2007

Analysis of harmonic distortion levels on a distribution network

Glenn Nicholson
Manukau Institute of Technology

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

Ashok Parsotam
Vector (NZ) Ltd

Analysis of Harmonic Distortion Levels on a Distribution Network

Glenn Nicholson, V.J. Gosbell, *Member, IEEE*, and Ashok Parsotam

Abstract**-- It is generally acknowledged that harmonic distortion levels on distribution networks are steadily increasing due to the proliferation of non-linear loads. While customer complaints relating to harmonic distortion levels are relatively uncommon, and measured levels are typically well within the limits specified by national regulations and international standards, the increasing trend may mean that more active management by utilities will soon be required.**

Effective management of harmonic distortion levels will require knowledge not only of the level of disturbance, but also of how the disturbance levels vary with time, location, and the connected load. Accepted methods for assessing harmonic levels that rely on cumulative probability statistics are inadequate for this level of insight. In this paper voltage total harmonic distortion levels (THD_v) from a distribution network power quality survey are analysed in terms of variation with time, system load and the physical characteristics of the monitored sites.

***Index Terms-- harmonic distortion, power quality*.**

I. Introduction

HARMONIC distortion levels are seldom the source of complaints from network customers. After issues of network reliability, most customer complaints arise from discrete power quality disturbances such as short-term interruptions, voltage sags or swells, and voltage fluctuations that cause light flicker. While harmonic distortion may not cause immediate and easily-observed impacts such as the discreet disturbances given above, it can cause some equipment to malfunction, and does result in additional power losses in both customer and network equipment [1].

It is generally accepted that the proliferation of non-linear loads is leading to a slow but steady increase in harmonic distortion levels on networks. Even if present levels of harmonic distortion are considered to be well within acceptable levels, this situation may well change if the increasing trend continues. Management of harmonic distortion levels will be assisted by knowledge of how distortion levels vary both in place and in time. The use of cumulative probability statistics calculated over the survey period does not give sufficient information for this purpose.

This paper will describe the analysis of harmonic distortion levels recorded as part of a continuous power quality survey on a distribution network. Measured levels of voltage total harmonic distortion have been analysed with regard to both variation over time and also the load characteristics of the monitored site.

II. Reasons for this study

The data on which this paper is based is taken from a continuous PQ monitoring programme carried out by Vector (NZ) Ltd. Vector have been actively involved in routine PQ monitoring since 1999 and now have over 30 PQ monitors installed in the Auckland network, including 13 monitors connected to the 11 kV bus in zone substations. It is the data from these zone substations that is analysed in this paper.

An earlier study [2] analysed variation in THD_v levels across the 13 monitored sites. For the purpose of this study, the sites were grouped according to whether the predominant nature of the connected load was commercial, industrial or residential. The survey consisted of two commercial sites, eight industrial sites, and three residential sites. 95% cumulative probability statistics were calculated for the purpose of reporting the THD_v levels at each site. It was found that THD_v levels were lowest at commercial sites, followed by industrial sites, with residential sites highest. This seemed counter-intuitive, as it could be expected that industrial sites would have a much higher proportion of non-linear loads than residential sites. One of the outcomes of the earlier study was identifying the need for further investigation into harmonic distortion levels on the network.

III. Analysis of THD_V Data

In this paper, THD_v data from the 13 monitored sites has been analysed, covering the period of the month of June 2004. The objective of the analysis was to identify any time-varying trends in THD_v levels, and also to identify any relationship between the THD_v and the predominant load type and load magnitude.

The steps in analysing the THD_v data for each site were:

Glenn Nicholson is with the Electrical & Computer Engineering Dept at Manukau Institute of Technology, Auckland, New Zealand (email: gnichol@manukau.ac.nz)

Prof. Vic Gosbell is an honorary professorial fellow and technical advisor to the Integral Energy Power Quality & Reliability Centre, University of Wollongong, NSW2522, Australia (e-mail: v.gosbell@elec.uow.edu.au)

Ashok Parsotam is with Vector (NZ) Ltd, where he is responsible for power quality and network modeling. (email: ashok.parsotam@vector.co.nz)

- Plot the THD_v measurements against time in order to identify any trends with regard to time (ref. Section IV).
- Compare the THD_v plot with the trend for site load current for the corresponding period (ref. Section IV).
- Calculate the correlation coefficient between THD_v and load current (ref. Section IV).
- Investigate the relationship between THD_v and harmonic current levels over the survey period (ref. Section IV-D).
- Compare the time trends for the site against all other sites (ref. Section V).

IV. THD_v Time Series and Load Current Analysis Results

A. *Commercial Sites*

The plot of THD_v levels against time clearly identified both daily and weekly cycles of variation. The plot for one of the commercial sites is shown in Fig.1.

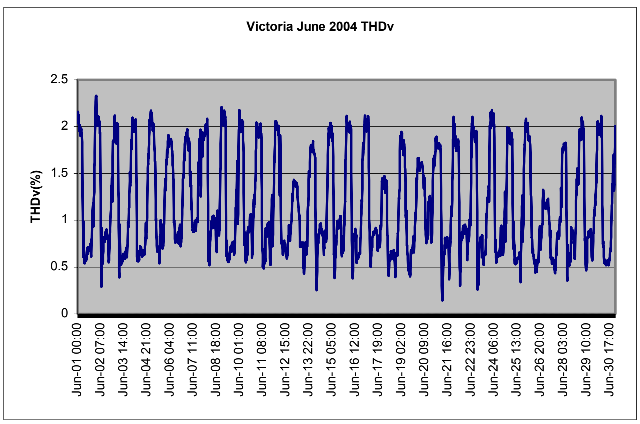

Fig.1. Monthly THD_v trend for a commercial site.

On a daily basis, THD_v levels peak between the hours of midnight and 5:00 a.m., and are fairly constant during this time at around 2%. Daily minium THD_v levels occur between the hours of 7:00 a.m. and 5:45 p.m. (at around 0.5%), and this coincides with commercial hours of business and the period of maximum load current. On a weekly scale, weekends (June 5-6, 12-13, 19-20 and 26-27) typically experience lower maximum levels and higher minimum levels of THD_v.

A scatter plot of THD_v and load current was used to compare measured THD_v levels against corresponding levels of load current for the same period. This plot is shown in Fig.2.

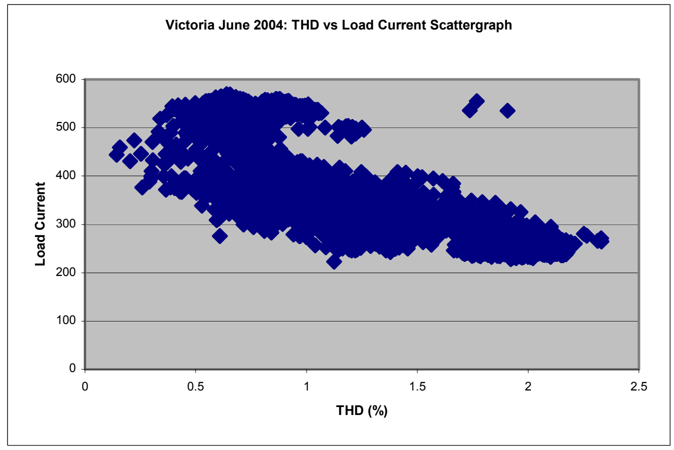

Fig.2. Scatter plot of load current against THD_v for a commercial site.

Fig.2 suggests that a negative correlation exists between load current and THD_v. Using the data analysis tools in Microsoft Excel, the correlation coefficient was calculated to be –0.79 for the month of June. Very similar results were obtained from the other commercial site, the only significant difference being the magnitude of the THD_v measurements.

B. *Industrial Sites*

Data from eight industrial sites was analysed in this study. It is worth noting that while these eight sites are all considered to have a predominantly industrial load, some sites are more industrial than others (i.e. some sites consist of a mix of industrial, commercial and residential load). Determining what may be considered representative trends across the eight sites is further complicated by the fact that at three of the industrial sites, THD_v levels are recorded hourly as opposed to the 15-minute recordings at the other five industrial sites. Despite these limitations, some trends were still found to be consistent across the eight industrial sites. Fig.3 shows the THD_v trend for what can be considered a typical site.

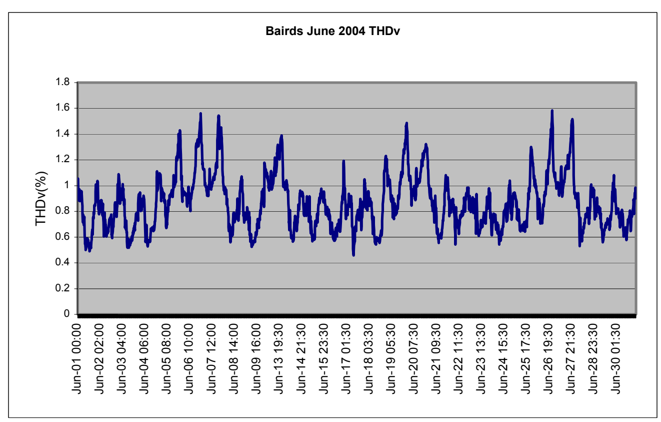

Fig.3. Monthly THD_v trend for an industrial site

The daily and weekly variation in THD_v levels typical of industrial sites can be seen in Fig.3. 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 night-time hours. At some sites this peak occurs before midnight, while at other sites the peak occurs between midnight and 5:00 a.m. Fig.3 also shows

a clear weekly trend in THD_v levels, with higher levels being recorded on weekends. This is true for most of the industrial sites, and coincides with periods of lower load current.

The relationship between measured THD_v levels and load current was assessed using a scatter plot. The scatter plot corresponding to the THD_v data from Fig.3 is shown in Fig.4.

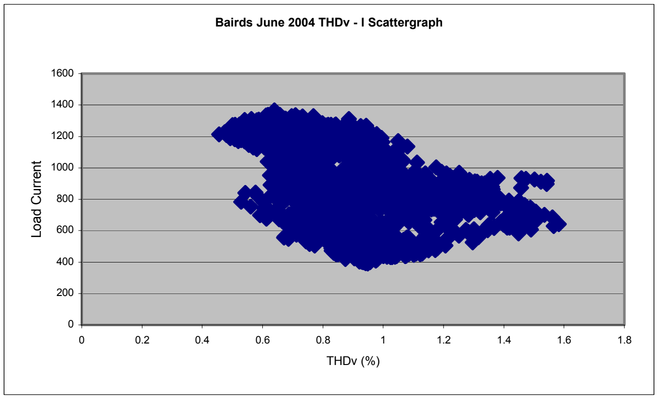

Fig.4. Scatter plot of load current against THD_v for an industrial site.

As for the commercial sites, the scatter plot suggests a negative relationship between THD_v levels and load current. For the example industrial site, the correlation coefficient was calculated to be –0.53. All industrial sites displayed a negative correlation coefficient between THD_v levels and load current, with the coefficients ranging between –0.34 to –0.86

Across the eight industrial sites, the range of peak THD_v levels recorded was between 1.5% to 3%.

C. Residential Sites

The Vector power quality survey included data from three residential sites. Cyclic variation of THD_v levels on both daily and weekly timescales was clearly apparent. Fig.5 shows the variation in THD_v levels for one of the residential sites for the survey period.

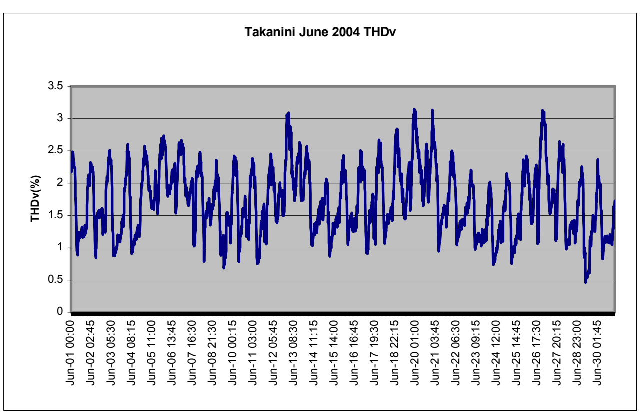

Fig.5. Monthly THD_v trend for a residential site.

For the residential sites, THD_v levels typically peak each day between the hours of 7:30 p.m. and 2:30 a.m. Within this range, most daily THD_v peaks occur around 10:30 p.m. Daily minimum THD_v levels typically occur between the hours of 6:30 a.m. and 9:00 a.m., which coincides with the morning peak in load current. During the late afternoon-early evening load current peak, THD_v levels also show a marked decrease.

On a weekly time scale, two of the three sites showed a clear weekly pattern, with maximum THD_v levels for the week being recorded on either Saturday or Sunday. For the third residential site, the weekly pattern was less clear, but again many of the weekly peak levels occurred on Saturdays or Sundays.

The relationship between THD_v levels and load current is less clear for residential sites than it is for commercial and industrial sites. For the example residential site shown in Fig.5, a strong negative correlation between THD_v and load current was evident for the month of June, as can be seen from the scatter plot in Fig.6. For this site, the correlation coefficient was calculated to be –0.8.

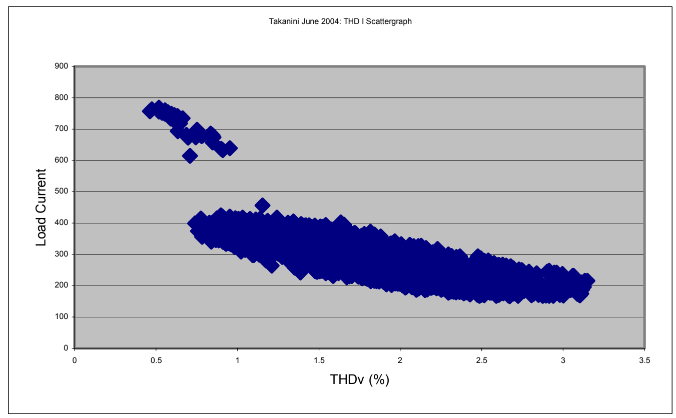

Fig.6. Scatter plot of load current against THD_v for a residential site.

For the other two residential sites, the THD_v-load current correlation coefficients were 0.22 and 0.54 (i.e. both positive).

D. Relationship Between THD_v Levels and Harmonic Current Levels

Given that the presence of harmonic voltages on the network is the result of the flow of harmonic currents, this raises the question of how do the harmonic voltage levels relate to measured levels of harmonic currents. The only harmonic current data available from each site are the 15-minute averages of current THD for each phase. The usefulness of current THD for comparing values at different sites or at different times is limited, as each measurement is divided by a different value of fundamental current as the load varies. A more useful value for comparison purposes is the magnitude of the distorting current.

With data for both average load current and current THD, the magnitude of the total distorting current can be calculated. Current THD is calculated as:

$$THD_i = \frac{I_h}{I_1} \quad (1)$$

$$\text{where } I_h = \text{total distorting current}$$
$$I_1 = \text{fundamental currrent}$$

and so the total distorting current can be calculated as

$$I_h = THD_i \times I_1 \quad (2)$$

For the purpose of this calculation, only the average rms value of load current (rather than the fundamental) is available, but given that

$$I_{rms} = \sqrt{I_1^2 + I_h^2} \quad (3)$$

it can be shown that the magnitude of the total distorting current can be calculated by:

$$I_h = \frac{I_{rms} \times THD_i}{\sqrt{1 + THD_i^{\,2}}} \quad (4)$$

The relationship between THD_v and the total distorting current I_h has been analysed with the aim of determining whether the source of this disturbance is harmonic load currents flowing downstream of the monitored site, or whether it originates from upstream of the monitored site. To analyse the relationship, the correlation coefficient between THD_v and total distorting load current I_h has been calculated for each site. The results are given in Table I.

Table I. Correlation between THD_v and distorting load current I_h.

Site	**THDv – I_h Correlation Coefficient**
Commercial	
Quay	0.88
Victoria	-0.41
Industrial	
Bairds	0.55
Carbine	0.90
Greenmount	0.71
McNab	0.48
Otara	0.43
Rockfield	0.76
Rosebank	0.91
Wiri	0.91
Residential	
Howick	0.41
Manurewa	0.75
Takanini	0.87

The results in Table I show that all sites except one show either a moderate or strong positive correlation between THD_v and total distorting current. This suggests that the voltage distortion levels present at the zone substations are likely due to distorting load currents downstream from the substation. It also indicates that harmonic current magnitude varies with time in a similar manner to voltage distortion. To check this, trends in THD_v and harmonic current I_h have been plotted together. The trend for an example site is shown in Fig.7, clearly illustrating the similarity in variation of THD_v and total harmonic current.

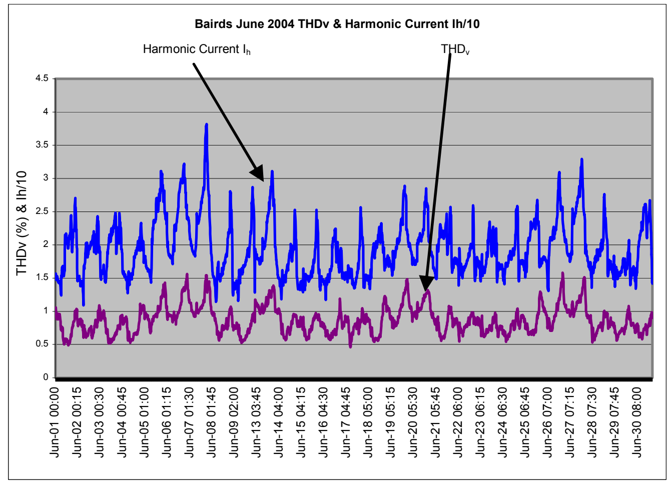

Fig.7. THD_v and Harmonic Current I_h for a sample site.

V. SUMMARY OF RESULTS

From comparison of the results from the three site categories, it is clear that there are significant differences in the patterns of THD_v variation, and that these differences can be attributed to both predominant load type, and the pattern of load current variation. There are also aspects of THD_v variation that are common across all sites.

A. THD_v Variation With Time

The first comparison that can be made is between the times at which peak THD_v levels occur for each site. Table II shows the typical times of daily peak THD_v levels for the surveyed sites. The shaded areas indicate the range of times of daily peak THD_v levels. The range of peak times is defined as range of times of day during which the daily maximum value of THD_v occurs over the one-month survey period.

Table II. Comparison of THDv peak times.

	06:00-08:00	08:00-10:00	10:00-12:00	12:00-14:00	14:00-16:00	16:00-18:00	18:00-20:00	20:00-22:00	22:00-00:00	00:00-02:00	02:00-04:00	04:00-06:00
Quay										commercial	commercial	commercial
Victoria										commercial	commercial	commercial
Bairds								industrial	industrial			
Carbine								industrial	industrial			
Greenmount										industrial	industrial	industrial
McNab								industrial				
Otara								industrial	industrial	industrial		
Rockfield								industrial	industrial	industrial		
Rosebank								industrial	industrial			
Wiri								industrial	industrial			
Howick								residential	residential			
Manurewa							residential	residential				
Takanini									residential	residential		

(blue) = commercial; (cyan) = industrial; (green) = residential

The two zone substations supplying predominantly commercial load both exhibited very similar patterns of variation of THD_v and load current. THD_v levels peak between midnight and 5:00 a.m., and fall to low levels during business hours when load current is high. The diurnal variation in THD_v levels is around 2%. Overall, THD_v levels for the two commercial substations are lower than for industrial or residential substations. The average 95% cumulative probability value of THD_v across the two sites for the month of June was 1.44%.

THD_v levels at zone substations supplying predominantly industrial loads likewise peak at night and are generally higher on weekends, and this coincides with periods of reduced load current. There is some variation across the eight substations in the time during the night at which peak THD_v levels occur. For most sites the peak occurs between 8:00 p.m. and midnight (similar to a residential site) while at one site the peak occurs between midnight and 5:00 a.m.

The average diurnal variation in THD_v levels at industrial sites is 1.6%, similar to that for commercial sites. The average 95% cumulative probability value of THD_v across the eight sites was 1.94%, slightly higher than that for the commercial sites.

THD_v levels at the zone substations supplying predominantly residential load also tend to peak mostly during night-time hours. For two of the residential substations, THD_v tends to peak between the hours of 8:30 p.m. and midnight. The one residential substation where THD_v levels peak after midnight also has a load current pattern that suggests that this residential site has a significant commercial or industrial load component. The average diurnal range in THD_v levels for the residential substations is 2.23%, larger than the range for either commercial or industrial sites. The average 95% cumulative probability value of THD_v across the three residential sites was 2.58%, significantly higher than the comparable values for both commercial and industrial sites. This reaffirms the findings of [2] that THD_v levels at residential sites are typically higher than those experienced at commercial or industrial sites.

B. THD_v Variation With Load Current

The second comparison that can be made between the sites is the relationship between variation in THD_v levels and daily and weekly variations in load current. The correlation coefficient between THD_v and load current for each site is given in Table III.

The two commercial sites show a strong negative correlation between THD_v and load current. Likewise, all industrial sites show a negative correlation between THD_v and load current. The strength of this correlation varies between sites, and this is likely due to variation in the degree to which the load is purely industrial or combined with some commercial or residential load. The most interesting feature of Table III is that two substations display a positive correlation between THD_v and load current, and both of these substations are supplying predominantly residential load.

Table III. Correlation coefficients for THD_v against load current

Site	**THDv – Load Current Correlation Coefficient**
Commercial	
Quay	-0.8
Victoria	-0.79
Industrial	
Bairds	-0.53
Carbine	-0.38
Greenmount	-0.86
McNab	-0.34
Otara	-0.39
Rockfield	-0.23
Rosebank	-0.78
Wiri	-0.62
Residential	
Howick	+0.54
Manurewa	+0.22
Takanini	-0.80

The daily and weekly cycles of variation in voltage harmonic levels have been observed and documented previously in a number of publications, and mention of this aspect of harmonic variation can be found in textbooks on power quality [3], [4]. In [3], a plot of fifth harmonic voltage against time over a one-week period shows strong similarity with Fig.5 in this paper. In [3], it is stated that the peak voltage harmonic levels can be attributed to user behaviour, and in particular the use of televisions. While this may seem a plausible explanation for such variation on a residential feeder, it does not explain the post-midnight peak in voltage harmonic levels that occur at commercial and industrial sites. Additionally, at two of the residential sites included in this study, THD_v levels typically peak at between 10:00 p.m. and 11:30 p.m., whereas it would be expected that the peak time for television watching would be between the hours of 7:00 p.m. and 10:00 p.m. ('prime time'). In [5] it is concluded that varying levels of television use have a surprisingly low impact on harmonic voltage levels. It maybe that relatively higher levels of THD_v are experienced during these periods of low load because of the damping effect on harmonic distortion that occurs during periods of higher load current.

In [4], it is stated that higher levels of triplen harmonic currents are commonly observed during the early morning hours when the load is low, and that this is due to transformer excitation current. This explanation is questionable given that transformer excitation current is typically much less than 1% of rated full load current. It also does not explain the variation in THD_v levels observed in this survey on a MV network, as triplen harmonics do not propagate back into the delta-connected MV distribution network.

A possible explanation for the negative correlation between load current and THD_v levels observed at most sites is harmonic cancellation by the mixing of non-linear single phase and three phase loads, as described in [6]. It has been found that mixing single and three phase loads can result in reduced THD_v, the reason being that the 5^{th} and 7^{th} harmonic

currents of single and three phase loads are often in counter-phase resulting in at least partial cancellation.

It could be suggested that voltage harmonic distortion is not a problem on the network due to the low levels recorded. Typical 95% cumulative probability values across all sites are in the vicinity of 2% to 3%. There is clearly no issue of non-conformance to national or international harmonics standards. International standard AS/NZS 61000.3.6 [7] specifies a compatibility level of 8% for harmonic voltages in MV power systems. The requirements of the New Zealand Electricity Regulations [8] only relate to measurement of voltage harmonic distortion levels at the point of common coupling, and so are not generally applicable to harmonic levels on an MV distribution network.

The negative correlation between load current and THD_v levels has possible implications for the management and regulation of harmonic levels on distribution networks. If the highest levels of distortion occur in the middle of the night when connected load is light, this would suggest that the impact on most customers (and network equipment) will be minimal. It also raises the question as to wether the application of cumulative probability statistics to specify acceptable harmonic levels on distribution networks is appropriate.

VI. Conclusions

Voltage total harmonic distortion levels (THD_v) from a variety of monitored sites on a MV distribution network have been analysed in terms of variation with time, predominant load type, and level of load current. It has been 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, but whether the peak occurs during the late night or in the early morning hours depends on the predominant load type. Weekly patterns of THD_v variation were also identified, with higher levels occurring at weekends.

The findings of this study cast doubt on previously accepted explanations for higher harmonic levels at night or early morning. The effects of television use, transformer excitation current, and the levels of triplen harmonics do not satisfactorily explain this phenomena. Further research is required into the source(s) of this harmonic disturbance.

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.

VII. Acknowledgements

The authors would like to acknowledge the support of Vector Ltd (NZ) for allowing access to network power quality data and for supporting this project.

VIII. References

[1] Integral Energy Power Quality & Reliability Centre Technical Note 3: Harmonic Distortion in the Electric Supply System, March 2000, www.elec.uow.edu.au/iepqrc/files/technote3.pdf

[2] Nicholson G, Gosbell V, Parsotam A, "The Influence of Site Physical Characteristics on Power Quality Performance", Proc. AUPEC 2006, December 2006, Melbourne Australia.

[3] Schlabbach J., Blume D., Stephanblome T., "Voltage Quality in Electrical Power Systems", IEE 2001, London.

[4] Dugan R., McGranaghan M., Beaty H., "Electrical Power Systems Quality", McGraw-Hill, New York, ISBN 0-07-018031-8

[5] Browne N., Perera S., Ribeiro P.F., "Harmonic Levels and Television Events" presented at IEEE PES General Meeting, 24-28 June 2007, Tampa Florida, USA

[6] Hansen S., Nielsen P., Blaabjerg F., " Harmonic Cancellation by Mixing Nonlinear Single-Phase and Three-Phase Loads", IEEE Transactions on Industry Applications, Jan 2000 pg.152-159

[7] AS/NZS 61000.3.6: Limits – Assessment of emission limits for distorting loads in MV and HV power systems.

[8] New Zealand Electricity Regulations 1997, www.ess.govt.nz/rules/pdf/electricity_regulations_1997.pdf

IX. 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.

Vic Gosbell (M'1975) obtained his BSc, BE and PhD degrees from the University of Sydney. He has held academic positions at the University of Sydney and the University of Wollongong where he became the foundation Professor of Power Engineering. He is now an Honorary Professorial Fellow and Technical Advisor to the Integral Energy Power Quality and Reliability Centre. He is currently working on harmonic management, power quality monitoring and standards. He is a member of Australian standards and CIGRE sub-committees and is a Fellow of the Institution of Engineers, Australia.

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 in Fiji Islands, 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.