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# Factor analysis of power quality variation data on a distribution network

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# Factor Analysis of Power Quality Variation Data on a Distribution Network

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***Abstract*—Continuous power quality (PQ) surveys of electricity networks generate large amounts of data that must be condensed for the purpose of interpretation and reporting. In this paper, summary indices for continuous PQ disturbances are calculated from distribution network data, and the relationship between these indices and the known physical characteristics of the site is investigated.**

**Results from this survey prompted further analysis into the relationship between voltage harmonic distortion ($THD_v$) levels and variation in load characteristics across the monitored sites. Accepted explanations for variation in $THD_v$ are evaluated against the observed levels and alternative explanations are proposed.**

***Index Terms*—harmonic distortion, power quality, PQ indices**

## I. Introduction

CONTINUOUS monitoring of power quality levels is now common amongst distribution network operators. Such surveys typically consist of a number of monitoring devices installed in carefully selected locations on the network. Commonly, monitors installed in different locations will record differing levels of power quality disturbances. This raises the question: what are the most influential factors about a given site that determine the typical levels of PQ disturbances experienced at that site?

This paper utilizes PQ data that has been recorded on the Vector distribution network in Auckland, New Zealand. Vector is an electricity, gas and telecommunications utility provider in Auckland, and has had PQ monitoring equipment installed on the network since 1999. Vector currently have more than 30 PQ monitors connected to the network at strategic points and at various voltage levels. The data for this survey has been taken from 13 monitoring instruments that are all connected to the 11 kV bus in zone substations on the network. The survey covers a 12 month period from July 2003 to June 2004. For the purposes of this study, the 13 sites have been grouped according to the predominant load type, giving two commercial sites, eight industrial sites, and three residential sites. This study deals only with what is termed 'continuous' PQ variation: voltage variation, voltage unbalance, and harmonic distortion. Data relating to discrete PQ events such as voltage sags/swells and interruptions has been omitted from this study due the different analysis techniques required.

Through the use of statistical factor analysis techniques, it has been possible to determine which of the known physical characteristics of a particular site are most influential in determining the power quality performance. Having found that voltage harmonic distortion levels are a good indicator of overall site PQ performance, further investigation has taken place into the relationship between harmonic distortion levels, site physical characteristics, and load variation.

## II. Initial Analysis of PQ Data

Power quality indices have been calculated in order to summarise the large amounts of data produced by continuous monitoring. The indices used in this paper have been developed by the Integral Energy Power Quality and Reliability Centre at the University of Wollongong. The indices are only briefly defined here, but a full description can be found in [1].

### A. Voltage Index (VI)

Method: 1. Calculate the Absolute Voltage Deviation (AVD) from the float voltage.

$$AVD = \frac{|V_{float} - V|}{V_{float}} \times 100\% \qquad (1)$$

Where $V_{float}$ is the system target voltage (11 kV for this survey), and V is the actual measured voltage.

2. Find the 95[th] percentile value of AVD across the 3 phases over the survey period.

### B. Voltage Unbalance Index (VUI)

Find the 95[th] percentile value of voltage unbalance over the survey period.

### C. Harmonics Index (HI)

Find the 95[th] percentile value of voltage THD for each phase across the 3 phases over the survey period. The Harmonics Index is the maximum of the 95% values across the

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three phases.

### D. Combined Site PQ Index

The above indices were calculated for each site in the survey. Additionally, an overall site index was calculated so that the 13 sites could be compared for overall PQ performance with respect to continuous disturbances. The overall site PQ index was calculated by combining the 'component' indices for voltage, voltage unbalance and harmonics for each site. So that each of the voltage, voltage unbalance, and harmonics indices could be effectively expressed in the same 'units', it was necessary to normalize each of the indices against the network average for that index. Having normalised each of the 'component' indices, the overall site index was calculated as the average of the three indices for each site. The use of a simple average is not ideal, in that it implies that high levels of one type of disturbance can be compensated by low levels of other disturbances, to give an overall satisfactory level of PQ performance. While this is clearly not the case, the use of an average has been found to give an acceptable indication of overall PQ performance for the purpose of ranking sites across the network, and has the advantages of ease of calculation and interpretation. Fig.1 shows the resulting PQ indices from the 13 monitored sites.

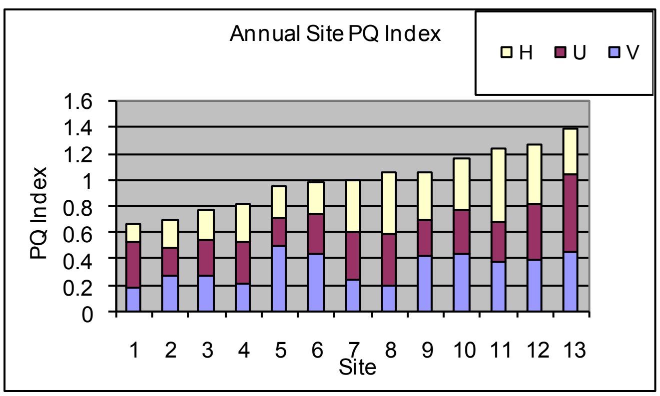


Fig. 1: Annual site PQ indices across the Vector network, showing contribution of voltage (V), voltage unbalance (U) and harmonics (H).

It is worth noting that the three worst sites (highest PQ index) in Fig. 1 are the three substations categorised as residential.

## III. PQ Factor Analysis

Factor analysis has been used to determine:

- Which of the component factors (voltage variation, voltage unbalance, or voltage THD) is most influential in determining the overall site index.
- Is there a relationship between the known physical characteristics of the site and the measured PQ levels?

### A. Relationship between individual PQ parameters and overall PQ index

Correlation analysis (using the Data Analysis tools in Microsoft Excel) was used to establish which of the component factors was most influential in determining the overall PQ index for a site. The results are shown in Table I below.

TABLE I
CORRELATION COEFFICIENTS BETWEEN INDIVIDUAL PQ PARAMETERS AND OVERALL SITE PQ INDEX

| | Voltage | Voltage Unbalance | Harmonics |
|---|---|---|---|
| Overall PQ Index | 0.61 | 0.65 | 0.78 |

While all parameters showed a positive correlation with overall site index, the strongest correlation was with the site harmonics index. This indicates that it is the harmonics index that is most influential in differentiating between good sites and bad sites. The reason for this is that there is more variation in the harmonics levels across the sites than there is variation in either voltage levels or voltage unbalance.

### B. Relationship between physical characteristics of sites and overall PQ index

Key physical characteristics of the 13 monitored sites were analysed in conjunction with measured PQ levels in order to investigate any possible relationship. The physical characteristics considered for each site were:

1. Prospective fault level (MVA)
2. Annual maximum demand (half hour average) (MVA)
3. Predominant load type (commercial, industrial, residential)
4. Total feeder length
5. Proportion of overhead lines to underground

A combination of correlation analysis and multi-variable linear regression (MVLR) analysis was carried out to investigate the nature and strength of any existing relationship. The correlation analysis indicated that load category was clearly the most influential physical factor in determining the overall site PQ index.

Results from the MVLR analysis indicated that length of feeder had no significant influence and this factor was removed and the MVLR repeated. The results are shown in Table II. The P-values in the table give a measure of the strength of the evidence against the null hypothesis (that the corresponding variable has no effect on on the overall site PQ index), where the smaller the P-value, the stronger the evidence against the null hypothesis. A P-value greater than 0.12 is considered indicative that there is no evidence that the corresponding variable has any significant influence on the dependent variable. [2]

TABLE II
RESULTS OF MVLR – SITE PHYSICAL PARAMETERS AND PQ INDEX.

| Variable | Coefficient | P Value |
|---|---|---|
| Constant | 0.342 | 0.19 |
| Load category | 0.32 | 0.0023 |
| Max demand/fault level | 0.349 | 0.81 |
| % O/H lines | -0.22 | 0.49 |
| Significance F | 0.0066 | |
| Adjusted R | 0.64 | |

While fault level, maximum demand and the proportion of overhead lines were found to have some influence, the load category was found to be by far the most influential physical factor in determining site PQ performance. A more detailed description of the MVLR analysis and the results can be found in [3].

Further MVLR analysis focused on the relationship between component PQ indices (voltage index, voltage unbalance index and harmonics index) and the physical characteristics of each site No clear relationship was found between site voltage indices and the known physical parameters. Load category was found to be the most influential factor for variation in the voltage unbalance index. This seems a reasonable result given that most commercial and industrial loads are balanced three phase, whereas it is more difficult to balance out single phase loads across the three phases on a residential feeder. Variation in site harmonics index is also strongly influenced by the load category. Based on the analysis results, commercial sites can be expected to have the lowest voltage harmonic distortion, followed by industrial sites. Residential sites have the highest expected harmonics index.

Summarising the results of the MVLR analysis, the overall PQ index of a site is mostly dependent on the load category. Of the three load categories, commercial sites can be expected to have the best (lowest) PQ index, followed by industrial sites, with residential sites typically having the worst PQ index. A caveat on this finding is that this result is only based on data from 13 sites on the network and may not be truly representative of the overall network.

## IV. $THD_V$ TIME SERIES ANALYSIS

Further investigation into the variation in voltage harmonic distortion levels was carried out in an attempt to explain why residential sites typically have higher harmonic distortion levels. It might be expected that industrial sites would have higher harmonic distortion levels due to the higher proportion of distorting loads, but from the results in III.B this is clearly not the case. PQ data from the month of June 2004 was analysed to identify relationships between $THD_v$ levels, load current, and harmonic current levels. It was found that greater insight could be gained by focusing on data from a single month rather than using data covering one year.

### A. *$THD_v$ time series and load current analysis*

$THD_v$ levels were plotted against time for each site in order to establish typical patterns of $THD_v$ variation for each load category. Clear daily and weekly cycles of $THD_v$ variation were identified for each load category. Example time series plots are shown below.

**Commercial sites:**

The time series plot for one of the commercial sites is shown in Fig.2.

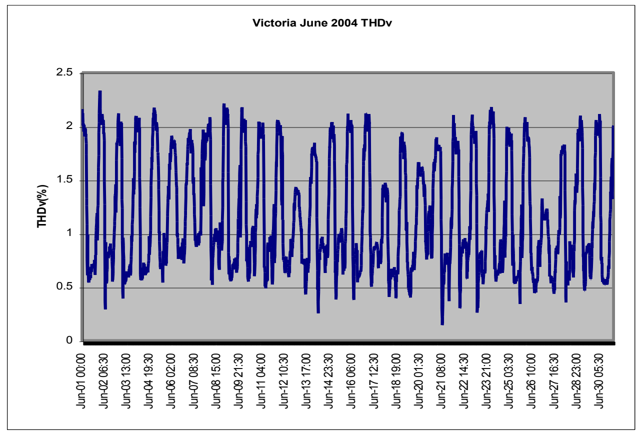


Fig.2. Monthly $THD_V$ trend for a commercial site.

For the two commercial sites, minimum daily $THD_v$ levels were found to occur during the hours of 7:00 a.m. and 5:45 p.m. (i.e. typical business hours and maximum load current), while peak levels were recorded between midnight and 5:00 a.m. This suggests that a negative correlation exists between $THD_v$ levels and load current for commercial sites. To test this assumption, a scatter plot of $THD_v$ levels against load current was plotted and the correlation coefficient calculated. The scatter plot is shown in Fig.3.

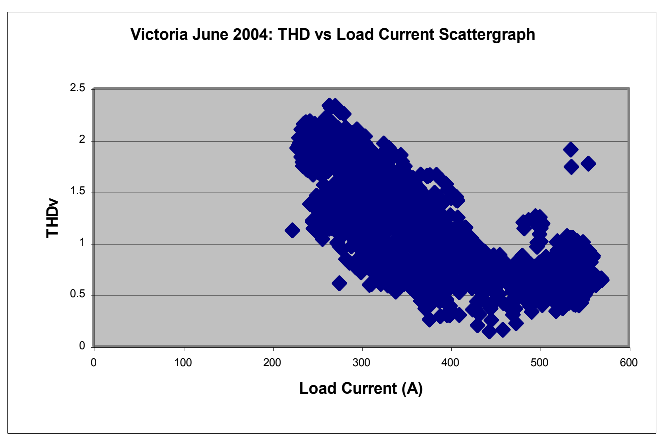


Fig.3: Scatter plot of $THD_v$ against load current for a commercial site.

The correlation coefficient was calculated to be –0.79. Similar results were obtained from the other commercial site in the survey.

**Industrial sites:**

While there were some differences in the daily cycle of variation in $THD_v$ levels across the eight monitored sites, some trends were found to be consistent. Fig. 4 shows the time series plot for a typical industrial site.

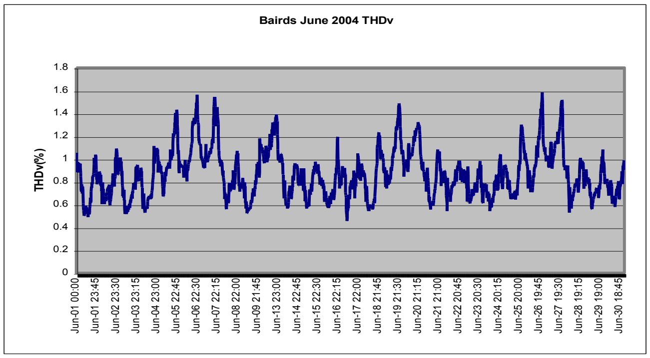


Fig.4: Monthly THDv trend for an industrial site.

For the site shown, $THD_v$ levels peak between 8:00 p.m. and midnight. For all industrial sites, $THD_v$ levels peak during the nighttime hours. There is also a consistent weekly pattern of higher $THD_v$ levels recorded on weekends.

Scatter plots of $THD_v$ against load current for industrial sites are suggestive of a negative correlation, and indeed data from all sites produced negative correlation coefficients, ranging from –0.34 to –0.86.

**Residential sites:**

Residential $THD_v$ levels typically peak each day between the hours of 7:30 p.m. and 2:30 a.m., with most occurring at around 10:30 p.m. The morning load current peak between 6:30 a.m. and 9:00 a.m. is when the daily minimum $THD_v$ levels are recorded, and there is a similar dip in $THD_v$ levels during the late afternoon load peak period. Weekly peaks in $THD_v$ levels occur during the weekends.

Fig.5 shows a typical time series for a residential site.

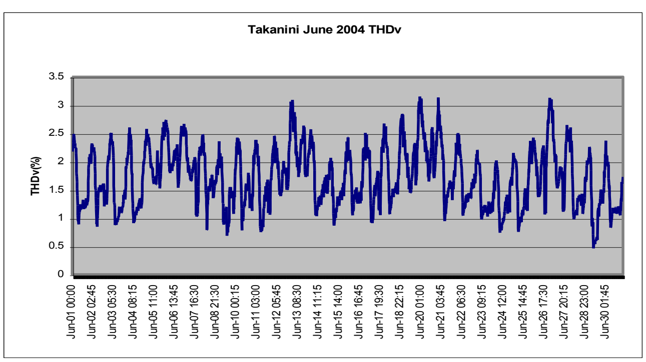


Fig.5: Monthly $THD_V$ trend for a residential site.

While the daily and weekly cycles of $THD_v$ variation for residential sites is similar to that for commercial and residential sites, the daily load cycle for residential sites is quite different. This results in a different relationship between $THD_v$ levels and load current. Two of the residential sites displayed a positive correlation between $THD_v$ and load current (correlation coefficients = 0.22 and 0.54). While the third residential site showed a negative correlation, the load pattern of this site suggests that it has a significant industrial load component combined with residential load.

*B. Discussion of results*

There are a number of features of the variation in harmonic distortion levels that are consistent across all sites. Regardless of load category, all sites experience maximum levels of voltage harmonic distortion at night and at weekends. In the case of commercial and industrial sites, the times of higher harmonic distortion levels coincides with periods of low load, while minimum distortion levels are recorded during the day when load current is highest. This negative correlation between load current and voltage harmonic levels does not typically occur at residential sites due to the different daily load cycle as compared to commercial and industrial sites.

Several explanations for higher levels of voltage harmonic distortion at night have previously been proposed in power quality literature. In [4], it is suggested that higher levels of harmonic distortion on residential supplies can be attributed to user behaviour, and in particular the use of televisions. However, in this survey, $THD_v$ at residential sites typically peaks at around 10:30 p.m., which does not match up with the time of peak television viewing (7:30 p.m. to 10:00 p.m.). Further, in [5], the conclusion was that levels of television viewing have surprisingly little influence on the variation in network harmonic distortion levels. This may be partly because of the tendency of many television users to leave the set in 'standby' mode when not in active use, resulting in a constant harmonic load. To date it appears that no similar study has been conducted with regard to network harmonic distortion levels and the use of home computers.

The explanation proposed in [6] is that higher levels of triplen harmonics due to transformer excitation currents are observed during the early morning hours when load current is low. As triplen harmonics do not propagate back into the delta-connected MV network, this fails to explain the harmonic distortion levels observed in this survey.

An alternative explanation for the lower levels of harmonic distortion during the day is harmonic cancellation by the mixing of non-linear single phase and three phase loads [7]. Because the $5^{th}$ and $7^{th}$ harmonics currents in single phase and three phase loads are often in counter-phase, this can result in at least partial cancellation.

It may be that the variation in harmonic distortion levels observed in this study is characteristic of the New Zealand transmission grid. The New Zealand grid includes a HVDC link between the North and South Islands. During periods of low load, generators in the North Island are ramped down, which may result in harmonic distortion from the HVDC inverters becoming more significant. Further investigation is required to determine if this is a significant source of distortion on the Vector network.

The principal negative impact of harmonic disturbance on network equipment is additional power losses. Given that the highest harmonic levels occur at night at times of low load, it is perhaps appropriate that maximum disturbance levels specified in standards and regulations should be reassessed. It should be noted that all of the harmonic levels recorded are well within the requirements of existing national and international standards. The New Zealand Electricity Regulations [8] only specify maximum harmonic distortion levels at the point of supply and do not apply to harmonic levels on MV networks. Standard AS/NZS 61000.3.6 [9] specifies a compatibility level of 8% for MV networks, compared to the typical 95% cumulative probability values of between 2% and 3% for the Vector network.

## V. Conclusions

Twelve months of data from a continuous PQ survey on a distribution network has been analysed and indices for voltage variation, voltage unbalance and voltage harmonic distortion have been calculated. A method for calculating an overall PQ index for continuous disturbances has been proposed and shown to be effective for comparison of performance of sites.

Factor analysis techniques have been used to analyse the relationship between observed PQ levels and known physical characteristics of the monitored sites. It was found that the predominant load type is the most influential physical factor in determining overall PQ performance. Correlation and multi-variable linear regression analysis revealed that of the three continuous PQ disturbances analysed, it is $THD_v$ levels that are most influential in determining the overall PQ performance of a sites. Ranking of sites for both harmonic distortion levels and overall PQ performance showed that commercial sites are typically best, followed by industrial sites, with residential sites worst.

Further analysis of the $THD_v$ data in terms of variation with time, predominant load type, and level of load current found that for commercial and industrial sites, there is a consistent negative correlation between $THD_v$ levels and load current. For the three residential sites surveyed, two of the sites had a positive correlation between $THD_v$ and load current. The remaining site had a negative correlation between $THD_v$ and load current, but this site also displayed some load characteristics more typical of a commercial or industrial site rather than a residential site.

Typical cyclic patterns of variation of $THD_v$ have been identified for each of the three main load categories. For all sites, peak $THD_v$ levels typically occur at night. Weekly patterns of $THD_v$ variation were also identified, with higher levels occurring at weekends.

The assessing and reporting of harmonic levels on MV distribution networks by use of cumulative probability statistics appears to be inappropriate, given that the highest levels of harmonic disturbance occur during periods of low load and when risk to equipment is lower than at times of higher load.

## VI. Acknowledgements

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## VIII. Biographies

**Glenn Nicholson** is a senior lecturer with the Dept. of Electrical and Computer Engineering at Manukau Institute of Technology (Auckland, New Zealand). He worked for 15 years in the electrical supply industry, followed by a further five years involved in the manufacture of electronic power supplies and transformers. He received a B Eng Tech degree from Manukau Institute of Technology in 2000, and in 2006 completed an ME degree in electrical engineering from the University of Wollongong.

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**Ashok Parsotam** was born in Tavua Town, Fiji Islands, in June, 1963. He graduated from the University of Auckland, New Zealand with BE (Electrical & Electronics) in 1985. His employment experience included work at Fiji Electricity Authority, New Zealand Electricity Department, Southpower and Vector Ltd (NZ). Ashok’s special fields of interest included tariff metering, power system earthing, distribution network planning and design, network modelling and power quality. He is member of joint Standards Australia/ Standards New Zealand Technical Committee ET-007 developing AS/NZS 3835 Earth potential rise - Protection of telecommunications network users, personnel and plant. He is a member of Australian CIGRE Panel C4 - System Technical Performance. Ashok is currently working for Vector Ltd in Auckland, New Zealand as Power Quality Manager.