Statistical Analysis of Power Quality in Office Buildings

A. O. Olatoke, S.S. Sultan and M. K. Darwish

Abstract— Power Quality monitoring and analysis of office buildings (buildings with large number of computers) are essential to the maintenance engineer and supplier as well. This paper presents the steady state monitoring performed on one part of the 11kV distribution system of Brunel University. The point of common coupling was chosen to be at the 415volts incomer of the secondary point of the 500kVA, 11/.415kV substation. The study includes measured waveform, trends and statistical analysis of the measurement data taken. The results are analyzed and comparison is made with International Standards in order to evaluate the quality of power in a typical office building with more 500 computers.

Index Terms— Office Buildings, Voltage Histograms, Average Peak Demand Currents, Power Quality Solutions.

1 Introduction

The modern day proliferation of non-linear load in the distribution systems has caused generation of harmonic currents and consequently harmonic voltages. Virtually all modern electrical-electronic equipments like Variable Speed Drives; PCs, etc. contain switch-mode-power-supply (SMPS) and are referred to as non-linear loads. While a small number of theses loads cause no harm to the quality of the power, a large number of such small non-linear loads can cause a devastating effect at the point of common coupling and it could be very costly problem [1], [9]. There was very little awareness of such problems since most of the buildings and their electric distribution were designed and built before the explosion of the number of computers used in such buildings. There is a need to monitor the effects that these loads introduce into the distribution system. The resultant distorted harmonic voltages affect the adjacent feeders and equipments which can cause problems like neutral conductor overheating, distribution transformer overheating, radio frequency interference, unnecessary overconsumption leading to overbilling and incessant tripping of circuit breakers [6],[7]. Industrial and commercial growth have witnessed massive increase in automation brought about by power-electronic equipment such as Adjustable speed drive (ASD), also known as Variable speed drive (VSD) and sometimes labeled as Adjustable frequency drive (AFD). Others include computer loads, compact fluorescent lamps (CFL), with electronic gear, photocopiers and other modern-electronic equipment using switch-mode-power supply (SMPS) [10]. Mostly all power-electronic equipments are the sources of steady state distortions in the distribution system, and they are the ones adversely affected by the distortions caused to the voltage system.

The aim of this paper is to analyse the power quality data in a typical office building and then to highlights the importance and the necessity to monitor the power quality in such buildings. The proliferation of computers and other sensitive devices in office buildings and factories warrant new design of electrical systems, making power quality issues to become very important. Office buildings could vary from small buildings with small number of computers to sky scrapers with hundred thousand of computers and office equipments.

Power quality was formerly associated to be of purely technical issue, but due to ever-growing non-linear loads in the distribution system it has become one of the most important concept in the modernization of electricity transmission and distribution systems [11], [12]. Power quality solutions reduce outages, downtime and high losses in the distribution system, making sure that stable power is provided as incorporated in smart grid technologies [13].

The principal reason for monitoring is economic, especially in critical processes where down-time means losses and damage to very sensitive equipment which cannot be tolerated. There is also the need to have a database of equipment tolerances and sensitivity leading to equipment compatibility. Monitoring and updating power quality for record purposes is of importance in modern buildings. The tolerance of all the sensitive equipment should be kept which could be used to diagnose and solve fresh problems.

2 Case Study

The case study considered in this paper is two university office buildings. The first building is a 4-story building which contains a number of academic offices as well as mechanical engineering and computer laboratories with more than 110 computers. The other building which share the same feeder as the first building consists of 3-stories, which includes some lecture rooms and a large lecture theatre with more than 150 computers. Both buildings have lifts, and they serve as research offices and computers labs with 24/7 access to them. The buildings are supplied by 500kVA 11/0.415kV transformer. The load includes heat-ventilated-air-conditioners (HVAC), fluorescent lightings, computers, photocopiers, lifts, Mechanical and Electrical/Electronic laboratories. The study includes measured waveforms, trends and harmonics for both voltage and current up to the 50th harmonics on all the 3-phases. A QualistarPlus.C.A 8335 analyzer was installed at the point of common coupling (PCC) in order to characterize the harmonic injections and monitor the current and voltage waveforms. The PCC was monitored for one week during the month of October 2010, which is considered to be one of the busiest months of the academic year. This period was sufficient to capture the steady-state monitoring data that are essential for power quality characterization.

2.1 Data Collected

The various types power quality monitoring include: Short-term monitoring to solve an existing problem; Long-term monitoring to characterize an existing or new installation. Steady-state monitoring is necessary in order to determine the electrical environment before installation and for record keeping. Each of these types of monitoring has specific things to be considered before monitoring for example, data size, what to monitor and measure. Some of the measurement should include input voltage waveform line-line, (most three-phase equipment operate on line-line voltages), line-neutral current waveform, harmonics of voltage and current and flicker. Long-term power quality monitoring is largely a problem of data management, which can run into several gigabytes of data each day, and detecting power quality problems within this mass of data could be very difficult. A summary of power quality variation categories and proffered solutions are included in the attached [2] on page 8.

2.2 Analysis of Active, Reactive and Apparent Powers

The one week recording of active, reactive and apparent powers at the chosen PCC is shown in Fig. 1. It could be seen that the apparent power (KVA) and the active power (KW) have no difference; this is as a result that the reactive power (KVAR) has been compensated for by the capacitors installed at the incomer. Thus the power factor could be said to be near unity.

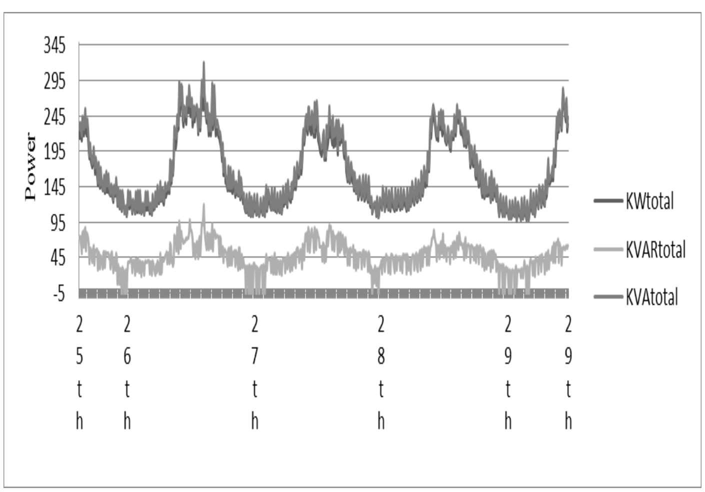

Fig. 1. Active, Reactive, and Apparent Power (25th – 29th) Oct

Another point of note is that reactive power is negative in the early hours of the mornings, which means that the capacitors are fixed and overcompensates for the reactive power when all equipment have been short down because this is a day-load establishment (offices and laboratories).

2.3 Analysis of Fundamental and Harmonic Voltages

The largest contributors of harmonics in a modern building are single-phase lighting circuits with electronic gear, computers, and the SMPS equipment. The major generators of 3rd harmonic currents are the SMPS. These listed above equipment generate 3rd harmonics. All forms of variable speed drives (VSD), like the six pulse converters or 3-phase full-wave Bridge are the major sources of 5th and 7th harmonics. The two main effects of harmonic currents on distribution system are electrical losses in the wires, transformers, busbars, and power factor correction capacitors. The other effect is the heating caused by these additional current on the RMS value of the fundamental current, thereby shortening the life of distribution equipment.

The one week recording of the fundamental as measured at the PCC is presented in Fig. 2. The measurement showed that the minimum voltage was 245.7 volts and the maximum was 257.5 volts as indicated in Table 1 instead of the nominal voltage of 230 volts (±10%).

TABLE 1
PHASE VOLTAGES AT LOAD V (1, 2, 3) RMS

	N	Minimum	Maximum	Mean	Std. Deviation
V1 RMS	651	246.8	257.5	252.339	2.0521
V2 RMS	651	245.7	256.5	251.393	2.0023
V3 RMS	651	245.9	256.5	251.381	1.9532
Valid N (listwise)	651				

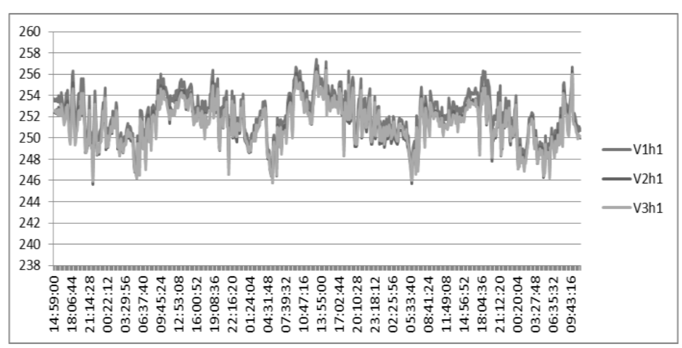

Fig. 2. Fundamental Voltage/Time in hours (25th to 29th) Oct.

The Histogram in Fig. 3 shows that the mean is 252.25 volts for the one week duration. This is a confirmation that the supply voltage is consistently high, even though it is still within the International limits.

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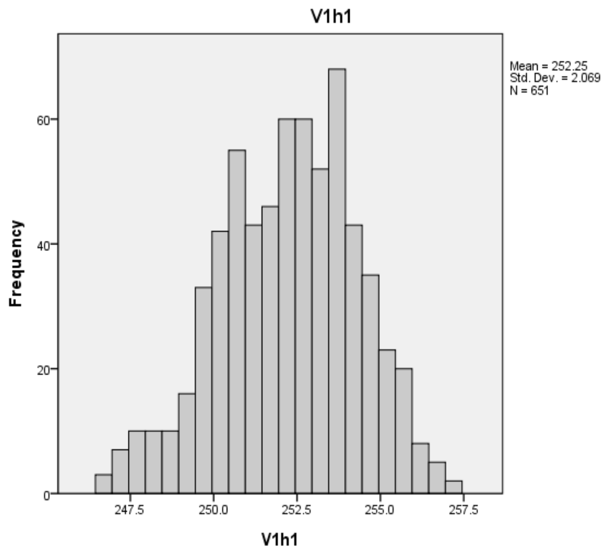

Fig. 3. Histogram of Density of the Fundamental Voltage (V1h1)

The histogram shows a good method of summarizing the time series. This is a plot of the number of occurrences of the harmonic voltages for the period of one week. The histogram indicates a normal or Gaussian distribution.

The significant harmonic voltages in this project were the 5th and 7th but the 3rd and 9th were not as pronounced, (as shown in Fig. 4). The 5th harmonic is over 8% and this has violated the International Standards (EN50160) which stipulates the limit to be less than 8% [3], [4].

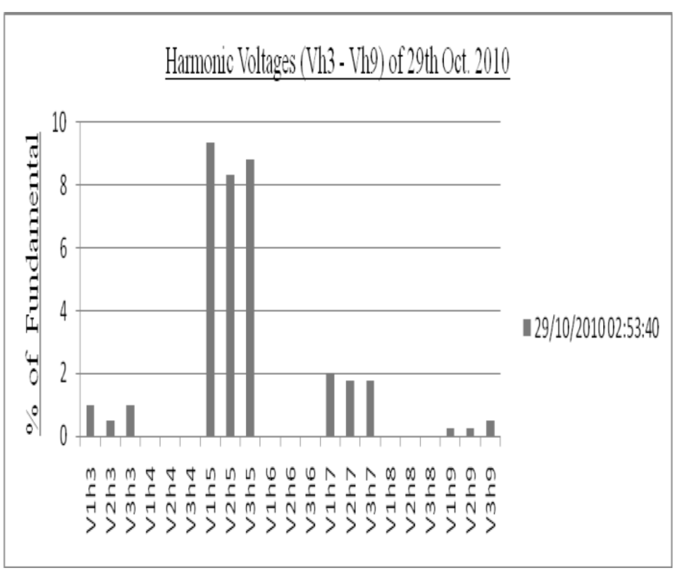

Fig. 4. Voltage 2nd -9th harmonics at Tower A Incomer

The 5th harmonic is very high in this block because of the harmonics created by variable speed drives (VSD), which are 5th, 7th, 11th, 13th, etc. The largest amount of which is the 5th, followed by 7th, because the labs are full of VSDs.

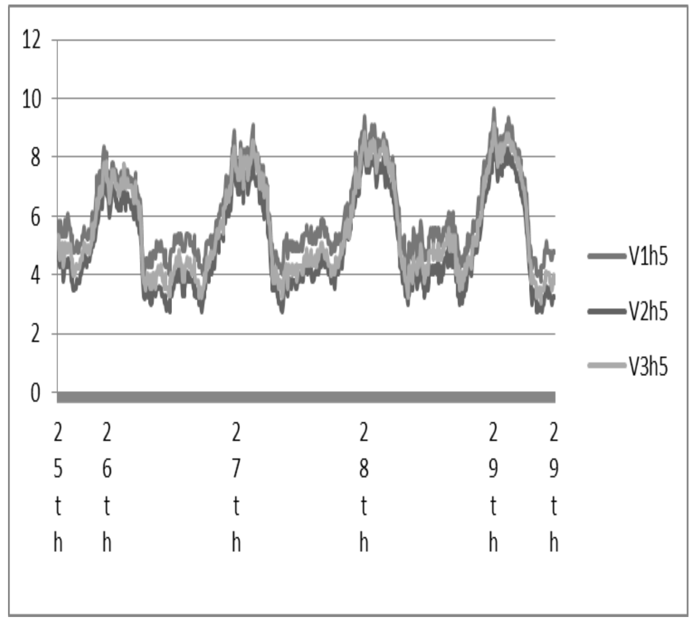

Fig. 5. The 5th harmonics in RMS volts with Mean of 6volts

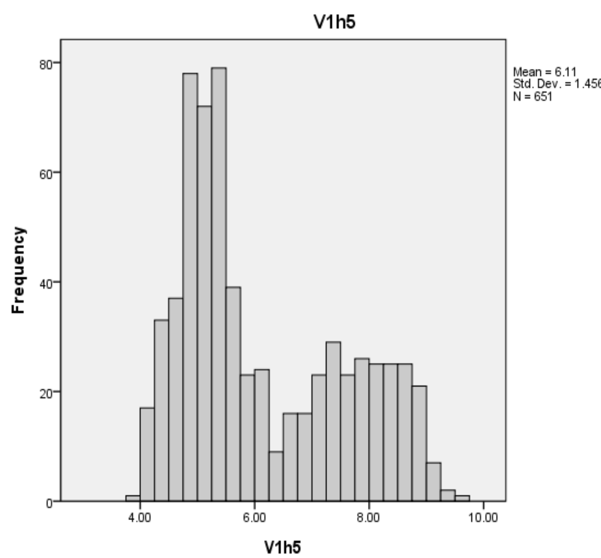

Fig. 6. Histogram of the 5th Harmonic Voltage (RMS) (V1h5)

The histogram of the 5th harmonic voltage is the actual RMS values, mean of which is 6.11 volts with skew to the right (positive skew), indicating that the majority of the data have values towards the lower end of the range. This histogram shows that even though this supply violated the EN 50160, it was not for majority of the time. Fig. 5 showed that the violation was mostly during the night hours only when the offices have closed.

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The next analysis considers the 7th harmonics, even though its effect was not pronounced. As the harmonic order increases so does the randomness.

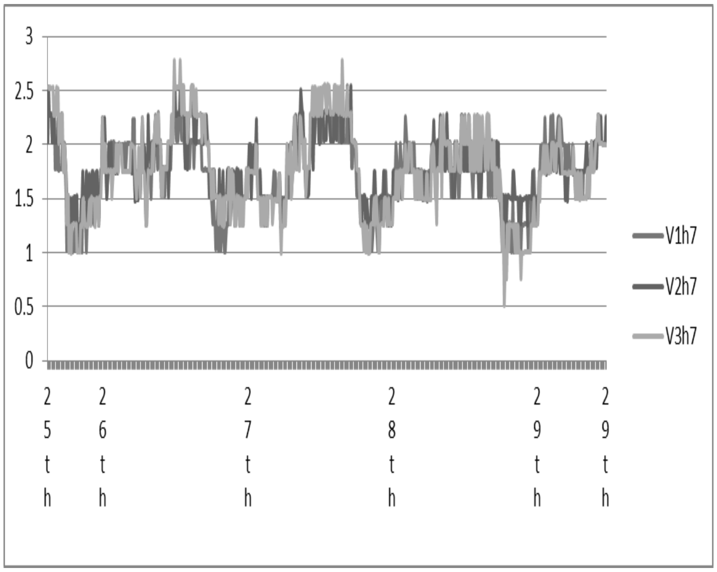

Fig. 7. The 7th harmonic in RMS volts with mean of 1.7volts

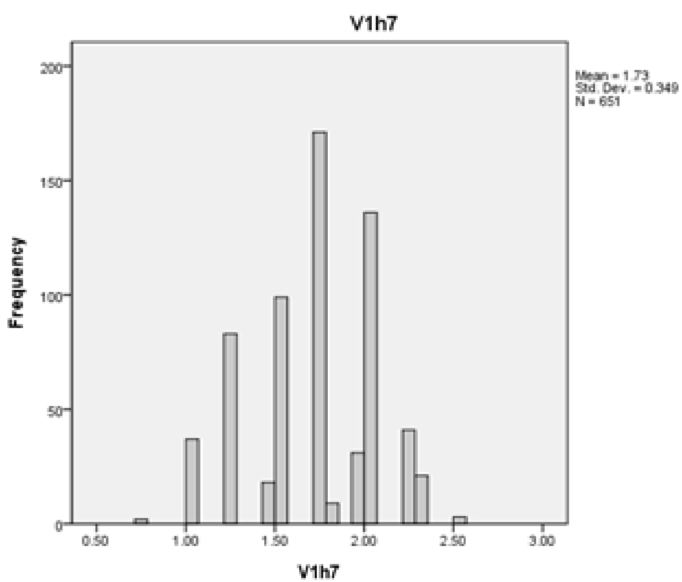

Fig. 8. Histogram of the 7th Harmonic Voltage (RMS) (V1h7)

The random nature of the 7th harmonics (and the higher ones) comes out clearly in the histogram in Fig. 8 having a mean of 1.73 volts. This cannot be of any consequence to quality of power supplied to the building.

The total harmonic distortion of the voltage (THDv) was also analyzed for the period of one week; the trend is shown in Fig. 9.

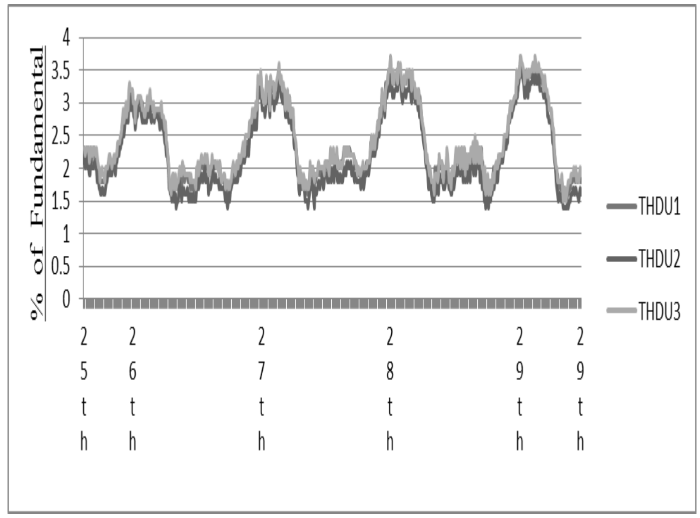

Fig. 9. Total Harmonic Distortion Input Voltage (THDv123)

The THDv has the lowest value of 1.5% and the highest was 3.5% of the fundamental voltage which is well within the EN 50160: 2000 of 8%, as shown in Table 2.
The statistical distribution of the voltage histogram for the THD confirms the minimum and the maximum % as indicated above, with the mean as 2.39% of the fundamental.

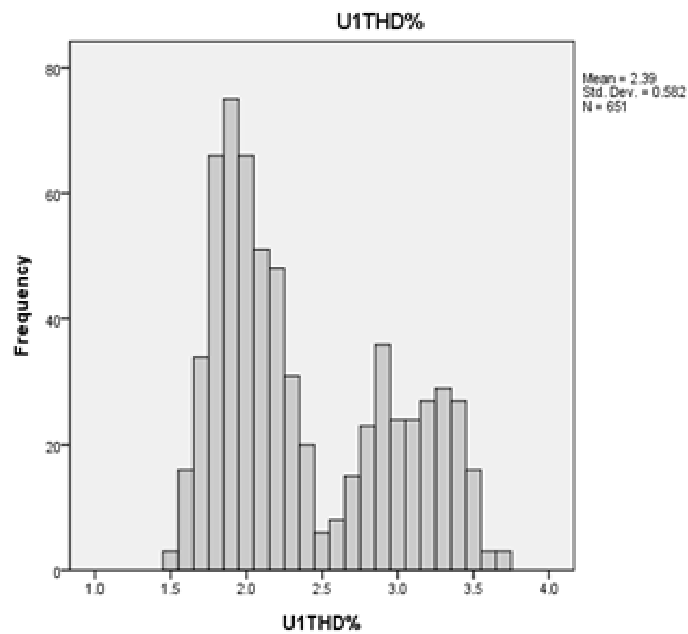

Fig. 10. Cumulative histogram of the voltage THD

3 Line Currents at the PCC

The various types power quality monitoring include: Short-term monitoring to solve
Voltage regulation is considered to be the duty of the Utility supplier, but the current is the commodity the consumer

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demands from the system. Though the voltage level is considered to be the most important parameter at the PCC, however the consumer current consumption can make the system voltage vary adversely if not controlled. The voltage drop in the supply network is dependent on the network reactance. This reactance should be constant most of the time, but voltage fluctuation is mainly caused by the varying load currents, taken by the consumer. The harmonics in the non-linear load currents of the consumers cause energy losses, poor power factor, and malfunctioning of the sensitive equipment in the system. The true power factor becomes much less, even though the displacement power factor is near unity.

The harmonics produced by non-linear load can be removed by passive and active filters. A passive filter can be used to remove specific types of harmonic currents (the 5th and 7th), while active filter can be used to remove all types of harmonics. These harmonic currents cause overheating in the neutrals which can lead to contact burning and fire out-break as a major problem. Specifically, all 3rd and its trip-N harmonics escape through the low tension side of the star-delta transformers to the high tension side (the delta side) where they cause overheating and subsequent deterioration of the transformers. Statistical study of the current at the PCC is therefore of paramount importance in the distribution system.

3.1 Line and neutral currents

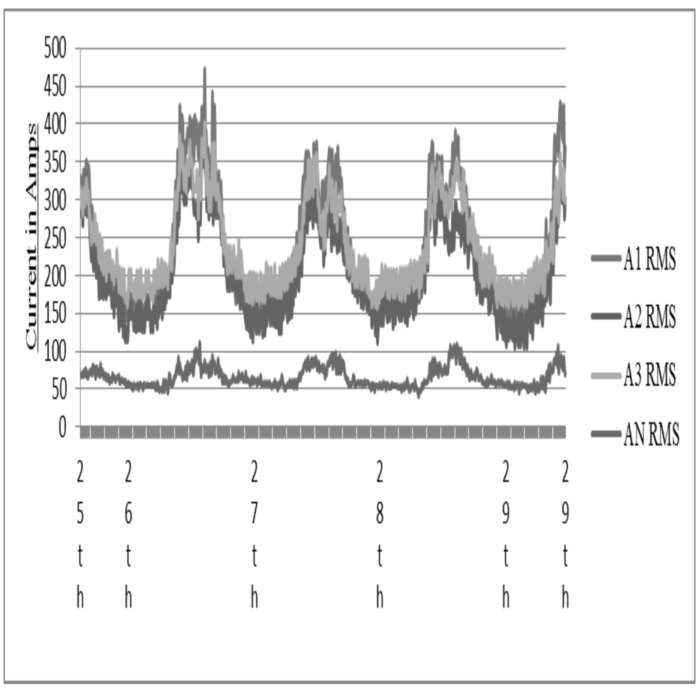

Fig. 11. Steady-state current waveform for 1week(ARMS)

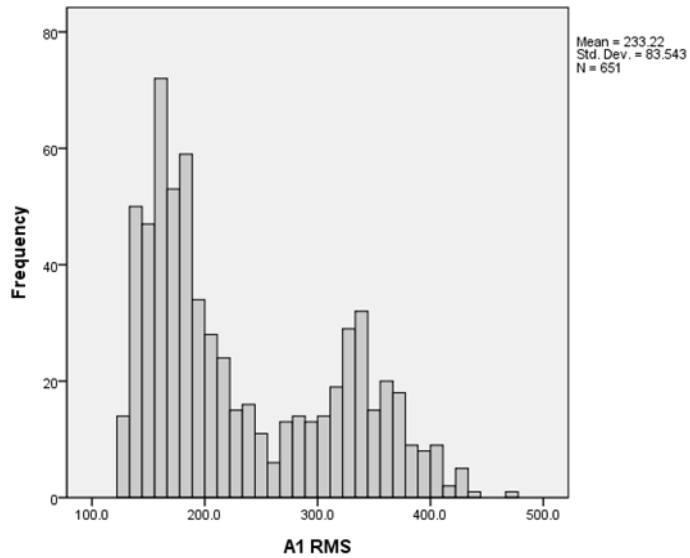

Fig. 12. Current density in the phase 1 in Amps (A1RMS)

TABLE 2
PHASES AND NEUTRAL CURRENT A (1, 2, &3) RMS

	N	Minimum	Maximum	Mean	Std. Deviation
A1 RMS	651	123.5	471.9	233.225	83.5427
A2 RMS	651	105.3	394.1	203.761	62.2867
A3 RMS	651	156.2	402.7	235.346	58.0772
AN RMS	651	41.1	111.3	65.541	13.1633
Valid N (listwise)	651				

The neutral current (ANRMS) had a minimum value of 41.1ARMS and maximum value of 111.3ARMS with a mean of 65.54ARMS which gave an indication that there was a degree of unbalance loading in the phases (Table 2). The phase 2 was the minimum load of the three phases, carried the mean of 203.76ARMS; the harmonic currents and the unbalance loading were responsible for this high neutral current.

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3.2 Harmonic Currents Analysis

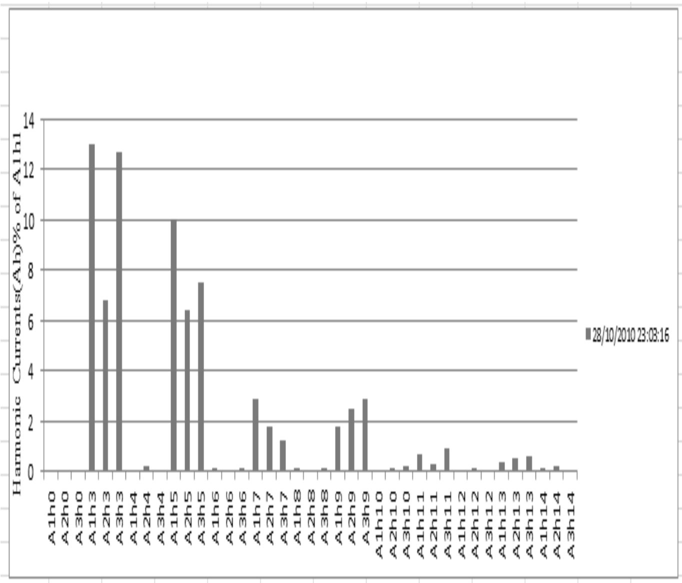


Fig. 13. (3rd to 14th) Harmonic currents for 28th Oct. at 22:03hrs

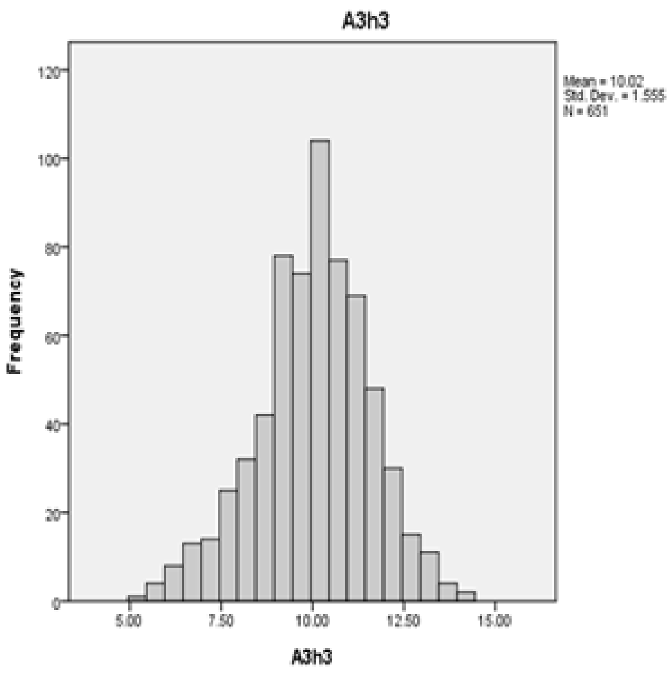


Fig. 14. Harmonic current A3h3 in % of fundamental.

The third harmonic of the current was nearly Gaussian distribution from the histogram, with a mean of 10.02% of the fundamental. Comparison of Fig. 13 and Fig. 14 showed that the 28th Oct. figure for A3h3 (12.5%) was higher than the mean (10.02%). The 12.5% harmonic is occurring at 22.03hrs. Needs some explanations as this is considered to be office buildings, and the computers are not in operation by this time.

4 Mean Value and Standard Deviation Analysis of the THDV

This analysis was necessary to establish whether the maximum deviation violated the international standards and for how long in the one week period of measurement.

The IEEE-519 Standard says that the maximum limit of total harmonic distortion of voltage must be less than 5%, and if over, it must not be for more than one hour. [5], [6]. The European Standard – 50160 says that the total harmonic distortion of voltage, (THDV) should not overpass 8% and the collected data should be for at least one week and at 10minutes rate. At least about 95% of the collected data should be established within this compatibility range of 8%. [5]. The collected data were at 8 minutes range, set before the beginning of the project.

Calculating the Probability of the THDV less than 8%: Z can be expressed as

$$Z = \frac{X - \mu}{\sigma}$$

σ = standard deviation; X = any number

μ = mean and z

= random variable

Table 3 for Tower A showed that the calculated dispersion range among the phases of each day of the THDV1 average values (from 2.262 to 2.118) for office Tower A on 26th was small. For this building, the phases V1 and V3 show higher THDV averages than V2 for the selected days.

TABLE 3

TOWER A CALCULATED MEAN AND STD VALUES

Days in Oct. '10	THDV1 %	THDV2 %	THDV3 %
Tues. 26th	2.262 ± 0.502	2.118 ± 0.524	2.332 ± 0.495
Weds. 27th	2.404 ± 0.543	2.250 ± 0.556	2.445 ± 0.549
Thurs. 28th	2.438 ± 0.607	2.294 ± 0.613	2.480 ± 0.608

The mean and standard deviation values for the one week as derived from the predictive analysis software statistics (PASW) are as listed in Table 4. The value gives better representation of the whole one week data.

TABLE 4
TOWER A MEANS AND STD VALUES FOR THE ONE WEEK

	N	Minimum	Maximum	Mean	Std. Deviation
U1THD%	651	1.5	3.7	2.391	.5824
U2THD%	651	1.4	3.6	2.242	.5961
U3THD%	651	1.5	3.7	2.445	.5821
Valid N (listwise)	651				

4.1 P95% Analysis

For the THDV1 to be less than 1%, considering the 28th October which has the highest Mean and STDEV:

$$Z = \frac{X - \mu}{\sigma}$$

$$= \frac{1 - 2.294}{0.613} = -2.11$$
$$\Phi = 1 - 0.98257 = 0.01743$$
$$= 0.017\%$$

$$THD < 2\%$$
$$= \frac{2 - 2.294}{0.613} = -0.48$$
$$\Phi = 1 - 0.68439 = 0.31561$$
$$= 31.561\%$$

$$THD < 3\%$$
$$= \frac{3 - 2.294}{0.613} = 1.15$$
$$\Phi = 0.87493$$
$$= 88\%$$

$$THD < 4\%$$
$$= \frac{4 - 2.294}{0.613} = 2.78$$
$$\Phi = 0.99728$$
$$= 99.73\%$$

	N	Mean	Std. Deviation	Std. Error Mean
V1THD%	651	2.577	.5485	.0215
V2THD%	651	2.180	.5875	.0230
V3THD%	651	2.424	.5705	.0224

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
V1THD%	119.882	650	.000	2.5771	2.535	2.619
V2THD%	94.695	650	.000	2.1803	2.135	2.226
V3THD%	108.389	650	.000	2.4237	2.380	2.468

TABLE 5
PROBABILITIES OF THE THDV1LESS THAN 5%

THDV	<1%	<2%	<3%	<4%	<5%
P	0.027	31.561	88.00	99.730	100

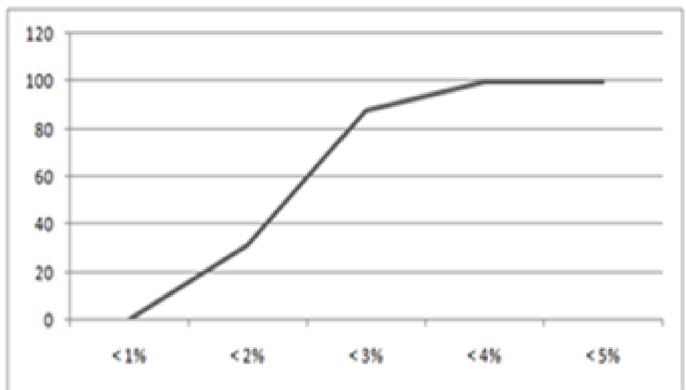


Fig. 15. The probability graph of THDV of phase 1

Considering the qualitative analysis of the collected data, limits were compared with the International Standards. The IEEE-519 and the European Standards were used for comparison. IEEE-519 standards stipulate that in a one-week period, the maximum THDV established in 5% should not be transgressed for a period of more than one hour [6]. Table 5 showed that the 5% was never transgressed. Fig. 15 also confirmed the Standards were not transgressed.

The European Standards EN 50160: 1999 stipulates that the data collected during the one week, with sampling rate of 10 minutes, 95% of the values should be in the established compatibility range. The THDV should not overpass 8% [3]. From Table 5, the highest value of THDV was never higher than 8%. The THDV was under the compatibility level of 8%.

5 CONCLUSION

It was established that the building follow the two international standards and the limits were not trespassed.

Regular steady state analysis are of paramount importance, not only when major faults and costly down-time occur and losses become inevitable but also to avoid polluting the utility supply affecting the adjacent feeders. Records of these analyses should be kept as data base for future reference and also when new electronic equipment is installed.

6 APPENDICES

Table 1: Summary of Power Quality Variation Categories

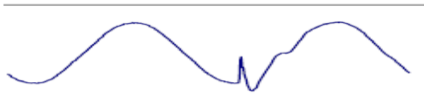
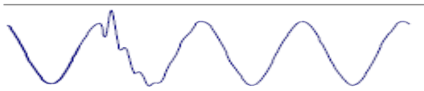
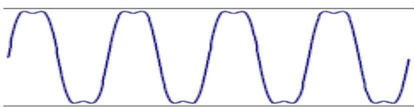
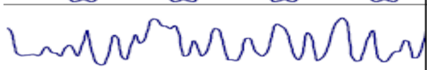
Example Waveshape or RMS variation	Power Quality Variation and Category	Method of Characterizing	Typical Causes	Example Power Conditioning Solutions
	Impulsive Transients Transient Disturbance	• Peak magnitude • Rise time • Duration	• Lightning • Electro-Static Discharge • Load Switching • Capacitor Switching	• Surge Arresters • Filters • Isolation Transformers
	Oscillatory Transients Transient Disturbance	• Waveforms • Peak Magnitude • Frequency Components	• Line/Cable Switching • Capacitor Switching • Load Switching	• Surge Arresters • Filters • Isolation Transformers
	Sags/Swells RMS Disturbance	• RMS versus time • Magnitude • Duration	• Remote System Faults	• Ferroresonant Transformers • Energy Storage Technologies • UPS
	Interruptions RMS Disturbance	• Duration	• System Protection • Breakers • Fuses • Maintenance	• Energy Storage Technologies • UPS • Backup Generators
	Undervoltages/ Overvoltages Steady-State Variation	• RMS versus Time • Statistics	• Motor Starting • Load Variations • Load Dropping	• Voltage Regulators • Ferroresonant Transformers
	Harmonic Distortion Steady-State Variation	• Harmonic Spectrum • Total Harmonic Distortion • Statistics	• Nonlinear Loads • System Resonance	• Active or Passive Filters • Transformers with cancellation or zero sequence components
	Voltage Flicker Steady-State Variation	• Variation Magnitude • Frequency of Occurrence • Modulation Frequency	• Intermittent Loads • Motor Starting • Arc Furnaces	• Static Var Systems

TABLE 6
COMPARISON DIFFERENT INTERNATIONAL STDS

Standards	Supply System Voltage at PCC	Max. Value of harmonic level measurable(N)	THD_V% Limits	Measurement duration
IEEE std 519	< 69kV	50th	5.0	To be agreed by all parties
IEC 61000-2-2	400V and 230V	50th	8.0	To be agreed by all parties
IEC 61000-2-4	400V and 230V at internally agreed PCC	50th	8.0	To be agreed by all parties
EN 50160	400V and 230V	40th	8.0	One week
ER G5/4-1	400V	50th	5.0	One week minimum

TABLE 7
THE POWER QUALITY STANDARD EN 50160: 2000

Supply voltage phenomenon	Acceptable limits	Measurement Interval	Monitoring Period	Acceptance Percentage
Grid frequency	49.5Hz to 50.5Hz 47Hz to 52Hz	10 s	1 week	95% 100%
Slow voltage changes	230V ± 10%	10 min	1 week	95%
Flicker Severity	P_{lt}	≤1	N/A	95%
Voltage Sags or Dips (≤1min)	10 to 1000 times per year (under 85% of nominal)	10ms	1 year	100%
Short Interruptions (≤ 3min)	10 to 100 times per year (under 1% of nominal)	10 ms	1 year	100%
Accidental, long interruptions (> 3min)	10 to 50 times per year (under 1% of nominal)	10ms	1 year	100%
Temporary over-voltages (line-to- ground)	Mostly < 1.5kV	10ms	N/A	100%
Transient over-voltages (line- to- ground)	Mostly < 6kV	N/A	N/A	100%
Voltage unbalance	Mostly 2% but occasionally 3%	10 min	1 week	95%
Harmonic Voltages	8% Total Harmonic Distortion (THD)	10 min	1 week	95%

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Mohamed K. Darwish (BSc, PhD, IEE Member 89–CEng 90, MIEEE). Dr. Darwish has received the BSc degree in Electrical Engineering from Helwan University, Cairo, Egypt, and the PhD degree from Brunel University in 1978 and 1987 respectively. Dr. Darwish is currently a Senior Lecturer in Power Electronics. He has over 20 years' experience of research and teaching in the area of Power Electronics. His research interests include active filtering techniques, UPS systems and Power Quality issues. Dr. Darwish has published over 100 papers in leading journals and conferences.

REFERENCES

[1] Aintablian, H.O., 'Harmonic Currents generated by Personal Computers and their effects on the Distribution System Neutral Current'. Industry Applications Society Annual Meeting vol. 2, 1993, pp. 1483 – 1489.

[2] D. Sabin, M. McGranaghan, A. Sundaram. A Systems Approach to Power Quality Monitoring for Performance Assessment. (p3)

[3] EN 50160:1999; ''Voltage characteristics of electricity supplied by public distribution systems''.

[4] Copper Development Association, Leonardo Power Quality Initiative. Power Quality Application Guide. Voltage Disturbances, Voltage; Characteristics in Public Distribution Systems, pp. 4-5.

[5] IEEE 519:1992, IEEE Recommended Practices and Requirements for Harmonics Control in Electrical Systems.

[6] Ferreira-Filho, A. L.; M.de Oliveira; Bonincontro, F. A.; A contribution to establish proceedings for Quantification of Voltage Harmonic Distortion in Commercial Buildings. IEEE Proceedings 0-7803-7671-4/02/S17.00 © 2002 pp. 21 – 26. DOI = 10.1109/ICHQP.2002.1221399.

[7] Conroy, E., 'Power monitoring and Harmonic problems in the modern building' Power Engineering Journal, vol. 15 Issue, pp.101 – 107, April 2001.

[8] Aintablian, H. 'The Harmonic Currents of Commercial Office Building due to Non – linear Electronic Equipment'. Southcon Conference Record, June 1996, pp.610 – 615.

[9] Chapman, D.; Power Quality Application Guide - The Cost of Poor Power Quality; Copper Development Association; Version 0b November 2001.

[10] Moreno-Munoz, A.; Gonzalez, J. J.; Analysis of Power Quality in High-Tech Facilities. Electrical Power Quality and Utilization, Magazine Vol. 1.No.2. 2005.

[11] Rogers, C. D.; McGranaghan, M. F.; Santoso, S.; Beaty, H.W. ''Electrical Power Systems Quality'' 2nd Edition. New York. McGraw-Hill 2002.

[12] Ewalk, F.; Masouum, M. A. S.; ''Power Quality in Power Systems and Electrical Machines.'' Elsevier Academic Press 2008.

[13] Bollen, M.H.J. ''Understanding Power Quality Problems'' IEEE Press Series on Power Engineering. 2000.