# POWER QUALITY INVESTIGATION WITH WAVELET TECHNIQUES

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## Abstract

Electric power quality is an aspect of power engineering that has been with us since the inception of power systems. However, the topics in power quality have only attracted interests over the past few years because of the increasing usage of electronically controlled equipments. The power quality problem causes interruptions to the sensitive electrical or electronic equipment and results in very expensive consequences. Wavelet techniques will be studied in this paper for analysing monitored power quality data. A case study based on the measurement of a University of Queensland site was studied using the proposed wavelet approach.

## 1. INTRODUCTION

The proliferation of microelectronic processors in a wide range of equipments has increased the vulnerability of such equipment to power quality problems. These problems include a variety of electrical disturbances, which may originate or manifest themselves at various places in the network and have very different effects on various kinds of sensitive loads. As a result of this vulnerability, electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power.

Recent advances in signal analysis have led to the development of new methods for characterizing and identifying various power quality problems. Most of the work done in the power quality area deal with these problems either from the detection and localization point of view or from data compression frame. Wavelet decomposition techniques provide a powerful tool, which can be used to help evaluate power quality problems. In this paper, we will review some general power quality phenomena and apply wavelet techniques with real world power quality case studies.

## 2. POWER QUALITY PROBLEMS

It is necessary to give a brief review of common power quality problems, as briefly defined in the sequel [1].

**Transients** refer to part of the change in variable that disappears during transition from one steady state operating condition to another; and they can be classified as either impulsive or oscillatory transients.

**Short Duration Voltage Variations** are caused by fault conditions and the energization of large loads, where high starting currents are involved. The faults can cause a ‘drop’, ‘rise’ and ‘supply void’ in the supply voltage, and are also known as sag, swell and interruptions respectively. The classification and identification of voltage variations are governed by IEEE 1159, and ANSI/IEEE-446-1987, which are also known as the CBEMA power acceptability curve.

A *sag* is a decrease to 0.1 ~ 0.9pu in Roots-Mean-Square (RMS) voltage or current magnitude at the line frequency for duration from 0.5 cycles to one minute. Voltage sag is normally caused by system faults, energisation of heavy loads and starting of large motors.

A *swell* is defined as an increase to 1.1 ~ 1.8pu in RMS voltage or current magnitude at the line frequency for duration from 0.5 cycles to one minute. Swells are usually associated with system fault conditions, but they are not as common as voltage sags.

An *interruption* occurs when the supply voltage or load current decreases to less than 0.1pu for a period of time not exceeding one minute. Interruptions can be caused by power system faults, equipment failures and control malfunctions.

**Long Duration Voltage** encompasses RMS deviations at power frequencies for longer than one minute. Long-duration variations can be either over-voltages or under-voltages.

**Voltage Imbalance** refers to the percentage maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents.

**Waveform Distortion** is defined as a steady-state deviation from an ideal sine wave of line frequency principally characterized by the spectral content of the deviation. DC offset, harmonics; notching and noise are the four major waveform distortions.

**Power Frequency Variations** are the deviations of the power system fundamental frequency from its specified nominal value. The size of the frequency shift and its duration depends on the load characteristics and the response of the generation control system to load.

**Voltage Fluctuations** are systematic variations of the voltage envelop or series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges specified by ANSI C84.1 – 1982 of 0.9 to 1.13 pu.

## 3. STATE OF ART OF POWER QUALITY RESEARCHES

In recent times power quality problems have been an interesting research topic for many researchers. Some of these researches were selected and listed in the paper for completeness [2-9].

### Niagara Mohawk Power Corporation (NMPC)

In mid-1989, the Niagara Mohawk Power Corporation sponsored a major power quality study of two distribution feeders in the Buffalo, New York region [2]. The results of the study proved that majority of the problems were actually caused by the customer’s own equipment.

### National Power Laboratory (NPL)

In 1990, the NPL initiated a five-year survey of single-phase normal-mode electrical disturbances [3]. Data was collected from 300 sites within the continental United States and Canada. The sites also included locations where participants felt they had power quality problems and locations where no problems were perceived. The results indicated that utility capacitor switching events may be observed at the majority of monitored locations, but the peak voltage magnitude is not usually that severe at most of these locations.

**Electric Power Research Institute (ERPI)**

Electric Power Research Institute (ERPI) contracted with Electrotek Concepts, Inc. (RP 3098-1) in 1990 to conduct a study of the state of power quality on distribution feeders in the U.S [4]. The result of these studies has shown that the most common type of faults found in the power disturbances were voltage sags, transients, harmonic distortions and momentary interruptions.

**University of Queensland (UQ)**

The power quality research at UQ St. Lucia campus has carried out at three different locations within the campus [5]. The power quality research is a continuing research topic with the Energy Systems Research Group at UQ. In the following sections, we will discuss the power quality research carried in UQ site.

The equipment used at UQ PQ research was the BMI 8010 PQNode, developed by Basic Measuring Instrument (BMI) of Santa Clara, California in conjunction with Electrotek Concepts Inc [6]. The BMI 8010 PQNode is designed for power quality monitoring over a long period of time. It can be set to stand-alone operation at the selected site to perform PQ monitoring. Communication between PQNode and computer is via RS-232 link.

The PASS software is used to provide the control, data display and database management functions for the instrument. It can be programmed to retrieve data from some or all PQNode(s) in the system. PASS provides a range of display options for viewing PQNode data offline or online, to produce steady state and latest disturbance waveforms, [10-11].

## 4 WAVELET TRANSFORM TECHNIQUES

Power quality problems are characterized by their maximum amplitudes, crest voltages, RMS, frequency, statistics of wavelet transform coefficients, instantaneous voltage drops, number of notches, duration of transients, etc. These characteristics are unique identifying features for different power quality problems [12-19], and introduced signal processing tools in power quality analysis.

Discrete Wavelet Transform (DWT) is a basic tool for analysing a time series signal. It provides a time and frequency representation of the recorded power quality signals. This is a very attractive feature in analysing time series because time localization of spectral components can be obtained. Classical methods of signal processing depend on an underlying notion of stationarity, for which methods such as Fourier analysis are very well adapted. In power quality researches, however, more properties other than stationarity are required, and thus make the DWT application more appropriate than Fourier transform [20].

If we denote $f$ as a function defined on the whole real line, then, for a suitably chosen mother wavelet function $\psi$, $f$ can be expanded as

$$f(t)=\sum_{j=-\infty}^{\infty}\sum_{k=-\infty}^{\infty} w_{jk}2^{j/2}\psi(2^j t-k) \tag{1}$$

Where the functions $\psi(2^j t\text{-}k)$ are all orthogonal to each other. The coefficient $w_{\mathrm{jk}}$ gives information about the behaviour of the function $f$ concentrating on the effects of scale around $2^{-\mathrm{j}}$ near time $t\times 2^{-\mathrm{j}}$. This wavelet decomposition of a function is closely related to DWT of a signal observed in discrete time.

One problem with DWT is that it is not a time-invariant transform. This means that the DWT of a translated version of a signal is not a translated version of the DWT of the signal [20]. The solution to restore the translation invariance is to use a redundant or non-decimated wavelet transform instead of the classical DWT. The àtrous algorithm [21], [22] can be used to achieve such stationary or redundant transform.

We give a brief introduction on how the *àtrous* transform is carried out [21], [22]. The basic idea behind this algorithm is similar to the classical DWT except there is no decimation step. The main purpose of decimation is to collect and store the minimum required data that allows an exact reconstruction of input data. By ignoring the decimation step, it simply requires a larger storage space.

A data series $c_0(k)$ is passed through a low pass filter $h_1$ first. This results in the first resolution level of the signal, or the first approximations signal, $c_1(k)$. Subsequently, $c_{\mathrm{n}}(k)$ is obtained when the time series goes through the filter $n$ times. The process is given in Figure 1.

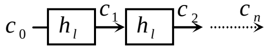


**Figure 1** The Filtering Process

This is achieved using the following equation:

$$c_j(k)=\sum_{l=0}^{L-1} h_l c_{j-1}(k+2^{j-1}l) \tag{2}$$

The difference between $c_j(k)$ and $c_{j-1}(k)$ results in the wavelet scale, or the details signal at level $j$. The can be expressed as:

$$w_j(k)=c_{j-1}(k)-c_j(k) \tag{3}$$

This algorithm provides a convenient way to reconstruct the original signal $c_0(k)$:

$$c_0(k)=c_n+\sum_{j=1}^{n} w_j(k) \tag{4}$$

Two decomposition filters and two reconstruction filters had been used to realize DWT.

The power quality data series $c_0(k)$ is passed through a low pass filter $h_l$ and a high pass filter $g_l$. This produces $c_1(k)$ and $w_1(k)$. $c_{\mathrm{n}}(k)$ and $w_n(k)$ are obtained by passing the time series through the pair of decomposition filters $n$ times, as shown in Figure 2, [23].

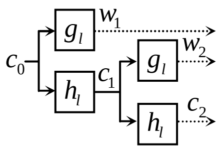


**Figure 2** The Decomposition Process

$c_j(k)$ is obtained using equation (2). Similarly, the wavelet scale at each level is obtained as follows:

$$w_j(k) = \sum_{l=0}^{L-1} g_l c_{j-1}(k + 2^{j-1} l) \tag{5}$$

Equations (2) and (5) can be used to reconstruct the original signal. The only difference is that reconstruction filters $\bar{h}_l$ and $\bar{g}_l$ are used instead. The block diagram given in Figure 3 illustrates the process, [23].

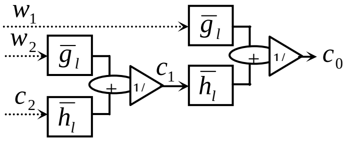


**Figure 3** The Reconstruction Process

$h_l$ is a wavelet filter if it has an even length $L$, $g_l$ is the scaling filter defined in terms of the wave filter via the 'quadrature mirror' relationship $g_l \equiv (-1)^{l+1} h_{L-1-l}$, [24]. *Daubechie* wavelet was selected in our case study using wavelet decomposition techniques.

## 5. CASE STUDY – MONITORING POWER QUALITY OF RITCHIE BUILDING AT THE UNIVERSITY OF QUEENSLAND (UQ)

The UQ Ritchie Building hosts several laboratories. Power supply to this building is from Substation 14 with a 1500kVA rated transformer. The monitoring process was carried out at this Ritchie Building for 32 days (28/8/01 to 28/9/01). The block diagram in Figure 4 shows the power system connections and the point of common coupling (PCC) of the PQNode.

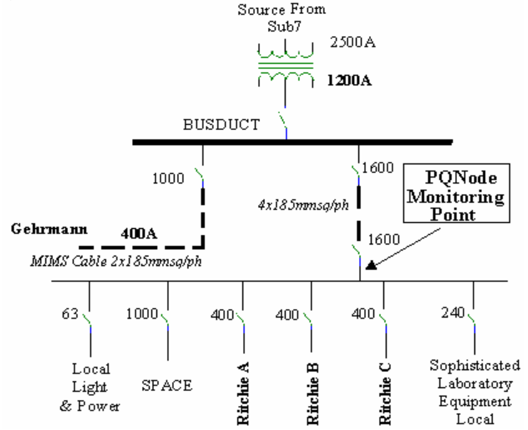


**Figure 4** Block Diagram of Ritchie site.

The Ritchie site had been experiencing disturbances because of transients with a large number of spike disturbances from incoming ac voltage waveforms. capacitor switching was not to a problem and therefore provided opportunities for a comprehensive power quality investigation with PQNode recorded data.

### (1) Transients analysis

There was no impulsive transient observed during the period of monitoring. However, there were a number of low frequency oscillatory transients observed in the mornings between 7:00am to 8:00am and the evenings between 4:30pm to 6:00pm – as shown in Figure 5. The low frequency oscillatory transients observed at 30 ms. ~ 40 ms. were indicated by an abnormal phenomenon in the voltage wave shape. Observations showed that this disturbance was triggered due to a sudden increase in the Phase B voltage. The whole event lasted for a period of 7 milliseconds and has a maximum magnitude of 0.979pu.

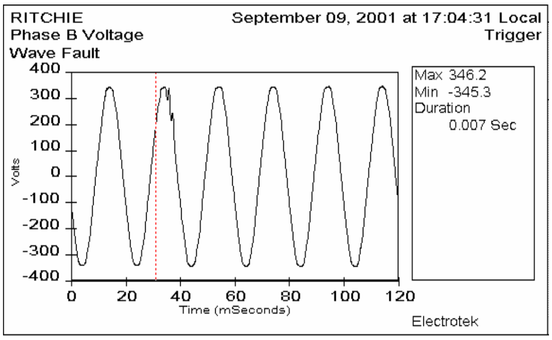


**Figure 5** Low frequency oscillatory transient

### (2) Short/long duration variations

The Ritchie site experienced 69 voltage sags and there was no voltage swell found during the period of monitoring. Out of these 69 recorded voltage sags, only eight voltage sags were sufficiently low in magnitude and long in duration to be classified by the CBEMA curve – see Figure 6.

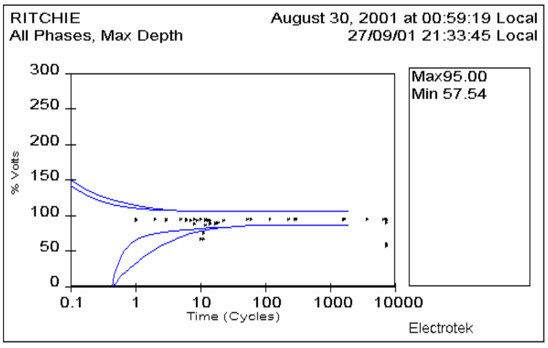


**Figure 6** The CBEMA curve, showing the fatal sags

The eight significant voltage sags located outside of the CBEMA tolerance curve were observed mostly during the night. These might have been associated with system faults but could also be results of energization of heavy loads. The end result was a large dip in the Phase A voltage – as shown in Figure 7. The fault was cleared by the circuit breakers in most cases.

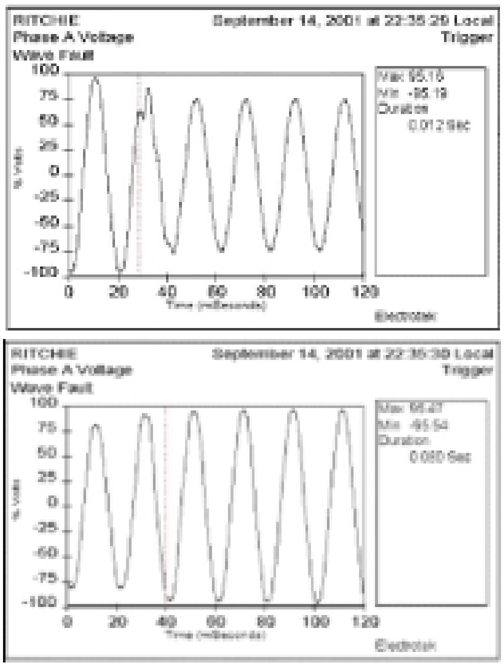


**Figure 7** Voltage sag disturbances waveform.
[No overvoltages or undervoltages detected]

### (3) Phase imbalance

The Ritchie site had produced irregular current trends, which were different in both phase *A* and *B*. It was also show that the neutral conductor had a continual current between 20A to 80A - see Figure 8.

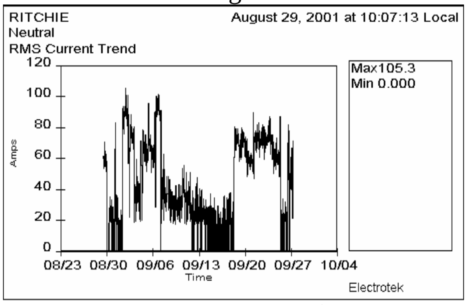


**Figure 8** The RMS Current Trends of neutral conductors

The irregular current trend waveform observed could be a result of an imbalance in the neutral current, phase A and B respectively. The voltage imbalance is calculated to indicate that all three phases were balanced, with a maximum deviation of 1%. However, Phase *C* has a maximum deviation of 1.8% but still within the 2% threshold. These plots constitute that the phase voltage were all within 2% deviation thresholds, proving that they were balanced.

### (4) Waveform distortion analysis

The Ritchie site had a high *Total Harmonic Distortion* (THD) levels. Especially on phase *C*, it even went above the specified 5% threshold set by the Australian Standard AS 2279 – Part 2. However, for phases *A* and *B*, the THD is still within the range of 1.5% ~ 3.5%. THD of the odd components are given in Figure 9, from which it is clear that the total odd harmonics exceeded the specified 5% only once on phase *C*; on phase A, the total odd harmonic also exceeded the specified 4% once; however total odd harmonic on Phase B remains within 4%.

Figure 10 shows the steady-state waveform on phase A with the higher odd harmonic distortion. The harmonic distortions observed in the Ritchie site were mostly caused by light and computer usage.

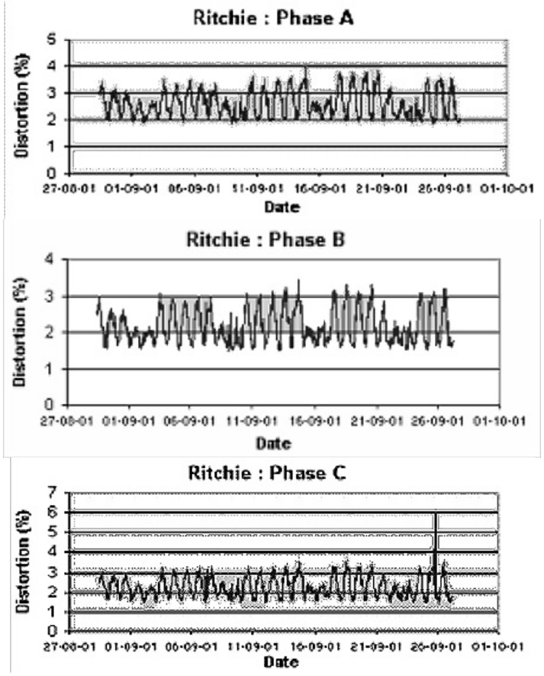


**Figure 9** Total odd harmonic distortion on phase A, B and C

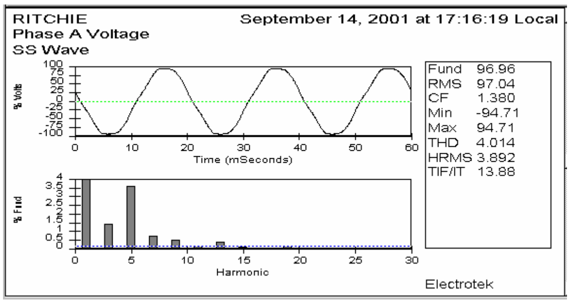


**Figure 10** Steady-state waveform on phase A voltage

The Ritchie site had been constantly experiencing a waveform that looked like *noise* added on the supply. This *noise* was commonly seen in the mornings between 6:00am to 8:00am and evenings between 5:00pm to 6:00pm. An investigation on this disturbance showed that a combination of higher frequency signals superimposed on the fundamental (50Hz) signal produced such noise like disturbances.

### (5) Power frequency variations

During the period of monitoring, Ritchie site had only one deviation of ±0.3Hz [18] from the fundamental frequency of 50Hz. This frequency variation was most likely caused by large disturbances on the transmission system.

### (6) Voltage fluctuations

Throughout the whole survey, there was no voltage fluctuations observed at the Ritchie site.

The distribution of PQNode triggers (detected on power quality problems) over a weekly period and during the office hours (8:30am to 5:30pm) in the Ritchie site were relatively high for Thursdays and Fridays, and lower for the rest of the week.

In the daily basis, the percentage of triggers occurring during the office hours (18%) is much lower than those outside office hours (82%). Customer usage was one of the major factors affecting the power quality triggering.

The analysis on the information gathered during the period of investigation in Ritchie site concluded that there were no major power quality problems within the site. However, a few irregular did occur such as phase imbalances and power frequency variations.

## 6. FURTHER INVESTIGATION WITH WAVELET TECHNIQUES

Wavelet techniques were applied to the measurement data from Ritchie site. The aim of introducing wavelet techniques was to classify power quality problems recorded in the Ritchie site that would not have shown clearly when using the PQNode alone. The wavelet analysis results were given in the sequel.

### (1) Multiresolution analysis of transient

There was an impulsive transient observed by using the wavelet decomposition technique when monitoring the Ritchie site – see Figure 11, which might be a result of a lightning striking. As shown in Figure 11, disturbance events were indicated by high values of wavelet coefficients, and the electrical noises were represented as small and random coefficient values. The detection results of this impulse disturbance event were observed only on scales 1 and 2. This is because at the lower scale, the analysing wavelet is most localized, thus the wavelet transform picks the disturbances that were most severe. The high level coefficient values at 39 milliseconds in scales 1 and 2 indicated on the voltage rises to its peak value then decay to half its peak value in very short duration in terms of microseconds. This observation clearly indicated the impulse transient events happened, with sudden changes in the steady-state condition of voltage that was unidirectional in polarity.

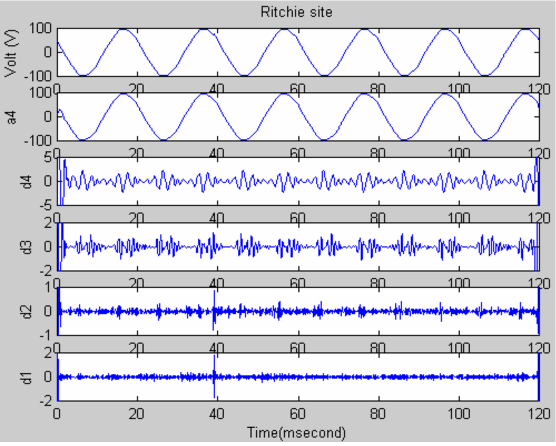


**Figure 11 I**mpulse disturbance detection, where, d1-d4 are the wavelet decomposition coefficients at detail scale levels 1 – 4.

However, there were a number of low frequency oscillatory transients observed when using the wavelet decomposition technique – as shown in Figure 12. The disturbance shown in Figure 12 had a very rapid oscillation disturbance at 20 msec, and is followed by a slow oscillation disturbance after 20 msec indicated of a drop in voltage in power system. This event is observed on decomposition scales 2, 3 and 4. From scale 3 of Figure 12, it was easy to identify the occurrence of a sudden, non-power frequency change in the steady-state condition of voltage that included both positive and negative polarity changes rapidly. This observation shows the detection of a low frequency oscillatory transient.

### (2) Multiresolution analysis of voltage sag

During the period of monitoring, the Ritchie site had experienced eight voltage sags and no voltage swells. Figure 13 showed the waveform of fault disturbances detection using Daubechies wavelets.

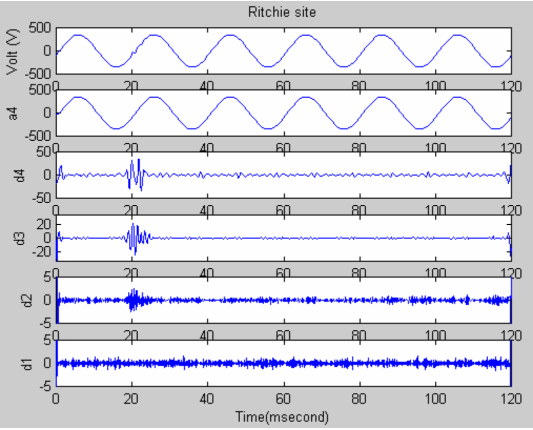
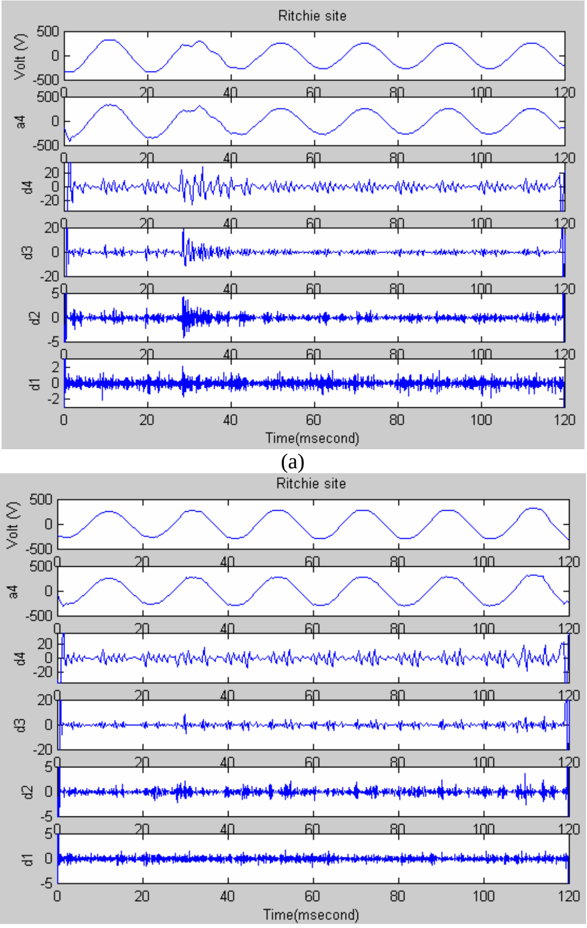


**Figure 12** Oscillatory transients disturbance detection**.**



(a)

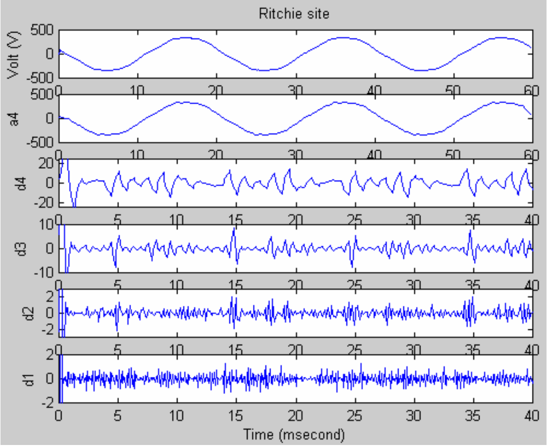
(b)

**Figure 13** Voltage sag disturbance, (a) 22:35:29 (b) 22:35:30

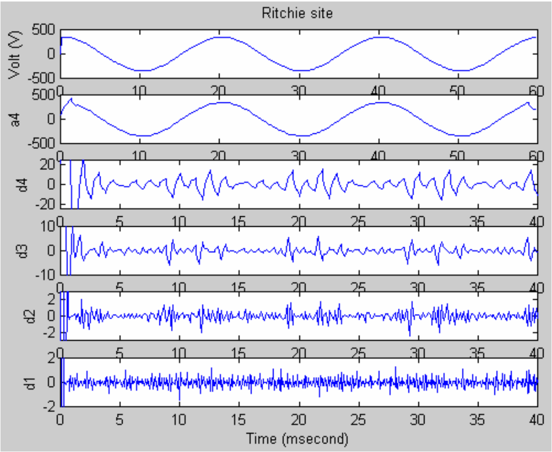
From Figure 13 (a), we observed that many coefficients had small values compared to the absolute highest value at each corresponding scale. These high coefficient values oscillating over time occurred at 30msec, indicated a line voltage drop. However, due to a following of high WTCs value indicated in scale 3 occurred in Figure 13 (b) at a 30 msec, they indicated that the voltage returned to its normal level. This was clearly shown on the voltage sag events observed during the monitoring period.

### (3) Multiresolution analysis of harmonic distortion

The Ritchie site experienced high level of *Total Harmonic Distortion* (THD). Figure 6-4 (a) shows discriminate high THD levels waveforms and figure 6-4 (b) shows discriminate low THD levels waveforms.



14 (a)



(b)

**Figure 14** Harmonic distortion disturbance detection, (a) higher THD levels, (b) lower THD levels.

In Figure 14, we observed that the coefficient values repeated themselves every cycle. These values were indicated on the different levels of harmonic distortions recorded. Figure 14 (a) has higher value coefficients indicated on the waveform than that of Figure 14 (b), which means a higher THD levels existed in (a) than in (b). This was confirmed by the recorded power quality problems in Ritchie site.

### (4) Correlation of results and findings

The detection and localization conducted in the power quality problems through the use of the wavelet multiresolution decomposition techniques in the Ritchie site implied that the numbers of power quality problems found in the Ritchie site were relatively low for Monday, Tuesday and Saturday, and higher for the rest of the week. In comparison to PQNode, wavelet technique placed higher emphasis on transient events instead of a general study of various disturbances.

From the information gathered using wavelet techniques in Ritchie site, it clearly classified the different types of power quality disturbances found in this power system. The information collected suggested that the power quality is relatively clean within the Ritchie site, with the exception of the transient disturbances.

## 7. CONCLUSIONS

This paper reviewed the general categories of power quality problems and previous analytical works by other researchers. A wavelet decomposition approach was discussed and applied to compare with power quality problems recorded by PQNode at University of Queensland. The case study showed the capability of wavelet decomposition in identifying power quality problems, which, might otherwise not be identified by PQNode alone.

## 8. REFERENCES

[1] R.C. Dougan, M.F. McGranaghan and H.W. Beaty, *Electrical Power System Quality*, McGraw-Hill, USA, 1996.

[2] P.P. Barker et al, " Power Quality Monitoring Of A Distribution System," *IEEE Transactions On Power Delivery*, Vol. 9, No. 2, April 1994, pp. 1136-1142.

[3] D.S. Dorr et al, " Interpreting Recent Power Quality Surveys to Define the Electrical Environment," *IEEE Transactions On Industry Applications*, Vol. 6, No. 6, November/December 1997, pp. 1480-1487.

[4] E.W. Gunther and H. Mehta, " A Survey of Distribution System Power Quality – Preliminary Results," *IEEE Transactions On Power Delivery*, Vol. 10, No. 1, January 1993.

[5] D.D. Sabin, T.E. Grebe, and A. Sundaram, "RMS Voltage Variation Statistical Analysis For A Survey OF Distribution System Power Quality Performance," *IEEE Power Engineering society: 1999 Winter meeting: 31 Jan-4 Feb, 1999, New York City, New York, USA/IEEE Power Engineering Society*, IEEE, Piscataway, New Jersey, USA, 1999, Vol. 2, pp. 1235-1240.

[6] Electrical Power Systems Quality, Internet Home Page, http://www.electrotek.com, (current April 9th, 2001)

[7] IEEE Recommended Practice for Monitoring Electric Power Quality (IEEE 1159-1995) http://www.pqnet.electrok.com/pqnet/main/backgrnd/terms/paper/table.htm (current April 18th, 2001)

[8] SEQEB System Investigation Department; *Supply and Demand : A Guide for Commerce and Industry*, 1st Edition, August 1994.

[9] IEEE Standard 446-1987, *IEEE Recommended Practice for Emergency and Standby Power System for Industrial and Commercial Applications* (IEEE Orange Book).

[10] BMI, User Guide, and PASS graphical software for the PQNode.

[11] Basic Measuring Instruments (BMI), *Handbook of Power Signatures*, 2nd Edition, Revised and Expanded, Basic Measuring Instruments, 1993.

[12] A.M. Gaouda et al, "Power Quality Detection and classification Using Wavelet-Multi-resolution Signal Decomposition," *IEEE Transactions On Power Delivery*, Vol. 14, No. 4, October 1999, pp. 1469-1475.

[13] W.M. Grady et al, "Power Quality Assessment via Wavelet Transform Analysis," *IEEE Transactions On Power Delivery*, Vol. 11, No. 2, April 1996, pp. 924-930.

[14] O. Poisson, P. Rioual and M. Meunier, "New Signal Processing Tools Applied to Power Quality Analysis," *IEEE Transactions On Power Delivery*, Vol. 14, No. 2, April 1999, pp. 561-566.

[15] S. Santoso, E.J. Powers and W.M. Grady, "Electrical Power Quality Disturbance Detection using Wavelet Transform Analysis," in *Proceedings of the IEEE-SP International Symposium on Time-Frequency and Time-scale Analysis*, Philadephia, PA, Oct. 25-28, 1994, pp. 166-169.

[16] W.M. Grady et al, "Characterization of Distribution Power Quality Events with Fourier and Wavelet Transforms," *IEEE Transactions On Power Delivery*, Vol. 15, No. 1, January 2000, pp. 247-254.

[17] S. Mallat, "A Theory for Multiresolution Signal Decomposition: The Wavelet Representation," *IEEE Transactions on Pattern Analysis and Mach. Intel.*, Vol. 11, July 1989, pp. 674-693.

[18] S. Santoso, E.J. Powers, and W.M. Grady, " Wavelet-based Power Quality Event Identification System, Part 1The Wavelet Transform and Feature Extraction of Power Quality Disturbances and Part 2: Design and Implementation," *ERPI Report*, August 1997.

[19] J. Wu, and T.K. Saha, "Simulation Of Power Quality Problems On A University Distribution System," *2000 Power Engineering Society Summer Meeting: Conference proceedings: 16-20 July 2000, Seattle, Washington, USA/sponsored by Power Engineering Society and Institute of Electrical and Electronics Engineers*, IEEE, Piscataway, New Jersey, USA, 2000, Vol. 4, pp. 2326-2331.

[20] G. Beylkin and N. Satio, "Wavelets, their autocorrelation functions and multiresolution representation of signals", *IEEE Trans. Signal Processing*, Vol. 7, pp.147-164, 1997.

[21] "Wavelet Toolbox User's Guide," The MATH WORKS Inc., version 2, September 2000.

[22] G. Zheng et al. "The Wavelet Transform for Filtering Financial Data Streams," *Journal of Computational Intelligence in Finance*, Vol. 7, No. 3, May/June 1999.

[23] A. Aussem, J.Campbell and F. Murtagh, "Wavelet-Based Feature Extraction and Decomposition Strategies For Financial Forecasting," *Journal of Computational Intelligence in Finance*, Vol. 6, No.3, pp.5-12, March/April 1999

[24] D. B. Percival and A. T. Walden, "Discrete Wavelet Transform," *Wavelet Methods for Time Series Analysis*, Cambridge University Press, United Kingdom, 2000, pp.56-158.