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Comparative Studies of Power Quality Issues in Offices and Residential Buildings

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Abstract
This paper presents the results of measurements made in an office and residential building, both located in the same site for a period of one week. It is estimated that more than 30% of the power currently being drawn from the utility companies is now consumed by sensitive non-linear load, and still increasing in both industrial and residential areas. Non-linear load is steadily increasing in residential areas also. The power quality analyzer was installed at the point of common coupling (PCC) to these buildings and was observed for five working days. The effect of continuous overvoltage was also considered even though the overvoltage was within the international standards. The result was proved to cause unnecessary and unwanted over consumption. Effects of compact fluorescent lamps with electronic gears (CFLs) were also investigated as a rising source of harmonic production in modern buildings.

Keywords: *Power quality issues, international power quality standards, power quality analyzer, THD*

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INTRODUCTION

Almost all modern commercial buildings take their supplies at 415 V from the secondary of the delta/star connected 11 kV/415 V transformers. In recent years a large number of distorting, non-linear loads such as computer equipments have been extensively used in commercial buildings. The result of using such highly non-linear load is that the current waveform is distorted, causing excessive harmonic voltages to be generated. According to a copper development association survey, it is estimated that power quality problems cost industry and commerce in the EU about €10 billion per year [1].

This figure goes to $50 billion per year in the USA as a result of power quality breakdown [2]. For example, a manufacturing company lost more than $3 million in one day in the summer of 1999 in Silicon Valley when the “lights went out” [3]. Another example, a voltage sag in a paper mill can waste a whole day of production of about $250,000 loss [4]. Also half of all computer problems and one-third of all data loss can be traced back to the power line [5].

With such high cost of poor power quality as shown above, researchers have developed so many technical solutions to eliminate or at least to reduce the impacts of poor power quality on modern buildings. Such solutions consist of the design of passive and active filters as well as designing switching regulators for computer power supplies. However, to install such power quality correction devices, people working in the building industry must first be aware of the problem and appreciate the cost of the problem as

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well as knowing the cost of the solutions. They should also be aware of the power quality components and the regulations for each of these components. The main aim of this paper work is to look at the power quality problems in modern buildings so that building designers can be aware of the challenges required in such buildings. Once they are aware of the problem, the decision to install or not to install correction devices could be clearly made.

POWER QUALITY DEFINITIONS AND STANDARDS

True power (also referred to as real power and active power) is measured in watts and is what the loads consume. However, due to the nature of inductive/capacitive loads, real power will not be the true measurements of the power drawn from the supply. In this case the supply generates what can be called apparent power (or total power). Long duration variations can be overvoltage or under voltage or sustained interruption depending on the specific circuit magnitude conditions. Short duration variations are for less than 3 min and could be instantaneous, momentary or temporary for interruption, sag or swell as defined internationally [6, 7]. Steady state variations include the normal rms voltage variation and the harmonic distortion. Voltage variations are measured, and then analyzed to find the maximum, the minimum and the average. The result is then compared with accepted international standards. The overvoltage noticed in these buildings is consistent and permanent and this condition could lead to overbilling of the site. The step-down transformer supplying this building could help to bring the voltage down by tap changing. The supply utility could also be of help, but consideration should be given to the close proximity of the site to the transmission injection substation. The nearer a load is to the injection substation, the higher the supply voltage.

The non-linear loads and devices that cause harmonics can be represented as current sources of harmonics. The system voltage appears stiff to individual loads but the loads draw distorted current waveforms. Harmonics are also sine-waves but at frequencies that are multiples of the mains frequency, that is, fundamental frequency. The IEC Power Quality standards are from IEC-61000.

POWER QUALITY ISSUES IN OFFICE BUILDINGS

Office-Building Which Contains a Number of Academic Offices

The power analyser was installed for a period of one week at the distribution point of the building (although data were collected only for five days). The power, line currents, phases and line voltages, P.F. and the THD of voltages and current in each of the phases were monitored and stored on a PC. These data were analysed in order to work out the quality of the power entering this building as well as determining if such quality is within the recommendation range of the international standards.

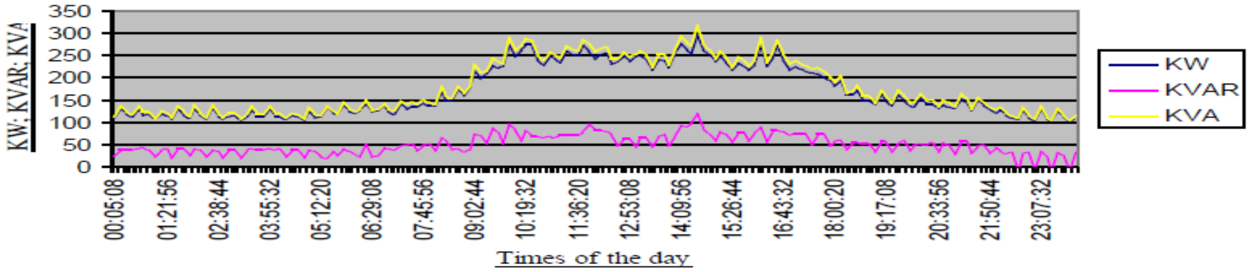

Fig. 1: *The Pattern of the Powers in a Typical Working Day.*

Figure 1 illustrates the total power consumption for a typical week day. As expected the maximum power was consumed during the peak time which is between 10:00 am and 4:30 p.m. The figure also illustrates the difference between the real and apparent powers. It should be noted that there are power factor correction capacitors installed at the PCC and therefore the reactive power shown in Figure 1 is after the PF correction, hence its low level. The figure also shows that even when the power consumption is at minimum there is still certain amount of reactive power drawn.

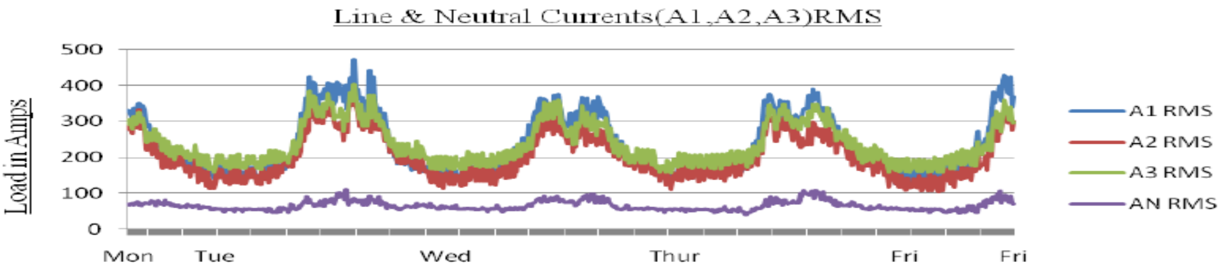

Fig. 2: *Line and Neutral Currents of Office Building.*

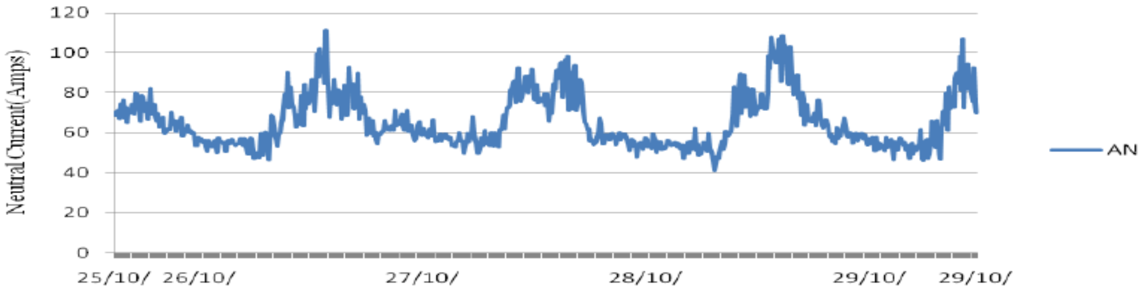

Fig. 3: *Trend Graph of RMS Current in Neutral of Office Building.*

Figure 2 shows that the line currents varied widely because of unbalanced loading. Percentage unbalance is the maximum deviation from the average of the 3-phase voltages or currents, divided by the average of the 3-phase voltages or currents expressed in percent. The highest current unbalance loading was noticed to be 15% as shown in Figure 3. The current unbalance occurs because the installation is constituted mainly by single phase loads and these loads are not distributed properly on the three phases. Poor load distribution may cause the system to become overloaded in a particular phase and have another phase underloaded. High neutral current leads to increase in power losses and overheating of equipments.

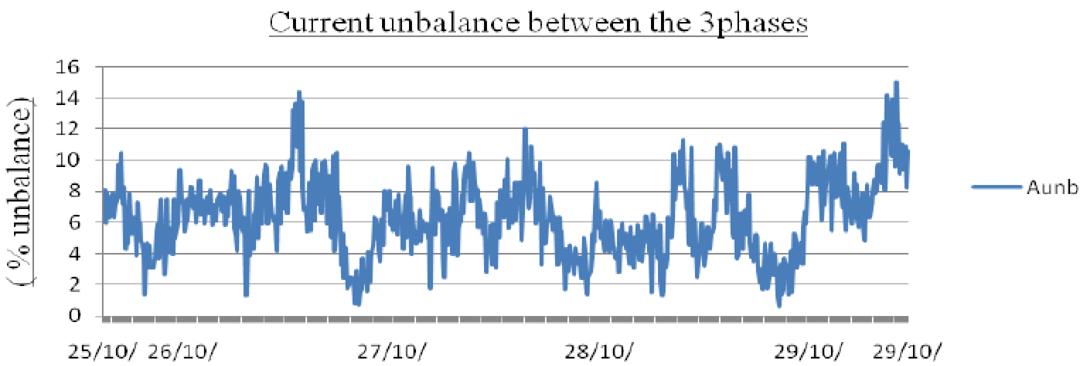

Fig. 4: *Graph of Percent Unbalance of Average Current in Office Building.*

The graph Figure 4 gives an idea of the possibilities to correct the problem, informing the times of the unbalance, making it easier to interchange loads between phases. The 100 A minimum on line A1 of the 28th and 200 A maximum on line A3 of the 29th might be as a result of little or no activities during the nights in the buildings. The weekdays of Wednesday and Thursday were not as high as that of Tuesday the 26th. The highest neutral current was observed to be 116 A (Figure 3). The high level of neutral current was due to the unbalanced loading between the phases and the harmonics caused by the non-linear loads in these buildings as noted in Figure 4.

The neutral current was quite high (about 116 A) on that Tuesday, because of unbalanced loading of the phases and most of the loads in these buildings are nonlinear loads, such as PCs, laser printers, adjustable-speed motor drives, UPS etc. All these electronic devices present non-linear characteristics, as they draw non-sinusoidal wave-forms of current from the supply. These devices have become the main cause of current unbalance and consequently voltage distortion. The neutral current, which is supposed to be zero or negligible for balanced 3-phase load, was high and this could make to neutral cable becoming hot and the link joint becoming severely burnt. This could lead to floating neutral, fluctuation in the supply voltage and a possible fire outbreak.

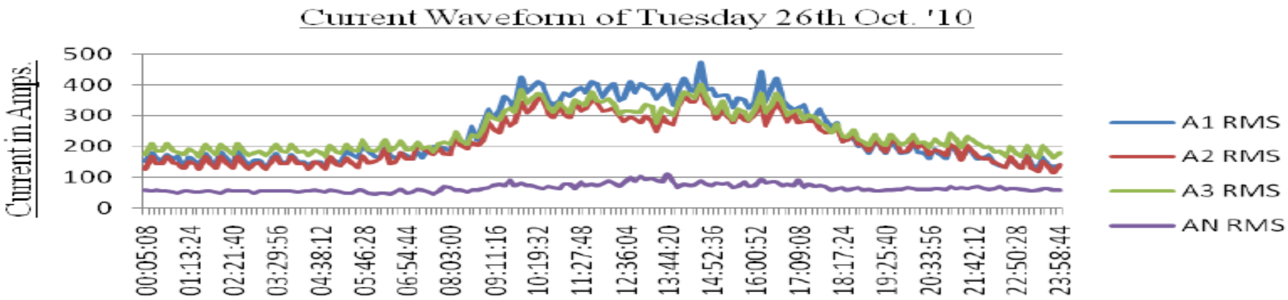

Fig. 5: *Current Waveform of Tuesday Oct, 26th in Office Building.*

However, the neutral conductor was noticed to be of the same size as the line conductors in this building. Even when the loading on the three phases looked balanced between 00:05:08 and 09:02:44 (Figure 5) the neutral current was not zero. This is as a result of non-linearity of the load which consists of so many PCs.

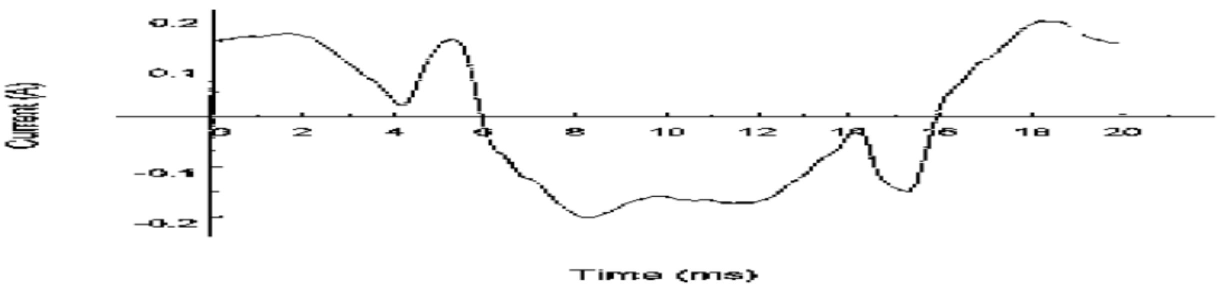

Fig. 6: *A Typical Computer Load Current in Sleep Mode.*

Although PCs should be turned off at night but the majority of the staff/students leave them on the sleep mode. PCs still draw the distorted current in the sleep mode as shown in Figure 6. The loading between 9:11:16 and 17:09:08 was above 300 A, the phase-1 load was about 400 A during the period (between 12:36:44 and

14:00:00), and this was the time that the neutral current reached the highest peak of 116 A (Figure 5).

The current in the neutral is originated by the 3rd harmonic (and its multiples) in the current of the phases, apart from the unbalanced loading in the phases. The high neutral current caused by these harmonic distortions may be mitigated by the use of passive filters or active filters or both, if this situation causes disturbance in the system. The non-linear loads in these buildings are on the increase due to the large amounts of switched mode power supplies used in PCs, and other electronic equipment not only in electronic/electrical labs but also in mechanical and design labs. Such impact of the non-linearity of the loads needs to be closely monitored on a regular basis.

The amount of the power consumed by a load depends not only on the size and nature of the load but also on the voltage applied to the load. Technically, in engineering terms, power is the rate of energy delivery and is proportional to the product of the voltage and current. p(t)=v(t).i(t). Increasing the voltage across a component invariably increases the power consumed and the heat generated by the component.

This can lead to overheating and even damage to circuitry. It is widely documented that over-voltage decreases the lifespan of a component, and the higher the voltage applied, the shorter the component's life will be. This is due to a combination of various factors, notably increased heat production and internal damage to the conductors from electro-migration.

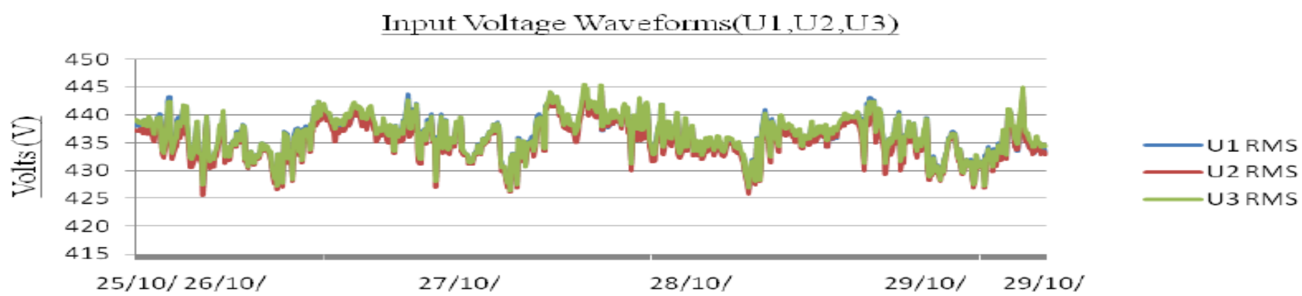

Fig. 7: *Supply Line Voltages U1, U2, U3 for the Week.*

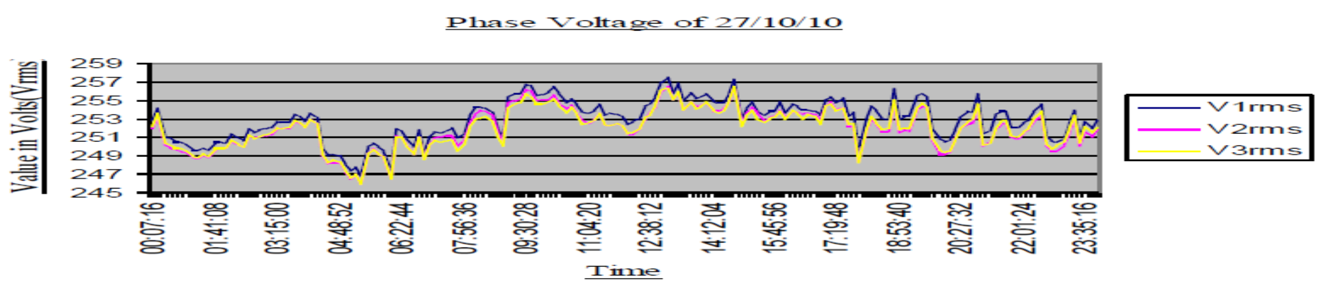

Fig. 8: *Phases Voltages of Wednesday 27th, Oct (Next Day).*

After 5 days of measurement (25th–29th Oct 2010), it was shown that the voltage harmonic distortion at the input was not high. The maximum total harmonic distortion did not reach 4% as shown in Figure 9 during the data collection period.

The maximum was 3.7% on line-3 of 28/10/10. However, the standard's limit of ≤8% for that harmonic order established in EN50160 was not violated [7–9]. For this period, the 7th harmonic maximum was 1.0% (5% for this limit) and the 5th

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harmonic level was 8.7% (6% for this limit by EN50160) on phase-1 as seen Figure 8. The daytime is the usual period that most electronic equipments are in use in the building. Compatibility limit for the THDA should not be more than 8% for voltage and 20% for current THD, as established in EN-50160 standard [8]. The building has many electronic types of equipment which are the main sources of harmonic distortion especially the 3rd harmonic level. These are air-conditioning systems and elevators, many PCs and terminals, several printers, copiers and other power electronic gadgets like microprocessor based control and instrumentation devices. Switch mode power supply (SMPS) produce a lot of harmonics, especially problematic in commercial buildings due to many computers and office equipments. The highest total harmonic distortion for current was less than 20% as shown in Figure 9. This value has not transgressed the standard of 20% [10].

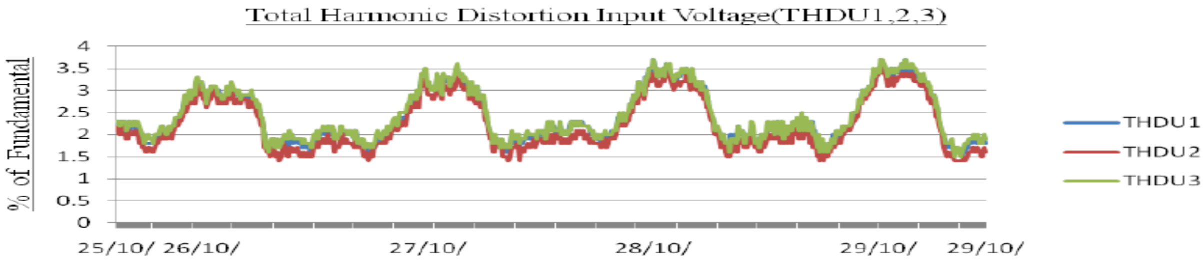

Fig. 9: *Incomer Line THDU in Office Building.*

Line and phase voltages, line currents, neutral current, harmonics, total harmonic distortion and power factor were analysed and were compared with the appropriate standards. The power consumed in a typical day (Figure 1) showed that apparent and real powers were close and the reactive power was very small due to the compensating effect of PFC capacitors, thus making the PF to be close to unity. The reactive power was negative late in the night as a result of over-compensation by the fixed capacitors, but during the daytime the reactive power was higher because of high apparent power, (Apparent power =356 KVA, Real power =300 KW while Reactive power =130 KVAR at 14:09:56).

The neutral current for a balanced 3-phase and linear load should be zero. High neutral current cause overheating and the triple-N harmonic currents could pass over to the delta side of the delta-star transformer and circulate there, thus causing overheating even when the transformer is not overloaded. The current THDA was 18.7% on the 29th on phase-1 (Figure 9).

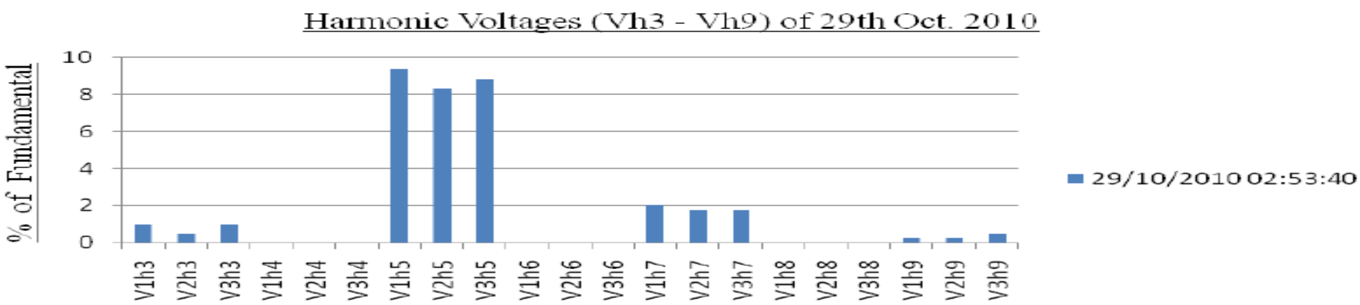

Fig. 10: *Voltage 3rd–9th Harmonics at Office Building Incomer.*

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The 3rd harmonic was the highest, 15.5% (Figure 10). The neutral current An was very high as shown in Figure 5, as the phase current was as high as 116 A on the 26th October. This could be due to unbalanced loading of the different phases and harmonic distortion. The unbalance was due to single-phase load in the buildings, which could be corrected by rebalancing the loads between the phases.

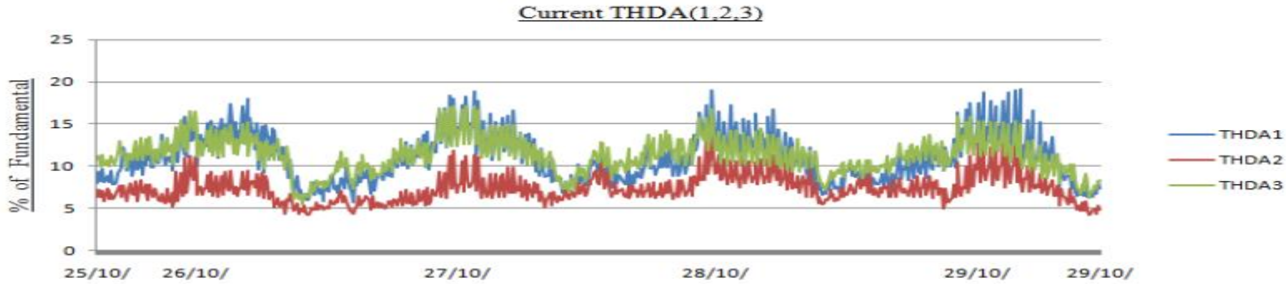

Fig. 11: *Total Harmonic Distortions of Current for Office Building.*

The reactance (KVAR) of the inductive loads is 180% out of phase with the installed capacitors and the resultant sum is reduction in the reactive load and improvement of the PF. Figure 11 shows the period of the night that the reactive load were negative indicating that the fixed capacitors over-compensated for the inductive load. The power factor in each of the 3-phases is shown in Figure 12. The power factor shown in the figure is the product of the displacement and the distortion factors. It can be seen that the phase-2 has the poorest PF compared to the other two phases. This could be due to the fact that this phase feeds most of the non-linear loads (e.g. computers). The phase-1 could be the one that feeds the lift and other linear loads.

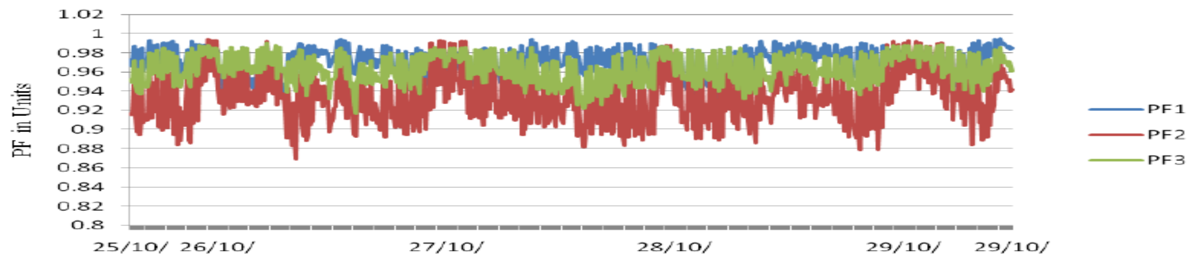

Fig. 12: *Power Factor (PF) in All the 3-Phases.*

The supply voltage (U1, U2, and U3) was high, as it varied between 427 and 445 volts on line-3 (U3) during the test period. This high voltage level could lead to unnecessary high consumption of energy even if the limits fall within the stipulated international standards EN50160. The phase voltages varied between 257.5 volts highest and 245.9 volts minimum on 27th October, this high voltage is unnecessary and leads to higher billing.

The THDV at the input was not high, it was 3.7% (Figure 7), and EN50160 puts this limit at ≤8%. But the individual harmonics presented different results; the 5th harmonic distortion of voltage was 8.7 instead of 6% limit as stipulated by EN50160, which showed that this limit was violated. The 7th harmonic distortion level was 1% and the standard limit is 5% all on phase-1 (Figure 8). This limit was not violated. All other harmonic levels were not violated. Mitigation of the high 5th harmonic should be by installation of passive filter tuned to that frequency.

POWER QUALITY ISSUES IN RESIDENTIAL BUILDINGS

This part of the paper presents a residential case study, introduced and investigated. The case study consists of real data which was collected over a period of one week for residential building in the same site. The building consists of equipments associated with wholly residential building with more computers, TVs, florescent lighting with magnetic and electronic ballasts, as well as the usual electric loads (boilers, electric heaters, etc.). The data was then analysed for each of the phases, the results critically analysed and some recommendations proposed for improvement of the quality.

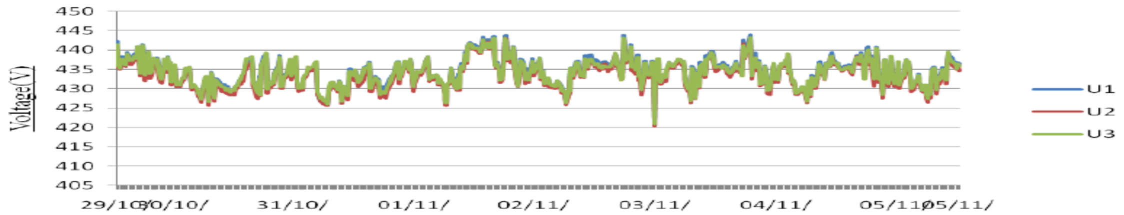

Fig. 13: *Line Voltages of Residential Building.*

A nominal rms voltage in UK is 240 V phase to neutral (Vrms), and 415 V phase to phase (Urms). The graph shown in Figure 13 illustrates the variation in the line voltages at different times of the test period (29th Oct–5th Nov"10). The data were collected during one week with a sampling period of 8 min. It could be seen from this graph that the voltages were not balanced.

They vary from 427.0 Urms on phase-1 and 445.0 Urms on phase-3. These recorded data at the input showed that the upper limit is outside the limits on the upper side (±10%) i.e. between 373.5 and 435.75 Vrms of the nominal line of 415.0 Vrms. The voltages in this building continually change as the load currents change leading to variations in the voltage, normally referred to as voltage variations. If the variations are within the acceptable limits, it is considered to be alright, but if it is outside the acceptable limits it becomes short or long duration voltage variation. Residential building is fed by one of the out-going 4-core cables. The monitoring equipment and the recording PC were installed on the ground next to the circuit-breaker of the cable, but the four current transformers (AMPIFLEX) were installed on the neck of the cables in the cubicle and a PC was connected to record the recorded data. The input voltages (U1, U2, and U3) and neutral cables were connected by tapping from the voltage circuit in the panel, while the flexible current coils called AmpiFLEX, four in number, were the current input sensors. Voltages and currents and other readings were monitored and recorded for a week (Fri 29th Oct–Fri 5th Nov 2010). By monitoring the current and voltage together with time resolution of (8 min) it was seen that they rise and fall together.

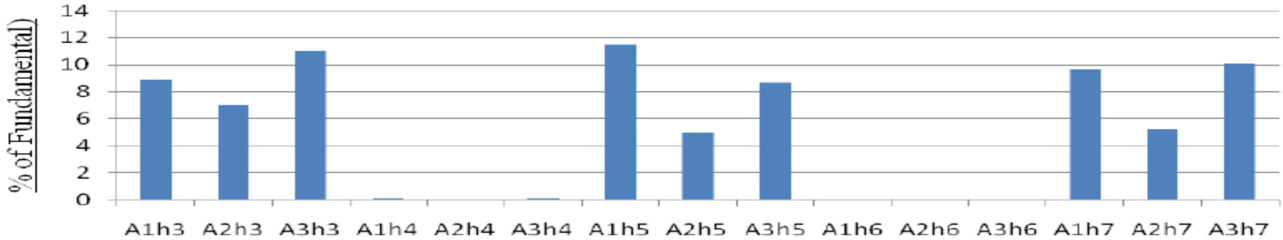

Fig. 14: *Harmonics for Residential Building on Wednesday, 03rd November.*

If by monitoring the supply at the point of entering the building, the current spikes up and the voltage spikes down at the same time, that means that some load within the building has drawn more current, but if they both move together, it means that most of the electronic equipments in the building that use switch-mode power supply (SMPS), and the corresponding harmonics have been compensated for by filtering. The residential building current harmonic distortions are as shown below. The prominent were the 3rd, 5th and 7th harmonics, the 9th and other harmonics were very small (Figure 14). The 3rd, 5th and the 7th harmonics are high unlike the office buildings where the 5th harmonic was the only high harmonic to deal with. Mitigating these harmonics would require more than one passive filter and probably active harmonic filters.

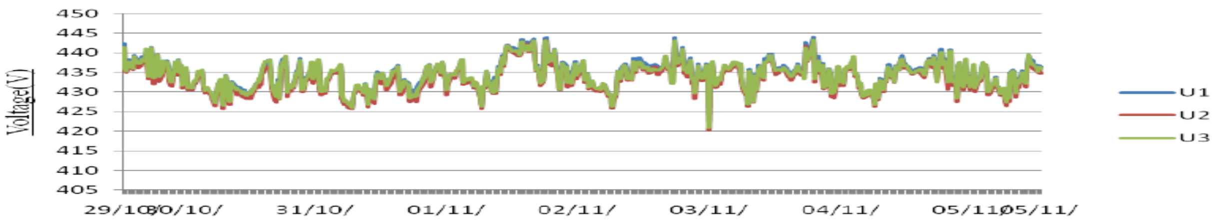

***Fig. 15:** Residential Building Incoming Line Voltages (U1, U2, U3).*

If there is any anomaly in the wave shape it will be necessary to carry out stage by stage approach in order to identify the problem circuit. This could be accomplished by turning off different loads within the building while monitoring until the cause is identified. The supply voltage was stable and was in the range of 420 V minimum and maximal value was 444.8 V, (Figure 15). Voltage margins as set in the UK are ±10% of 415 volts, line voltage that is from 373.5 to 435 V. There are different standards set for different countries. Although these measured voltages fall within the accepted standard of EN50160, they are high and could lead to unnecessary high consumption and subsequent overheating of cables and transformer. The transformer taps could be changed as an immediate relieve.

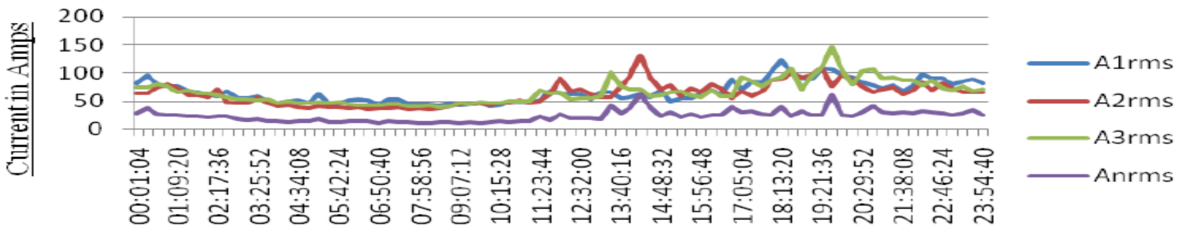

***Fig. 16:** Residential Building Load Currents of Wednesday, 03rd November.*

The line currents are seen to be balanced, but the neutral current was quite high for the load currents. The loading of 3rd November was particularly studied because it has the highest neutral current as shown in Figure 16. There was balanced loading on the 3-phases between 00:35:12 to 10:49:36 hrs of 3rd Nov. But between 10:49:36 and 23:54:40; the unbalanced loading was highest, and this occurred at 14:14:24 hrs. The loads were A1=62A; A2=131A; A3=72.1A; AN=62A. The neutral current (AN) should be zero, but had a minimum of 10.1A at 09:11:12 hrs (Figure 18). The 62 A on the AN is 47.3% of the highest load current of A1 of 131A, and 70% of the average load current.

This causes overheating of the neutral conductors, especially if the neutral cables are not adequately rated. If the harmonic currents are not removed, they flow back to the supply causing harmonic voltage distortion on the supplier due to supply impedance. The triple-N harmonics add up and circulate in the primary of the delta-star transformer and do not flow back into the system. However they increase the eddy current losses thus overheating the transformer. The age of the transformer could be greatly reduced.

The week's recorded data of active, reactive and apparent powers of residential building as shown in Figure 16 showed the same pattern from day to day. Minimum loadings were noted in the early hours of the morning, and rising to maximum in the day, only to reduce down to the minimum again from day to day (Figure 17 showed typical day load consumption). It could also be seen that the reactive load reduces to below zero during the period of minimum loads. This was as a result of over compensation by the power factor correction capacitors. This fact was further confirmed by the plots of the real and apparent power which are so close because of the power factor correction which was near unity.

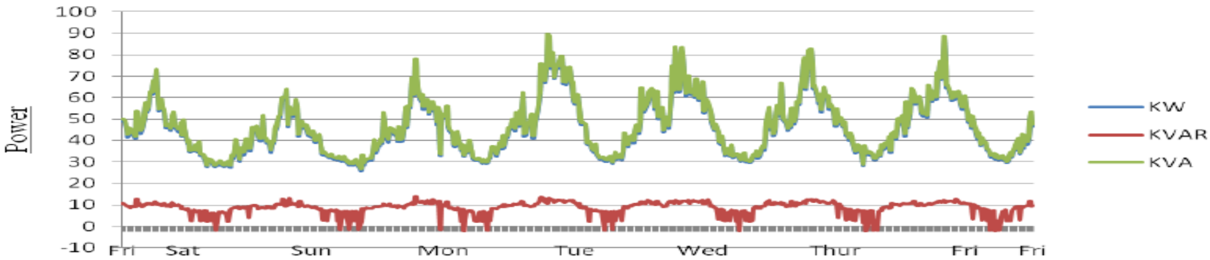

Fig. 17: *Residential Building Loading of the Week (Friday, 29th October to Friday, 05th November).*

Figure 17 shows that the highest apparent load of 89.64 KVA was recorded on 01/11/10 at about 19:17:20 hrs. This is a residential hall with minimum load in the morning unlike office building. This is an indication that the fixed capacitors over-compensated between the hours of 03:38:40 and 08:11:44 when the reactive load had reduced to minimum.

The odd multiples of 3rd harmonics i.e. 3rd, 9th, 15th, 21st etc. are all in phase and add up in the neutral conductor. Switched mode power supply (SMPS) produce a lot of 3rd harmonics and this is a major problem in modern (commercial) buildings due to large number of computers, office equipments etc. in such buildings. For a 3-phase delta-star connected, the primary side of the distribution transformer traps the trip-n harmonic currents in the delta windings. This prevents the current summation to flow back into the system,

but all other harmonics pass through. The load of November 3rd showed the neutral current (An) rms to be as high as the phase current (A1) rms at 14:14:24 hrs. A1=61.8 A; A2=131.0 A; A3=72.0 A and An=62 A. This high neutral current was as a result of the unbalanced loading of the phases and the presence of harmonics, especially the 5th (Figure 18).

The EN50160 gives the limit of 8% for THDV for LV system, in one week monitoring period and the highest THDV was 3.5% on phase-1. Therefore the limit is not violated [7]. The individual voltage harmonics chart showed that the 5th and 7th harmonics are present as shown in Figure 18. The highest distortion was the 5th harmonic which was 3%, and the 7th harmonic was about 0.5%. The

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international standard EN50160 gives the limits of 5th harmonic distortion to be 6% and the 7th to be 5% [7]. These limits were not violated.

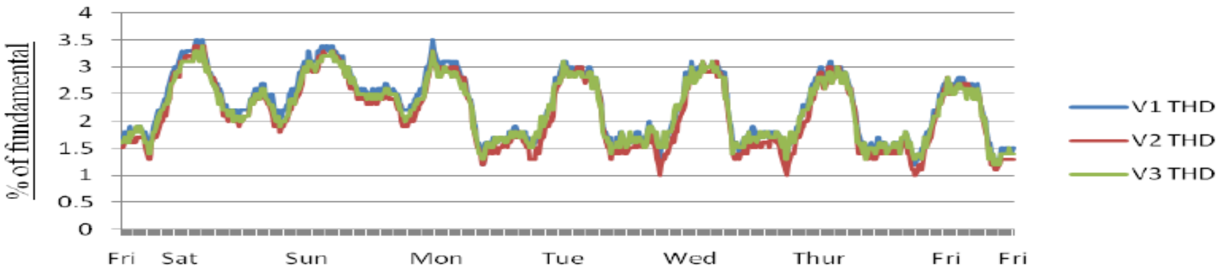

***Fig. 18:** Residential Building Total Harmonic Distortion of Voltage.*

The results of the case study for residential building (29th Oct–5th Nov) had its highest measured short-term flicker on the 5th of Nov as shown below in Figure 18. At exactly 10:19:44 of the 5th of November the highest flicker was on 2nd phase (Pst2)=1. This happened only once during the test period of one week. Short-term flicker (Pst) is normally measured over a ten minute period, while Long-term flicker (Plt) is a rolling average of Pst values over a two-hour time frame. The value of the short-term flicker was 1, but not for upto 10 min, so it has not transgressed the International limits. The International Standards requires that the value of the short-term flicker severity index Pst≤1.0, and the value of the long-term flicker severity index Plt≤0.65 [11]. If the changes in the voltage are caused by load, and are less frequently than once per hour, or if the changes are the result of manual switching, then allowable values of short term flickers could be increased by 33%.

In this chapter the data monitored from 29th October to 5th November indicated that input voltage was consistently high (445.0 V). This high input voltage could lead to overheating and unnecessary excessive power consumption. It was also noted that the dominant 5th harmonic distortion was 20% at the highest point. The 5th harmonic is caused by computer connections and other SMPS. The THDA maximum was 28.4% when it should have been less than 20% [12]. There was high neutral current AN, which was as high as line current at one instant.

This was an indication that there was unbalanced loading between the phases and the presence of harmonics. Highest apparent load was 89.4 KVA recorded on 01/11 at 19.17 hrs unlike the office building where the peak was in the morning. Reactive compensation was by fixed capacitors, the difference between the apparent power (KVA) and the active power (KW) was unnoticeable because of the capacitor compensation. The nuisance tripping reported on this breaker was as a result of the unbalanced loading; therefore mitigation should by load balancing and installation of passive filters for the 5th and the 7th harmonics.

Lastly, there was short-term flicker was up to the maximum permissible level of 1, but for less than 10 min, this has not violated the EN50160 standards on short-term flicker.

CONCLUSION

This paper provides an overview for power quality problems that exist in modern (office and residential buildings). The proliferation of non linear loads (computers and other electronic equipments) and consequently the harmonics within such establishments were investigated. The residential load pattern shows that the neutral current is also a problem. The massive application of compact fluorescent lamps with electronic gear in modern buildings could be worse than the computers as they produce harmonic pollution causing network voltage distortion. Comparison of the office with residential buildings showed the changing load pattern of the residential having increasing harmonics and neutral currents like the office building. This paper brought into focus the need to constantly monitor the power quality for record keeping. A basic understanding of how distortion is created and the effects of circuit impedances on the levels of distortion helps in resolving the problems created by distortion.

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