Unified power quality index (UPQI) for continuous disturbances

V. J. Gosbell
University of Wollongong, vgosbell@uow.edu.au

B. Perera
University of Wollongong

H. M. Herath
University of Wollongong

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Unified Power Quality Index (UPQI) for Continuous Disturbances

V.J. Gosbell, *Member, IEEE*, B.S.P. Perera, *Member, IEEE* and H.M.S.C. Herath, *Student Member, IEEE*

***Abstract*-Power quality indices are being developed that attempt to quantify certain aspects of service quality. There has been considerable amount of work on the characterization of individual types of power quality disturbances and corresponding indices. However, there does not exist in the literature a standard approach that allows one to quantify the overall power quality. This paper proposes a Unified Power Quality Index (UPQI) as a useful tool for ranking sites as to their overall power quality.**

***Index Terms*-Power quality, indices.**

I. INTRODUCTION

Power Quality (PQ) monitoring of many sites of a utility produces an enormous amount of unstructured data covering the various types of power quality disturbances. 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 that exists on the characterisation of individual types of power quality disturbances and particular indices [1-3] there exists no framework that allows one to examine the overall power quality.

PQ disturbances can be classified into "continuous" and "discrete" disturbance types. Continuous disturbances are present in every cycle to a greater or lesser degree and typically include voltage level, unbalance, flicker and harmonics. This disturbance type can be represented by a parameter for every cycle or shown as a trend graph giving the disturbance magnitude as a function of time. The discrete types appear as isolated and independent events. Discrete events can be given as a series of diary entries, where for each date and time-stamped event a captured waveform (rms in case of sags, instantaneous in the case of transients) is given.

Many studies have been undertaken on continuous disturbances and problem of disturbance characterisation has largely been solved. Characterisation of discrete disturbances is poorly described in the literature where for example characterisation of irregular voltage sags. time and phase aggregation and the transient characterisation need attention. This paper concentrates only on the continuous disturbances.

There is a need to characterise the level of PQ disturbances in a power system at many levels. One may talk about the variation of harmonics over a week, or seek to give an index, which is a single number, that summarises the harmonic performance at a site over a week or a year. This requires over 40 existing harmonic indices to be compressed into a single index. The process of normalisation and consolidation has been proposed in [4] to give a single disturbance index for each disturbance type.

Where there are many sites under investigation, there is a need for a single number, which we call the Unified Power Quality Index (UPQI), to summarise the overall level of PQ disturbances. If properly defined, a UPQI will have several useful applications

1. Sites with poor power quality could be easily ranked to determine the priority for PQ improvements.
2. It will be easy to represent the levels of PQ across large networks and see if there are meaningful patterns.
3. Network planners will have a single index which they can correlate with planning, protection or maintenance practices.
4. A simple performance indicator can be developed to allow utilities to be compared with each other for benchmarking purposes.

This paper begins by discussing a conceptual framework for power quality data analysis (The Power Quality Analysis Triangle) which we have developed at the University of Wollongong, followed by the development of a single index for describing each disturbance type. A UPQI is defined for continuous disturbances with an application example. Disturbances covered include long term voltage variations, voltage unbalance, flicker and harmonics. Other types such a interharmonics can be easily incorporated by a slight extension.

II. POWER QUALITY DATA ANALYSIS

A. The Power Quality Analysis Triangle (PQAT)

The Power Quality Analysis Triangle (PQAT) given in Fig.1 has been developed to show the different data types, indices and their relationships arising from utility PQ survey measurements [4]. A brief discussion of the PQAT is given below.

The base of the triangle is made up of the raw data (Block 1), with a typical sample rate of 4 kHz. a monitor

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V.J. Gosbell, B.S.P. Perera and H.M.S.C. Herath are with the School of Electrical Computer & Telecommunications Engineering, University of Wollongong, NSW2522, Australia (Corresponding E-mails of author's: v.gosbell@uow.edu.au, s.perera@uow.edu.au and chandana@ieee.org).

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collecting three phase voltage measurements from a site might produce 10GB of data per week. The lower half of the triangle involves a reduction in the dataflow from a site in a series of steps, a process we call 'time compression'. The first step is to break up the data into the different disturbance types and characterise each separately (Blocks 2,3,4). At Block 6, each disturbance is represented by one or more indices giving a measure of the disturbance levels over a specified survey period.

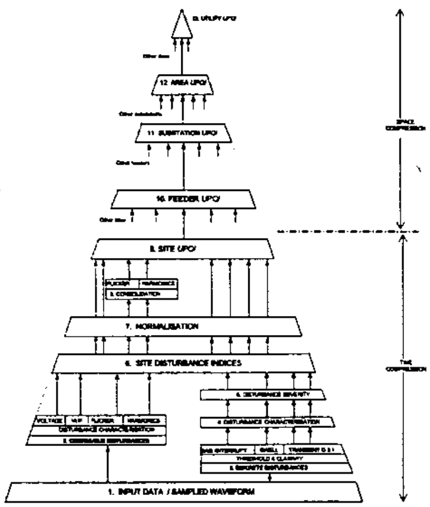

Fig. 1 PQ Analysis Triangle

Block 7 is the level at which the above indices are compared against the set standards limits to see the severity of the site disturbance levels. At the input to Block 9, each disturbance type is represented by one index which is a quotient of the measured level and the set limit. These indices are brought together into form one Unified PQ Index (UPQI) at Block 9. Further movement to the top of the triangle involves incorporation of the unified PQ indices of larger and larger collections of sites into area and utility indices, a process we call "space compression". The following sections give further details on time and space compression.

B. 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 ITIC 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.

A *Site UPQI* 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 *III.*

C. 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 UPQI* represents the average PQ along the feeder using the Site *UPQIs* from all monitored sites. Weighting could be applied according to the number of customers or the maximum demand of customers. Feeder *UPQIs* can be lumped in to substation indices, then district indices, and finally a single index for the utility. However, this is more futuristic and much research required on this aspect.

D. Flexibility of PQAT

PQAT gives an overall framework for describing the PQ data analysis process, not limited to eight disturbance types. Once the characterisation process has been finalised, any number of disturbances can be included into the PQAT framework when an acceptable parameterisation scheme has been developed for particular disturbance type (e.g. Mains signalling).

III. Continuous Disturbance Indices

A. General Introduction

For continuous disturbances the output of Block 2 of the PQ Analysis Triangle 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 a Cumulative Probability (CP) Value of the 10 minute readings taken over one week – typically the 95% value. For a surveying period of several weeks, it is proposed that the worse case value, that is the maximum of the weekly CP values, be taken.

It is noted that standards differ in detail in their approaches to defining the limiting values for continuous disturbances. For example CENELEC EN 50160 [5] refers to the 95% CP value of P_{lt} whereas the corresponding IEC standard refers to the 99% value for both P_{st} and P_{lt}. We shall use the second approach for illustrative purposes here in our discussion of flicker.

It would not be useful to determine voltage level, unbalance and harmonics during the sag periods as these represent unusual operating regime which are going to be reported in any case. IEC 61000-4-30 [6] Draft Standard treats this situation by "flagging" the continuous readings during the sag period to record that they are "exceptional". We prefer that these readings be removed from the record.

It is recommend that the voltage distortion and unbalance are calculated relative to the nominal rather than the actual voltage, as otherwise periods of sustained low voltage lead to apparently high values for harmonic distortion etc.

B. Disturbance Indices

(1) 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. The 95% value is best found for 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.

We propose the 95% value of the absolute voltage error since it has the useful property that its most acceptable value is zero. 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 should 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.

(2) Unbalance: The 95% negative sequence unbalance factor can be taken.

(3) Flicker: Following AS/NZS 61000.3.7 [7], which gives limits for the 99% weekly values of P_{st} and P of 0.9 and 0.7 respectively, we shall take the 99% value for each phase of both P_{st} and P_{lt} and record the maximum over the three phases. Over a longer surveying period, the maximum of these two recorded values is held.

(4) Harmonics: AS/NZS 61000.3.6 [8] gives limits for each harmonic up to the 40^{th} and for the total harmonic distortion. Again, there will be a variation between three phases. Rather than follow this complex approach precisely, we shall take the 95% weekly value of each of the 40 harmonic "indicators" above. For each indicator, the weekly values are recorded for the year and the maximum over the survey period used as the indicator.

AS/NZS 61000.3.6 gives limits on other parameters to limit the short term effects. The short time value (every 10 minutes) has to be limited to the planning level and the 99% of the very short time value (every 3 seconds) has to be limited to 1.5-2 times the planning level. This complexity can be incorporated into the above discussion if required, but we do not think that this has been shown to be necessary yet.

C. Normalisation and Consolidation

There is proposed a two step process involved in the derivation of single index for each disturbance type where there is more than one indicator per disturbance. We called the two steps (i) normalisation and (ii) consolidation.

Normalisation, represented by Block 7 in the PQ Analysis Triangle, is the process of dividing an index by its maximum acceptable value, so that it has the value one when it is at the limit of acceptability. In the case of the flicker indices P_{st} and P_{lt}, [7] gives limits for 99% cumulative probability values of 0.9 and 0.7 respectively. For example, if the 95% values of these indices were measured at 0.8 and 0.8, the normalised indices would be 0.89 and 1.14, showing immediately that the P_{lt} value is worse than for P_{st}. For LV harmonics the 95% values for V_{THD}, V_2-V_{40} are normalised by dividing them by numbers ranging from 0.065 to 0.002 as given by the planning levels in [8].

Consolidation combines all the normalised values for one disturbance type into a single index. We recommend the maximum value be used – for example, in the above flicker case, the consolidated flicker index is 1.14. When a similar approach is applied to the 40 harmonic indices, a single harmonic "consolidated index" can be determined. This method can be extended in an obvious manner to consolidate the 120 harmonic indices of AS/NZS 61000.3.6 into one index. This method is more comprehensive than that described in [3] where harmonics are represented by an indicator of V_{THD} only.

The symbols V, U, F and H will be used to represent the normalised and consolidated disturbance indices for voltage, unbalance, flicker and harmonics respectively.

IV. Unified Power Quality Index (UPQI)

Consolidation and Normalisation has been shown to reduce 48 continuous disturbance indices (or more, depending on the standards used) to four, one for each of voltage, unbalance, flicker and harmonics. Moreover the "consolidated indices" have the simple property that their maximum acceptable value is unity. Nevertheless, the assessment and ranking many sites each represented by these four indices will be difficult. Therefore a single number, the Unified Power Quality index (UPQI) for a site, is proposed to give a insight to give a simple measure of its overall power quality and allow ease of site ranking.

There are a couple of intuitive ways of approaching this, involving the average or the maximum of the consolidated indices. However, these will be shown to be not fully satisfactory and an alternative will be proposed.

One has to have a clear idea of the purpose of a single PQ index before one can critically compare different proposals. We recommend that the main purpose is to allow the prioritising of sites for power quality improvements. The site which would rank last ought to be the one where customers are having most problems with the operation of their equipment. In developing this idea, we will assume that there is an equal mix of customers having the full range of equipment at each monitored site. We also assume that all equipment meets normal equipment emission and immunity requirements.

We shall compare some different proposals by assuming the consolidated indices V, U, F and H to have the values at several sites as given in Table I.

TABLE I
EXAMPLE PQ INDICES

	Sites		
Indices	1	2	3
V	0.6	0.0	0.0
U	0.6	0.0	0.0
F	0.8	1.4	0.0
H	0.8	1.4	1.4
$PQI_{average}$	0.7	0.7	0.35
$PQI_{maximum}$	0.8	1.4	1.4
UPQI	0.8	1.8	1.4

One possibility is to use the average of the consolidated indices, symbolised here by $PQI_{average}$. This implicitly assumes that the effect of power quality is the sum of that of the individual disturbance types, and in particular that excessive disturbances of one type can be mitigated by reducing other types of disturbances. In Table I, Sites 1 and 2 have equal $PQI_{average}$. At Site 1 all disturbances are within acceptable limits and there should be no difficulty with customer equipment. However, at Site 2, there will be excessive light flicker and problems with high harmonics affecting capacitors and three phase induction motors. Clearly this approach does not give a single index which is useful for the ranking of sites.

There have been proposals described in the literature using weighting factors to combine separate PQ indices. These have similar features to the above and should also be discounted.

Another possibility is the use of the maximum of the consolidated indices, symbolised here by $PQI_{maximum}$ as used by [3]. This implicitly assumes that the number of customers affected by each disturbance type is identical and independent of the magnitude of other disturbances present. Now compare the situation at Sites 2 and 3 in Table I, having identical values of $PQI_{maximum}$. At Site 3, those customers with three phase induction motors will experience additional losses. At Site 2, customers with three phase induction motors will be similarly affected, but in addition there will be customers experiencing light flicker and it should be ranked as worse than Site 3. Hence we discount the maximum as a good overall PQ index.

Our proposal called the Unified PQ index (UPQI) and was devised to have the following features

1. If all disturbance indices are less than one, the index should measure the headroom to the disturbance which is most likely to affect customers.
2. If some disturbance indices are more than one, the UPQI gives a measure of the combined effect of all the problem indices.

The calculation of the UPQI is conveniently expressed using the concept of Exceedance, a measure of how much a disturbance type exceeds the maximum acceptable value. If a PQ index is less than one, the corresponding Exceedance is zero. If the index is more than one, the Exceedance is equal to the index minus one. For example, the voltage at Site 1 above has an Exceedance of 0 while the harmonics at Site 2 have an Exceedance of 0.4.

We now define the UPQI as follows

1. If all the consolidated disturbance indices are less than 1, UPQI equals the maximum of the indices.
2. If one or more of the indices exceeds 1, UPQI equals 1 plus the sum of the Exceedances.

One of the convenient properties of the UPQI which follows from its definition is that a value of one represents the limit of acceptability.

This index has been calculated and displayed for the three sites in Table I. The UPQI gives Site 2 as the worst, followed by Site 3, with Site 1 acceptable, as would be felt intuitively. The merit of the UPQI is that it can be applied by computer to hundreds of sites giving a ranking without time-consuming human intervention.

This concept can be extended to include other types of continuous disturbances which can be represented by indices, providing normalisation and consolidation are first applied.

We are at present developing a method for determining a single index for discrete disturbances such as voltage sags. This can be normalised (consolidation should not be necessary if there is only one index) providing a maximum acceptable limit can be agreed. We foresee that the UPQI can be extended to encompass discrete disturbance levels within the existing definition.

V. APPLICATION EXAMPLE

The analysis given below has been carried out using synthetic data for 69 sites. Confidentiality prevents us giving the exact data that we measured at sites over eleven of Australian distributors, and we have constructed the synthetic data to show a similar range of variation. The measurements took place over one week, sufficient to give useful results for continuous disturbances. Let us now consider the task of ranking these sites.

A. Individual Disturbance Analysis

Fig. 2. below shows that the normalised and consolidated disturbance indices for the sites for each disturbance type. It is shown that the best site for harmonics is not the best site for

voltage level, flicker or unbalance, and the worst site for unbalance is not the worst site for voltage level, flicker or harmonics etc. These plots illustrate that it is not possible to obtain a quick impression of the overall level of continuous disturbances over the sites by visual inspection.

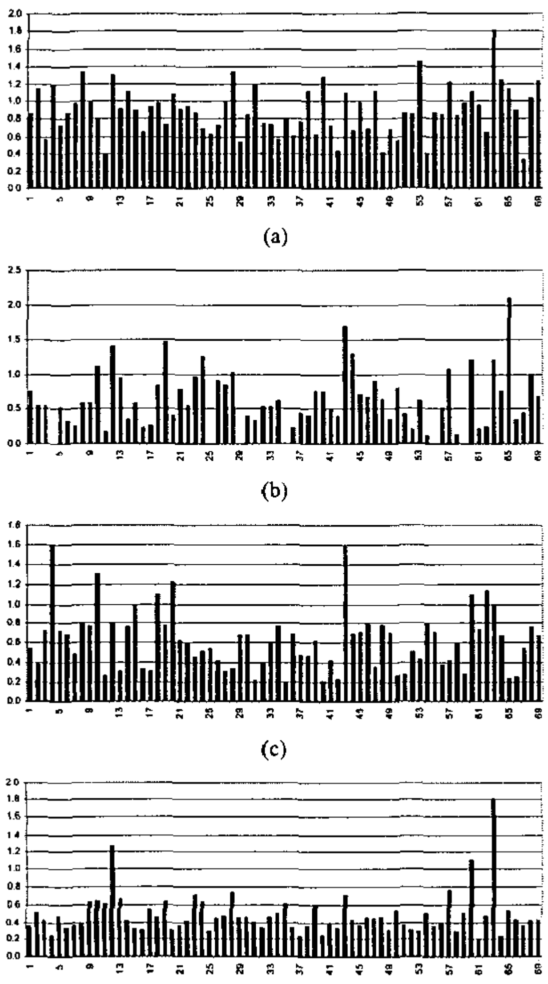

Fig. 2 Consolidated Indices for Individual Disturbances
(a) Voltage V, (b) Unbalance U, (c) Flicker F, (d) Harmonics H
(Horizontal axis gives site number, vertical scale gives normalized and consolidated index)

B. UPQI for Continuous Disturbances

The overall PQ index for each site has been determined by each of the three proposed methods ($PQI_{average}$, $PQI_{maximum}$ and UPQI). The ranking of the sites has then been determined by each method, with 1 being the best site and 69 the worst.

Fig. 3 shows a comparison of the rankings by means of scatter graphs of ranking by UPQI (horizontal scale) with the ranking by the other index ($PQI_{average}$, $PQI_{maximum}$) shown by the vertical scale. It is clear that $PQI_{average}$ gives a ranking which is very different from that given by the other two PQ indices. The $PQI_{maximum}$ and UPQI rankings agree for most sites except for the worst sites because the two algorithms are equivalent except when a site has two or more disturbances exceeding allowable limits. Since the basic aim of an overall PQ index is to allow selection of the worst few sites, this discrepancy is an important issue.

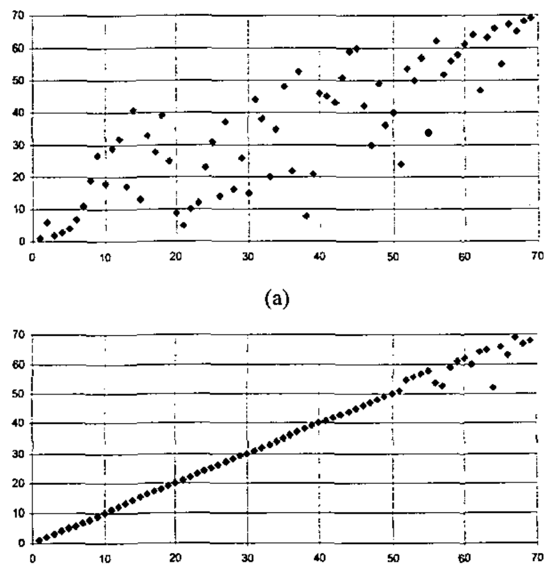

Fig. 3 Scatter graph of rankings by two appraoches
(a) $PQI_{average}$ vs UPQI, (b) $PQI_{maximum}$ vs UPQI
(Horizontal scale gives rank according to UPQI, vertical scale gives rank according to the other PQ index)

Table II shows for comparison the best and worst 5 sites determined by the three methods, with the sites listed in decreasing order of power quality. We note that there is surprising agreement between $PQI_{average}$ and UPQI for the five worst sites, with two sites being ranked identically and another two ranked closely. Broadly such agreement is expected for the worst sites because both indices emphasize sites for which all disturbance indices are roughly equal.

We note that $PQI_{maximum}$ and UPQI differ as regards the worst ranking, with the UPQI selecting Site 63 (with V, U, F and H equal to 1.8,1.2,1.0,1.8) and $PQI_{maximum}$ selecting 65 (disturbance indices 1.1,2.1,0.2,0.5). In support of the choice of Site 63 as worse than Site 65, it is noted that

1. Site 63 exceeds the allowable limits for three of its disturbance indicators and is marginal for the fourth while Site 65 exceeds in only two.
2. Site 63 has an average disturbance indicator greater than that of Site 65
3. If the problem to the customer is in proportion to the total amount of exceedance, Site 63 is worst because its total is 1.8 while that for Site 65 totals 1.2.

TABLE II
BEST 5 AND WORST 5 SITES BASED ON DIFFERENT PQ INDICES

	Site no		
Rank	Ranked by $PQI_{average}$	Ranked by $PQI_{maximum}$	Ranked by UPQI
1	42	42	42
2	11	67	67
3	25	11	11
4	16	25	25
5	35	16	16
65	65	19	4
66	60	4	12
67	12	43	65
68	43	63	43
69	63	65	63

VI. CONCLUSION

The paper has given a comprehensive discussion of the determination of a single index representing the overall PQ level at a site and developed to give a measure of the number of customers having equipment problems. The index has the useful features that it begins to exceed one when one type of PQ disturbance begins to exceed the maximum acceptable level. For sites of low PQ levels, it gives a measure of the headroom of the dominant disturbance type. For sites of high PQ levels, it gives a measure of the levels of all disturbances which are excessive.

The first stage in the determination is to measure all relevant parameters defined in PQ standards at 10 minute intervals. Values which occur during sags or swells are ignored. Statistical values (eg 95% levels) are found over a defined period, usually weekly. Voltages are treated in a new way by taking the 95% value of the absolute voltage error form the middle of the voltage range. Maximum values are found across the three phases. Where several weeks of monitoring are involved, values are found for each week and the overall maximum found.

The next stage is normalisation, so that an index has the value of one when it is at the limit of acceptability. Consolidation combines all the values describing one disturbance type (eg the short and long term flicker indices) by taking the maximum value to give a single disturbances index for each disturbance type.

The separate disturbance indices can then be combined to give a unified PQ index by the method described, involving the exceedances. It has been shown that the method can easily be extended to include additional types of continuous PQ disturbances. It can also incorporate discrete PQ disturbances providing they can be represented by a single index with an agreed maximum acceptable value. The method has been applied to representative data to show its power in quickly ranking sites for PQ work without the need of a detailed inspection of the detailed characteristics of each site. Further detailed work is required to develop indices for the discrete disturbances, especially sags, momentary interruptions, swells, impulsive transients and oscillatory transients. Another area of work is to investigate the aggregation of UPQI over many sites to find an overall index for a feeder, substation, region within a utility or the whole utility. All areas of work will require involvement with monitoring campaigns to ensure that the developed techniques give useful results.

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VIII. BIOGRAPHIES

Vic Gosbell (M'1975): Dr Gosbell obtained his BE degree in 1966 and his PhD in 1971 from the University of Sydney. In 1973 he commenced lecturing at the University of Sydney and in 1990 took up a position of Associate Professor at the University of Wollongong where he is now the Professor of Power Engineering. His research interests are in power electronic simulation, harmonics and power quality. He is a Fellow of the Institution of Engineers, Australia and the immediate past Chairperson of the Australasian Committee for Power Engineering.

Sarath Perera (M'1995): Dr Perera graduated from the University of Moratuwa, Sri Lanka with a BSc (Eng) degree (1974) specialising in Electrical Power. He obtained his MEngSc degree (1978) from the University of New South Wales and the PhD degree (1988) from the University of Wollongong. He was an academic at the University of Moratuwa, Sri Lanka for nearly 12 years and is now a Senior Lecturer at the University of Wollongong. His research interests are in Power Quality.

Chandana Herath (M'2000): Mr. Herath obtained his BSc. Eng. and MSc degrees from Moscow Power Engineering Institute (Technical University), Russia in 1992 & 1993. His employment experience included the Engineering Consultants Limited, Sri Lanka, the Shin Nippon Air Conditioning Engineering Co., Ltd., Sri Lanka, Singapore & Zimbabwe and the Mitsubishi Heavy Industries Ltd/ Mitsubishi Corporation, Singapore. He joined the University of Wollongong in 2001 and studying towards his PhD in Power Quality.