determine voltage level, unbalance and harmonics during sag periods as these represent unusual operating regimes. It is recommended that voltage distortion and unbalance are calculated relative to the nominal rather than the actual voltage, as otherwise periods of sustained low voltage will lead to apparently high values for harmonic distortion etc.

#### Voltage level

The utility has some control over the fundamental voltage while the harmonic voltages are the result of loads. It is recommended that the voltage recorded is that for the fundamental value, not the rms value.

#### Unbalance

The IEC definition of voltage unbalance factor is

$$VUF = \frac{V_n}{V_p} \quad (1)$$

where  $V_n$  is negative sequence voltage and  $V_p$  is the positive sequence voltage. This can be determined using the three line-to-line voltages and

$$\beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2} \quad \text{VUF} = \sqrt{\frac{1 - \sqrt{3 - 6\beta}}{1 + \sqrt{3 - 6\beta}}} \quad (2)$$

### Flicker

Australian standards define two factors related to flicker severity;  $P_{st}$  and  $P_{lt}$  for short term and long term respectively [5]. The second is determined from the first using a cubic law.

### Harmonics

Australian standards require individual harmonics up to the 40<sup>th</sup> and the THD to be determined [6]. Hence the harmonic output of Block 2 will be 40 numbers every 10 minutes.

## 3.2 Discrete PQ disturbances

### Overview

Block 3 has the task of testing the monitored waveform against prescribed thresholds and determining the start and finish of the different discrete events. For example, a sag is a voltage drop to 10-90% for less than one minute. The event waveform is passed to Block 4 where it is characterised depending on the disturbance type.

### Voltage sags and momentary interruptions

Balanced rectangular sags can be characterised by the voltage level and duration. The maximum voltage depth is taken if the voltage envelope is not rectangular. For unbalanced sags, the phase with the greatest sag depth is used to characterise the disturbance, a process called "phase aggregation".

When there are several sags in quick succession, usually as part of protection operation, these are considered to be part of one customer event. The sag with the greatest depth is taken to be the one used for characterisation. This process is called time aggregation and the aggregation period is usually taken as 1 minute [7].

### Voltage swells

A voltage swell is described in [8,9] as an rms voltage rise of up to 120% of the nominal voltage, with a duration of up to 0.5s. Phase aggregation can be used as for sags. It is unlikely that several swells will occur in quick succession and time aggregation is not an issue.

### Transients

IEC 61000-2-5 classification divides transients into two groups: oscillatory and impulsive. Oscillatory transients are the ringing which follows the switching in of power factor correction capacitors while impulsive transients are due to lightning strikes. Oscillatory transients can be characterised by magnitude, oscillatory

frequency and decay time. Impulsive transients can be characterised by rise time, magnitude and decay time.

## 4. DISTURBANCE INDICES

Here we consider the processes of Blocks 5 and 6 whereby annual indices can be determined for each disturbance type.

### 4.1 Continuous disturbance indices

#### General introduction

The output of Block 6 for continuous disturbances is one or more numbers for each 10 minute interval. Some statistical measure is necessary to summarise the disturbance level over a year. Standards are increasingly recognising the 95% Cumulative Probability (CP) Value, the value which is not exceeded 95% of time. Although this measure can be applied in general to continuous disturbances, it will be shown that voltage level requires a special treatment.

#### Indices for voltage level

The 95% cumulative value cannot be applied to voltage level since this will take no account of the separate limits for high and low voltage. This concept is best applied to a parameter which is most acceptable when it is at zero value.

Voltage error is also not appropriate, since positive and negative numbers cannot be combined to give a sensible 95% value. Separate 95% levels for the positive and negative error periods has the difficulty that the 95% period will vary from site to site, depending on whether the voltage is higher or lower than nominal for most of the time.

Absolute voltage error should be chosen since its most acceptable value is zero and its 95% value is a good measure of voltage acceptability. Care must be used when the voltage range is unsymmetrical, as with the new LV Australian standard of 230V +10%/-6%. An absolute voltage error based on 230V would not give proper allowance to the larger margin in the overvoltage direction. The absolute error must be taken with respect to the middle of the voltage range, in this case 234.6V.

Where there is voltage unbalance, the question arises as to how to combine the readings from the three phases. Since there are many single phase customers, an undervoltages in two phases does not excuse an overvoltage in the third. We propose that the 95% absolute error be determined for each of the three phases and the maximum of the three then taken.

### **Unbalance**

The 95% unbalance factor can be taken with none of the difficulties which apply to voltage level.

### **Flicker**

EN50160 [1] refers to the 95% value of the flicker indices  $P_{st}$  and  $P_{lt}$ . In general, these may differ between the three phases. We recommend that the maximum of the three 95% values be taken as a measure of flicker.

### **Harmonics**

AS/NZS61000.3.6 [6] gives limits for each harmonic up to the 40<sup>th</sup> and for the total harmonic distortion. Again, there will be variation between the three phases. Hence, for each of the 40 harmonic "indicators", the three 95% values need to be calculated and the maximum used as the annual index.

## **4.2 Discrete disturbance indices**

### **General Introduction**

The process of finding a single annual index for each discrete disturbance is poorly described. In the case of sags, there have been several papers referring to two or three dimensional histograms [7,10]. This does not lead to a single index and does not enable one to rank sites for mitigation purposes. [11] describes a method where a site can be described by the number of sags which lie outside the CBEMA curve. We now seek to generalise this for the other discrete disturbances.

We define here a *Disturbance severity index* as a number which gives the relative ranking of discrete disturbances as regards its adverse effect on customer equipment. It can be thought of as a number which gives a measure of the percentage of customers who are affected. This is determined in Block 5 and some possible approaches are discussed below for each disturbance type. The Disturbance index is then found by combining the severity index for each event over the year in Block 6. Straight addition of the severity indices is proposed as a simple approach to determining an annual disturbance index.

### **Sags and momentary interruptions**

Discrete PQ disturbances can be simply characterised by the voltage level during the disturbance and duration. The boundary of acceptability can be shown as a plot giving what is sometimes called a voltage tolerance curve or power acceptability curve [8,12]. There are several such curves, such as FIPS, CBEMA, ITIC [13]. The boundary of acceptability can be used to give a number proportional to customer complaints as discussed in [3].

A similar approach is to use the Sag Aggressiveness, being the area of the missing part of the voltage envelope during the sag [14].

The sum of these individual event indices can be used to give the disturbance index. For example, if a site has 10 sags per year, each of duration 0.2 seconds and with a depth of 50%, the Sag Aggressiveness approach would give a severity index of 0.1 for each sag event and an annual sag index of 1.

### **Voltage Swells**

A similar approach can be applied to voltage swells as for voltage sags using the overvoltage part of a voltage tolerance curve such as the CBEMA curve.

### **Transients**

The development of severity indices for transients is poorly developed and much work needs to be done on equipment immunity before proposals can be developed with confidence. Transient standards tend to characterise the impact of an impulsive transient by the energy content, proportional to  $\int v^2 dt$ . This can be determined from the rise time, magnitude and decay time. Alternatively, the rise and decay time allow an equivalent duration to be determined, so the transient can be represented on a CBEMA or ITIC curve. The severity index can be based on the position of the point relative to the voltage tolerance curve. For example, a point lying exactly on the CBEMA curve is given a severity index of 1. Addition of these indices gives the annual transient index.

For oscillatory transients, it appears that the major impact is on equipment such as variable speed drive overvoltage protection [4] and hence the magnitude alone is suitable severity index.

## **5. SITE PQ INDEX**

The disturbance characterisation process described in Section 3 leads to 48 different disturbance indices: voltage (1), unbalance (1), flicker (2), harmonics (40), sag/interruption (1), swell (1), impulsive transient (1), oscillatory transient (1). We now discuss a process whereby these may be reduced to one single index representing the overall PQ performance of the site. There are three steps involved (i) normalisation, (ii) combination of indices for the same disturbance type, (iii) combination of indices for different disturbance types.

Normalisation, represented by Block 7, is the process of dividing an index by the maximum acceptable level. In normalised form, an index is at the limit of acceptability when its value is one. Block 8 then combines the two flicker indices into one overall flicker index. We recommend that the maximum value be taken, with a similar approach for harmonics.

The input to Block 9 consists of 8 indices for each distinct disturbance type. Block 9's output is an overall PQ index. A number of possible algorithms have been proposed, for example: (i) the average of the inputs, (ii) the maximum value of the inputs, (iii) the number of inputs which exceed 1.

The first applies if poor PQ in one area can be made up by good PQ in another. Since the different PQ disturbances affect equipment differently, (i) is not considered to be a good proposal. The second would apply if all equipment types were affected equally. As some types might not be affected at all by very high levels of harmonics, but could be affected by small sags, it is felt that (ii) is also not appropriate. (iii) is a good measure for regulators and the best of the three proposed. Further clarification of the role of overall PQ indices is required before a satisfactory algorithm can be found.

## 6. CONCLUSION

It is clear that the power quality measurement data can be represented at many different levels ranging from the raw measurement data to highly summarised indices. For the first time, this paper has presented a framework which shows the different data formats and processes which link them. Some of these processes are defined in the standards or in the literature. However, there are many areas where clarification is still required.

Research effort is seen to be required in handling the discrete disturbances. For example, the characterisation of irregular voltage sags, time and phase aggregation and the development of corresponding severity indices needs attention. Transient characterisation and the respective indices is also another area open for research.

The development of an overall site PQ index and the subsequent aggregation of indices over large areas is seen as one needing development to give useful insights to network planners.

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