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Harmonics Effect in Industrial and University Environments

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1. Introduction

1.1 Analyzing harmonic distortion produced from lead blast furnace (LBF)

A major cost to a steel factory facility is the energy used to power the arc furnace for the melting and refining process. Operation at low power factor results in additional voltage drop through the power system yielding a lower system voltage on the plant buses. Low system voltage increases the melt time and will add to the overall plant operating costs per ton. Low power factor can also result in additional costs in the form of penalties from the electric-utility company [1-2, 8]. Capacitor can be applied in steel factory facilities for a wide range of benefits. The capacitors will improve the power factor of the system; reduce billing penalties imposed by the electric power utility, and increase system voltage-boosting productivity. The system losses are also reduced improving the electrical system efficiency. However, harmonic sources in the steel mill can interact with capacitor banks resulting in problems if they are not properly applied. The effect of harmonics varies depending on the type of load. In some cases such as a resistance heating load all of the applied voltage does useful work; although, in most cases involving transformers and motors only the 60-Hz component of the voltage does useful work and the harmonic component generates useless heat. Sensitive electronic control circuits, timers, and logic circuits may be affected if the supply voltage is distorted [3-5].

The harmonic current generated by any non-linear load flows from the load into the power system. This current, seeking a low impedance path to ground, causes a voltage of the drop through the system according to Ohm's Law. The harmonic voltage combines with the 60 Hz voltages producing a distorted power system voltage. The harmonic laden power system voltage is then imposed on all of the remaining loads connected to the system this voltage distortion may result in more harmonic currents being produced as other linear loads experience the distorted system voltage.

A few industries like steel mills and aluminum smelters used electricity to power arc furnaces, which distorted the waveform, because the current flow was not directly proportional to the voltage. These loads are called non-linear loads. Non-linear loads cause waveforms that are multiples of the normal 60 Hertz sine wave to be superimposed on the base waveform. These multiples are called harmonics. Harmonic is defined as a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. For example, the second harmonic is a 120 Hertz waveform (2 times 60 Hertz), the third is a 180 Hertz waveform, and so on.

Harmonic distortion may or may not create a problem for own facility. A plant may have harmonics present, but experience no adverse effects. However, as harmonic levels increase, the likelihood of experiencing problems also increases. Typical problems include:

- Malfunctioning of microprocessor-based equipment
- Overheating in neutral conductors, transformers, or induction motors
- Deterioration or failure of power factor correction capacitors
- Erratic operation of breakers and relays
- Pronounced magnetic fields near transformers and switchgear

To make matters worse, harmonics can sometimes be transmitted from one facility back through the utility's equipment to neighbouring businesses, especially if they share a common transformer. This means harmonics generated in one facility can stress utility equipment or cause problems in other neighbour's facility and vice versa.

Electric utilities have recognized this problem and are adopting standards, like the Institute of Electrical and Electronics Engineers (IEEE) Standard 519 which defines allowable harmonic distortion at customer service entrances. This standard is designed to protect both businesses and utilities, many other standards are also available and set limits for such harmonic penetration.

Harmonic analysis, load flow analysis, and power factor correction in Metal Scrap plant in Saudi Arabia, were considered for two reasons: 1) the planned installation of a new Induction furnace; and 2) the correction of the overall plant power factor to a value above 0.90 lagging to eliminate utility penalties.

2. The behavior of electric arc furnace

The voltage across an electric arc, which is relatively independent of current magnitude, consists of three components, anode drop, cathode drop and arc column component; which amount to about 12 volts/cm of arc length.

Typical values of arc voltages are in the range of 150-500 volts. Since the arc is extinguished at current zero, the power factor plays an important role on arc re-ignition. The figure 1. shows how arc voltage, power factor, input power; arc power and reactive power vary with arc current for a particular tap setting on the furnace transformer. The furnace is normally operated near maximum arc power, which corresponds to a power factor of 70% [9].

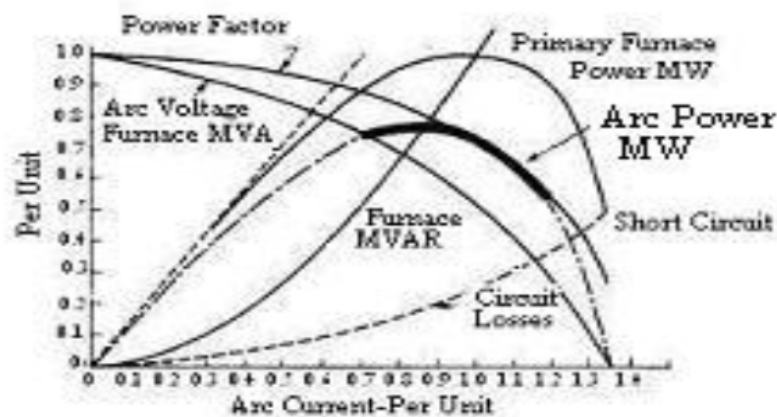


Fig. 1. Electrical Characteristics of Electric Arc Furnace

The three basic changes in operating states of an electric arc furnace, which can produce distinguishable voltage disturbances on power system, are open circuit condition, short circuit condition and the normal operation. The measurable data of interest for an electric arc furnace load include the following three phase quantities: supply voltage, real and reactive power, flicker, frequency and total harmonic distortion in respective phases. Because of the non-linear resistance, an arc furnace acts as a source of current harmonics of the second to seventh order, especially during the meltdown period. Voltage fluctuations are produced in this way through impedance on the value of harmonic currents supplied and the effective impedances at the harmonic frequencies. The harmonic current I_v of the arc furnace forms a parallel tuned circuit consisting of capacitor C with reactive power and mains inductance, resulting from the mains short circuit power. When this tuned circuit resonates at a harmonic frequency, its reactance is high and a harmonic voltage arises, which is damped by the resistance of the resistive component of the supply system consumers' equipment. The Q factor of this tuned circuit is low at times of full load, and no resonant peaks occur. But in slack periods with combinations of low load with high resistance and Q factor values, harmonic voltages are expected at levels sufficient to cause appreciable interference [11].

3. Harmonic mitigation

Several methods of mitigating harmonics have been developed over the years. The most common method is using filter, either passive or active. Passive filter block certain harmonic bandwidth while active filter injects current into the system to cancel the current harmonic waveforms. Both methods have their advantages and disadvantages, for example, advantage of passive filter is easy to design and active filter can monitor many frequencies simultaneously while disadvantage of passive filter is bulky in size and active filter is costly. Harmonic filters are useful and practical to be implemented by consumer near the proximity of the non-linear load at the low voltage system. Another method which is normally used by consumers is using phase cancellation method using twelve pulse converters instead of six pulse converters [12].

Similar application using filters for utility at higher voltage level such as distribution network requires extensive economic consideration. This is due to the size and cost of the equipment while most of harmonic pollutant is caused by consumer. There is little study on a feasible and cost effective means for utility to mitigate harmonic, especially harmonic voltage. A study was conducted on method using shunt harmonic impedance which can act like a central damper to reduce harmonic at distribution network [13]. This method is considered to be less expensive compared to active filter. The method uses power electronic to emulate resistive behavior for harmonic. However, the method is still under further study. Currently, all harmonic mitigation techniques involve equipment required to be installed on the system. There is yet a study on using other factors which can affect harmonic voltage distortion such as network impedance. Optimizing network impedance to mitigate harmonic can be cost effective for utility to apply. Because of mitigating harmonic is expensive, many utility company have resorted in imposing penalty to consumer for injecting current harmonic above the standard steady state limit into the system. This process requires method of determining harmonic contribution by the consumers and the equipment need to be installed at all consumers' feeder which is very costly [13].

4. Brief steel plant system description

The steel plant system consists of 49 buses and 38 two winding transformers. The plant is fed from two utility substations at 230 KV and through four 230/34.5 KV transformers. From 34.5 KV many 34.5/13.8 KV transformers are installed to feed difference load including three electric Arc Furnaces (EAF1, EAF2, EAF3) and two Ladle Furnaces (LF1, LF2). Part of The single line diagram of the arc furnaces of this system is shown in figure 2.

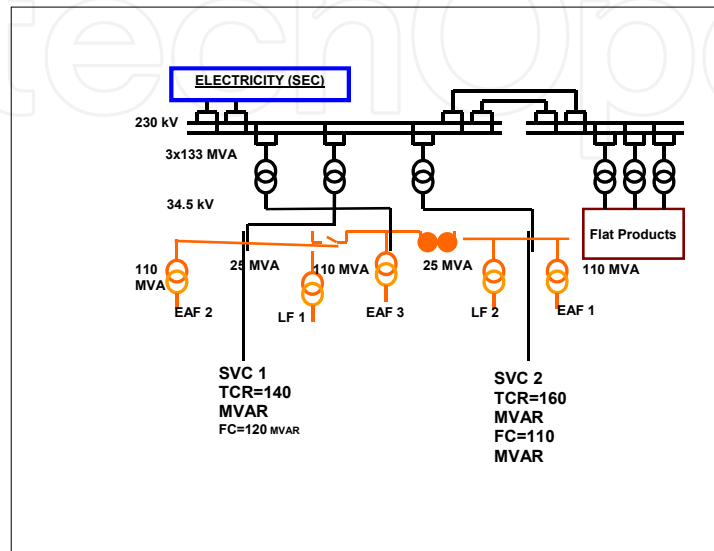


Fig. 2. Partial single line diagram of steel plant system.

This system was simulated by using a software package and the results of load flow, total harmonic distortion, and power factor at some buses are shown in table 1.

Bus#	Nominal Voltage (KV)	LF Voltage (p.u)	LF Angle (deg)	THD (%)	Power Factor
1	230.00	1.00	0.00	6.47	56
2	34.50	0.95	-1.90	10.31	59
3	34.50	0.95	-1.90	10.31	59
5	34.50	0.95	-1.90	10.30	59
45	0.48	0.91	-3.80	10.11	58
46	0.48	0.91	-3.80	10.11	58

Table 1. Load flow, THD, and power factor results

Filter Location	Order	Rated KV	Kvar	XL	Q
Bus # 1	2 nd	230.00	35035.00	377.47	75.00
Bus # 5	5 th	34.50	30572.00	79.00	39.50
Bus # 5	7 th	34.50	24745.00	120.20	84.10

Table 2. Filtre Data

Bus #	Nominal Voltage (KV)	LF Voltage (p.u)	LF Angle (deg)	THD (%)	Pf
1	230.00	1.00	0.00	1.24	0.98
2	34.50	0.99	-2.30	2.95	0.99
3	34.50	0.99	-2.30	2.95	0.99
5	34.50	0.99	-2.30	2.95	0.99
45	0.48	0.95	-4.00	2.92	0.97
46	0.48	0.95	-4.10	2.92	0.97

Table 3. Load Flow, THD, and Power Factor Results

Single-tuned filters were designed for the metal plant system according to the next paragraph theories and its input data are provided in table 2. The results of load flow, total harmonic distortion, and power factor of buses 1, 2, 3, 5, 45, and 46 after installing filter are shown in table 3. Also the spectrum and waveform of bus 34.5 kV is provided in figure 3.

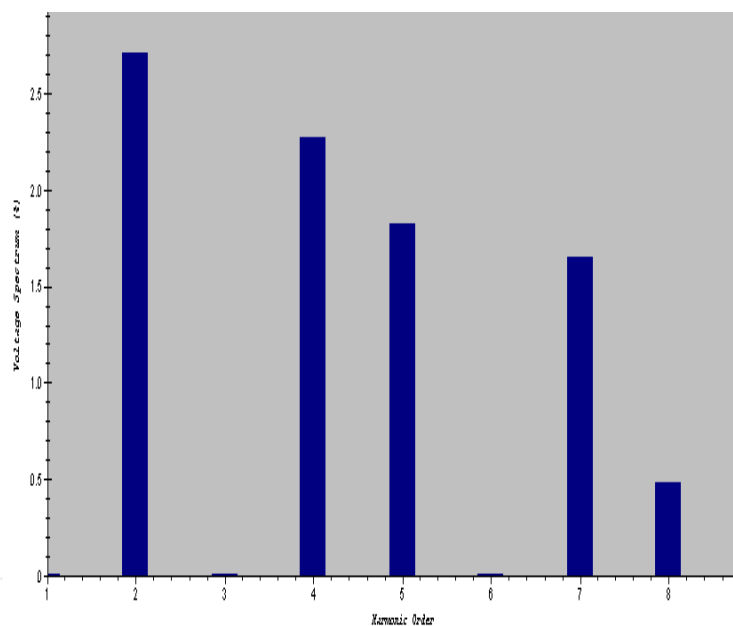


Fig. 3. Spectrum of voltage at bus 34.5 kV

5. Filter design

Harmonic filters are designed to suppress system harmonics as well as to improve power factor. They allow a system to meet IEEE Standard 519 harmonic limits while avoiding power factor penalties. Filter designs are tailored to individual project objectives such as meeting a harmonic limit and/or a power factor level. This is a complex and involved engineering task, where alternative designs are checked to ensure that the final one will meet study objectives [14].

Typically, single tuned shunt filters are designed with a reactor and capacitor in series, connected as a shunt load on the system. In more complex studies, other types of filters, like 2nd or 3rd order, C-type, and/or double tuned filters are designed. In a complex filter design,

a combination of filter types could be required. A generic term used to describe those types of equipment whose purpose is to reduce the harmonic current or voltage flowing in or being impressed upon specific parts of an electrical power system, or both [4,11].

The filter is tuned slightly below the harmonic frequency of concern. This allows for tolerances in the filter components and prevents the filter from acting as a direct short circuit for the offending harmonic current. Further allows the filter to perform its function while helping to reduce the duty on the filter components. It also minimizes the possibility of dangerous harmonic resonance should the system parameters change and cause the tuning frequency to shift slightly higher [6, 7].

Once the filter type and the components (reactors, capacitors and resistors) are determined, the design program is used to model these filters. Overall power system operation can then be analyzed to determine the effectiveness of the filtering scheme. Ratings of all filter components along with the protection schemes and control methods are identified, and detailed specifications are developed for the manufacture of the filters. All designs are based on relevant IEEE Standards for capacitors and reactors [15].

5.1 Filter components

5.1.1 Capacitors

Capacitors are composed of standard units that are connected in series or parallel for obtain the desired overall voltage and KV rating [5]. The capacitor's are designed and chosen with the following considerations:

- Harmonic current peaks have a 100% coincidence.
- Nominal System over-voltage of 5%.
- Ambient voltage distortion equal to the limits set forth by IEEE 519.
- Adherence to IEEE/ ANSI peak and RMS voltage ratings.

5.1.2 Inductors

Inductors used in filter circuit need to be designed bearing in mind the high frequencies involved. Inductors rating depend mainly on the maximum RMS, current. The inductors and resistors form the ground side of a tuned filter [5]. The reactor current ratings are based on the following considerations:

- The reactor core will not saturate for currents less than 250% of the fundamental current rating of the filter bank.
- Peak flux density of the core will be less than 1.2 - 1.4 Tesla assuming all harmonic current peaks is 100% coincident.

5.2 Tuned filter

A single tuned filter is a series RLC circuit tuned to the frequency of one harmonic .its impedance is given by

$$Z_1=R + j (\omega L-1/\omega C) \quad (5.1)$$

Which at the resonant frequency f_n reduces to R. There are two basic design parameters to be considered prior to the selection of R, L and C. these are the quality factor Q, and the relative frequency deviations. It is generally more convenient to deal with admittances rather than impedance in filter design

$$Y_f = 1/R(1+j2sQ) = G_f + jB_f \quad (5.2)$$

Where

$$G_f = Q/X_0(1+4s^2Q^2) \quad (5.3)$$

$$B_f = 2sQ^2/X_0(1+4s^2Q^2) \quad (5.4)$$

$$X_0 = \sqrt{\frac{L}{C}} \quad (5.5)$$

The harmonic voltage at the filter bus bar is

$$V = I/Y_f + Y_s \quad (5.6)$$

Therefore, to minimize the voltage distortion it is necessary to increase the overall admittance of the filter in the parallel with the a.c system. The harmonic voltage increases with (s) [4]. In term of Q and s can be equation (6) can be written as follows:

$$V = I\{(G_s + 1/R(1+4s^2Q^2))^2 + (B_s - 2sQ/R(1+4s^2Q^2))^2\}^{-1/2} \quad (5.7)$$

6. University Personnel Computers (PC) effect on line currents harmonics

6.1 Introduction

Power Quality problems are increasing with the proliferation of nonlinear devices, which draw none sinusoidal current waveforms when supplied by a sinusoidal voltage source. When these devices are present in an electric power system, they cause harmonic distortion of voltages and currents. Individually, single phase nonlinear load may not pose many serious harmonic problem, but large concentrations of these loads have the potential to raise harmonic voltages and currents to unacceptable high levels which results in increased neutral currents in four wire system, over heating of distribution system components and may cause mechanical oscillations in generators and motors. Other unwanted effects are capacitor and insulation failure due to harmonic resonance, malfunction of installed protection systems, transient voltage fluctuations, over heating of system transformer and cables, error of power electronic equipments operations and telephone interference.

Many desktop personal computers still present a nonlinear load to the AC supply. This is because they have a power supply design known as a "capacitor input switch mode power supply". Much of today's Information Technology equipment including servers, routers, hubs, and storage systems almost universally use a different power supply design known as "Power Factor Corrected". These devices present a very linear load to the AC supply and do not generate harmonic currents. In fact they are one of the cleanest loads on the power grid and generate less harmonic current than many other devices such as fluorescent lighting or variable speed drives. The 3rd harmonic currents, the predominant harmonic in PC power supplies, causes overloaded neutrals, overheated transformers, and annoyance circuit breaker tripping. Very high price may be spent on equipment which will either filter or block the harmonics or withstand the heating effects of the harmonics.

Studies on the monitoring of power quality at computer sites have been conducted as early as 1969, [16, -18], and continuing interest in this area has maintained regular publications thereafter [19-21]. Most early studies were concerned with the effects of power disturbances

on the correct operation of the computer facility. However, with the advent of relatively inexpensive personal computers (PC), the emphasis of computer power quality monitoring has also moved towards investigating the effects that large concentrations of PCs can have on other utility customers.

Personal computing impacts on power quality are increasing due to the common place usage of switched mode power supplies (SMPS) for converting single phase AC into low voltage DC for supplying processing electronics. Such power supplies, which are responsible for the generation of odd line current harmonics, are the main concern of this paper. However, in turn harmonically polluted line currents can distort supply voltages causing power quality problems for other consumers connected at a point of common coupling [22]. Additionally, and somewhat ironically, the switched mode power supply itself can be affected by non-sinusoidal supply voltages [23], which can increase or decrease current harmonics depending on the nature of the voltage distortion.

Switched mode power supplies are by no means restricted to PCs and can be found in a variety of other widely used electrical equipment including low energy lighting, battery chargers, televisions and their peripherals.

A recent study [24] has shown that the line current harmonics from a single PC differed considerably to the harmonics generated collectively by several PCs of the same type. One widely held theory [25] regarding this effect introduces the concepts of *attenuation* and *diversity*. Attenuation describes the reduction in harmonic magnitude, and change in phase angle, as a load connected to a SMPS increases, and attributes this effect to the change in the spectrum of the line current pulse which widens to allow more power flow through the SMPS. Attenuation is also observed where several identical loads share the same source impedance. Diversity describes a The influence of personal computer processing modes on line current harmonics similar effect where a reduction, or even cancellation, of harmonics is possible due to loads of different levels, or connected through different impedances, presenting differing phase angles to the supply. These findings have not been proved using large-scale studies; although predictions based on results taken from individual computers have been reported [26].

The primary aim of this investigation is to investigate how the mode of operation of a PC affects the harmonics produced in the line current. This is an area barely mentioned in previous literature although these effects are closely related. One published study has made limited investigations of this type, but, again, only for individual computers [27]. In new construction or renovation, many power disturbances can be prevented or significantly lessened by designing for power quality assurance, at surprisingly small cost.

In view of the concerns regarding cumulative effects of large collections of PCs, this study was conducted within a University library building containing over 370 PCs. Furthermore, the study was intended to investigate the primary effect on line current harmonics caused by mode of operation, in isolation from additional secondary effects caused by distorted supply voltages. Investigation of this primary effect was achieved by monitoring during periods when the PCs represented the only load on the transformer supplying the library building and consequently the supply voltage waveforms were relatively undistorted. Most of these disturbances originate right within the building. Personal computers, laser printers and other switched-mode power supply equipment within your building are usually the culprits for most of the power supply irregularities affecting other computers. It's a problem

that has only recently begun to be recognized in the building industry, as more and more computers and similar equipment are installed, turning the modern office or factory into a high-tech computer environment. [28]

The objective of section six is to investigate the effect of an University-PC and other harmonic contributing sources on the line currents that may have influence on processing modes and to measure the actual Total Harmonic Distortion during such modes.

7. Power quality issues related to computers

Although harmonics is the subject of several international standards [16], the difficulties of regulating harmonics emissions from small, individual devices employing switched mode technology, such as a personal computer, is compounded by the fact that the harmonic generation capabilities of these devices varies according to the number of parallel connected devices.

In the last decade, power quality has become a major issue for electric utilities and their customers, and indirectly to almost all manufacturers of equipment that depend on sinusoidal supply voltage waveforms. The proliferation of solid-state switching devices in both industry and home has increased the harmonic levels found on electricity supply systems. In the past, sources of harmonics were limited and in most cases tolerable. However today, virtually all high performance electronic equipment uses switched mode power converters, conducting current for part of a cycle through multiple paths in order to efficiently convert alternating current to direct current. In response to this increased demand some countries encouraged the development of more efficient ways of getting full benefits from electrical energy by various switching methods.

On the other hand a new technique of manufacturing circuits called integrated electronic circuits have been invented and led directly to increasingly complex systems such as in industry ,communications, domestic appliances ... etc because its size, weight and cost. These circuits, although increased speed of operations and complexity of tasks, typically use a technique called switch mode power supplies [26- 29].

The majority of modern electronic units use switched mode power supplies (SMPS). The advantage-to the equipment manufacturer- is the size, cost and weight is significantly reduced and the power unit can be made in almost any required factor [28]. But unfortunately switch mode power supplies act as non-linear loads or they can be considered as a noise generators which get down the quality of the electricity supply.

Equipments with switch mode circuits are usually more sensitive to main variations and disturbances than liner loads [30]. For this reason power quality has become a major issue for electric utilities and their costumers and almost all manufactures of equipment that despond on sinusoidal supply voltage waveforms. The increasing of solid state switch devices such as Personal computers in both industry and homes will draw rather than continuous current from the supply; the power supply unit will draw pluses of current which contain large amount of harmonics [29, 32].

The switching mode power supplies used in personal computers are major sources of harmonic currents. An experiment [26, 28, and 32] has been done for different types of computers to measure the harmonic generated by each type and the result was scheduled as:

	Mac IIsi	IBM XT	IBM PS/30	Mac Plus	IBM PS/70
I_1	106.82 (100%)	165.93 (100%)	199.02 (100%)	83.35 (100%)	541.88 (100%)
I_3	89.31 (83.6%)	122.45 (73.8%)	152.63 (76.7%)	72.30 (86.7%)	458.83 (84.7%)
I_5	65.18 (61.0%)	68.03 (41.0%)	94.76 (47.6%)	55.80 (66.9%)	333.54 (61.5%)
I_7	40.51 (37.9%)	26.71 (16.1%)	39.16 (19.7%)	36.53 (43.8%)	192.04 (35.4%)
I_9	21.25 (19.9%)	5.64 (3.4%)	10.39 (5.2%)	17.78 (21.3%)	71.18 (13.1%)
I_{11}	8.70 (8.1%)	3.98 (2.4%)	3.53 (1.8%)	3.31 (4.0%)	17.75 (3.3%)
I_{13}	2.95 (2.8%)	8.46 (5.1%)	1.49 (0.7%)	4.95 (5.9%)	49.02 (9.0%)
I_{15}	3.46 (3.2%)	8.29 (5.0%)	2.30 (1.1%)	7.51 (9.0%)	48.01 (8.8%)

Table 4. Magnitudes of harmonic currents of various PC's in mA [32]

The phase current is given by:

$$I_p = \sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_9^2 + I_{11}^2 + I_{13}^2 + I_{15}^2} \quad (6.1)$$

The IBM XT™ has the lowest percent third harmonic current (74%). Since the computer is connected line-to-neutral in a 3-phase system, the neutral current is approximately equal to three times the vector sum of the third and ninth harmonic currents flowing in each phase.

$$I_n = 3\sqrt{I_3^2 + I_9^2} = 367,764mA \quad (6.2)$$

$$I_p = 219,226mA \quad (6.3)$$

$$\frac{I_n}{I_p} = 1,677 \quad (6.4)$$

The Mac Plus™ offers the worst case third harmonic current (87%). In a similar manner I_n & I_p are obtained.

$$I_n = 223,377 \quad (6.5)$$

$$I_p = 130,507mA \quad (6.6)$$

$$\frac{I_n}{I_p} = 1,712 \quad (6.7)$$

With a large number of personal computer loads, the neutral current is expected to be 1.7 times the phase current. It will certainly overload the neutral conductor that is designed to handle lower currents than the phase currents [14]. Non linear loads connected to a sinusoidal source inject harmonic currents into the source. Much attention has been focused

on large power converters as sources of harmonics due to the high magnitude of the currents evolved. Nevertheless, harmonics generated by low power converters become significant when large numbers of converters are used simultaneously [14, 15]. Indubitably the personal computer is an ideal place for these converters. The power supplies employed in most personal computers are of the switching mode type. In switching mode power supply, the 60 Hz AC voltage is converted to into DC through a single phase rectifier and the output voltage of the rectifier is stepped down using AC to DC converter [13, 14]. The main advantage of the switching mode power supply over the traditional linear power supply is its high energy efficiency since the switching elements used (BJT's, MOSFETS) are either completely off or completely on.

Personal computers impacts on power quality are noticeable due to the common place usage of switched mode power supplies (SMPS) for supplying processing electronics. Such power supplies are responsible for the generation of odd line current harmonics. However, in turn harmonically polluted line currents can distort supply voltages causing power quality problems for other consumers connected at a point of common coupling (PCC). Switched mode power supplies are by no means restricted to PCs and can be found in a variety of other widely used electrical equipment including low energy lighting, battery chargers, televisions and their peripherals. For power quality considerations, the PC is the most significant item for a variety of reasons including.

- On an individual basis, it represents one of the larger loads consuming typically 200-300 W per unit.
- The current drawn is affected by user behavior.
- Large numbers of PCs can be connected to a single supply point.

The last point is one of the major concerns of increasing PC usage and has resulted in power quality studies of the cumulative effects of many PCs connected to the same bus bar [27]. A recent study has shown that the line current harmonics from a single PC differed considerably to the harmonics generated collectively by several PCs of the same type. One widely held theory regarding this effect introduces the concepts of attenuation and diversity [25].

Attenuation describes the reduction in harmonic magnitude, and change in phase angle, as load connected to a SMPS increases due to the change in spectrum of the line current pulse which widens to allow more power flow through the SMPS. Attenuation is also observed where several identical loads share the same impedance. Diversity describes a similar effect where a reduction or even cancellation of harmonics is possible due to loads of different levels, or connected through different impedances, presenting differing phase angles to the supply. These findings have not been proved using large scale studies [25-28].

8. Study procedures and results

8.1 Introduction

The University consists consists of 60 buildings including students housing. Almost each student at the university has a laptop regardless of the number of PC's in each, laboratories, or rooms. The university in-house that there are around 6000 PCs distributed unequally . Most of the PS's in the university are of model HP, DELL, Compaq dc 7800P; they use Intel core 2 Dual processors.

8.2 Measurement plan

This investigation adapted the following steps which include:

- Obtaining all line diagrams of the area of investigation.

- Securing the total number of the university PC's and most PC's concentration area.
- Circulate Questionnaire to major PC users such as ITC to develop a sense where are the major area that may have harmonics as to affect ITC line currents and servers etc...
- Locate and prepare the building (14, consist of 263 PC's and 58 consist of 280 PC's) switchboard to be able to conduct different measurements being the highest building containing PC's.
- Conduct Harmonic measurements at these buildings and monitor and check harmonics at different loading processing modes and times.
- Recommendation and findings are to be clearly drawn out of results and stressing the mode of operations and size of PC lab.
- Identify the sources and causes of harmonics at such selected locations: use such data in the process of making the appropriate mitigating actions.

To conduct harmonic measurement the team members attended intensive lectures and training on Power Quality and measurements. Training focused on how to use the power quality analyzer (PQA).

Single line diagrams for each of the building under investigate were obtained as shown in Figure 4. Permissions to conduct measurement and open switch boards of the different feeders were also obtained through the university Electrical Maintenance department.

The whole Excl file containing total PC's provided by from ITC indicating all the university PC's record and their distributions at the different building and labs etc... The total February 2009 PC's numbers was 6,344.00.

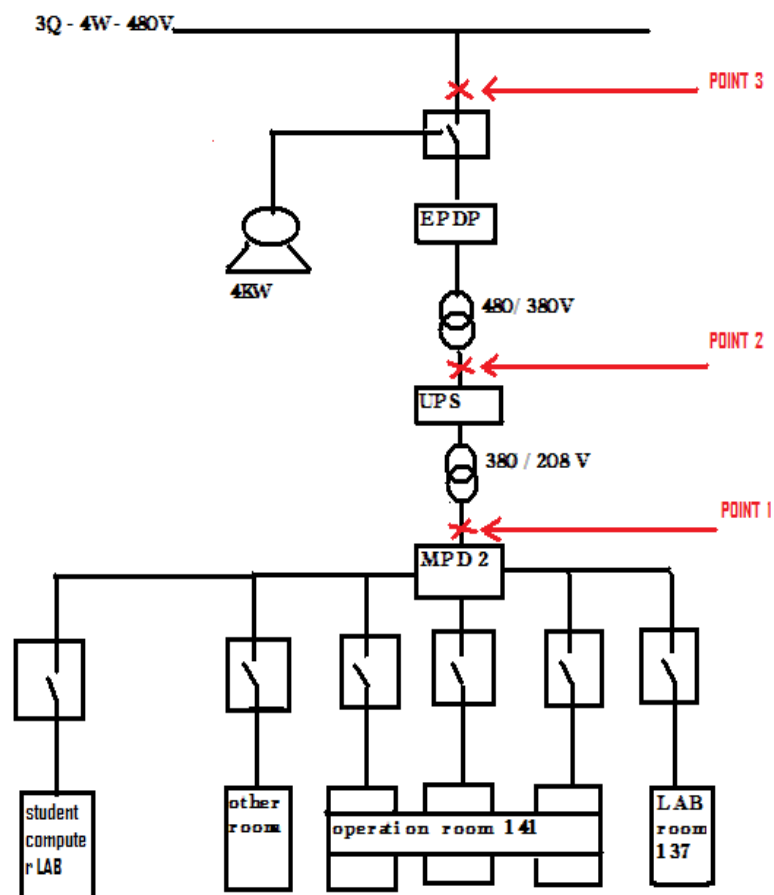


Fig. 4. Building 14 Single Line Diagram and Points of Measurements and switch boards

8.3 Measurements at normal load

The measurements have been conducted by the team members of the project according to the following time Table:

Day	Reading #1 period	Reading #2 period	Reading #3 period	location inside the substation
Monday	9:00AM-12:00Pm	12:10Pm-1:30PM	1:40PM-4:00PM	At point 1*
Tuesday	9:00AM-12:00Pm	12:10Pm-1:30PM	1:40PM-4:00PM	At point 2**
Wednesday	9:00AM-12:00Pm	12:10Pm-1:30PM	1:40PM-4:00PM	At point 3***

*indicates the point between MPD2 &the transformer 380/208 v

**indicates the point between UPS &the transformer 480/380 v

***indicates the point between EPDP & the main feeder 3 ϕ -4w 480v

Table 5. Time table of measurements

At the first point shown in the single line diagram (Figure 4), three measurements have been conducted over the three periods as listed in table 5.

8.4 Measurements and results

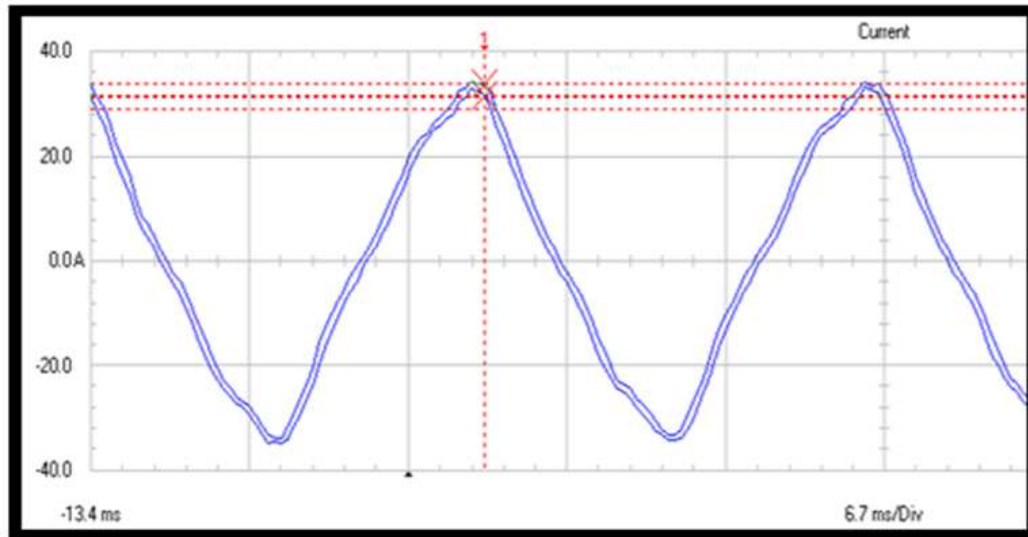
The measurement of the harmonics caused by PC's and any other nonlinear elements were conducted at each bus (points 1, 2, and 3) as indicated in the single line diagram.

At the first point shown in the single line diagram (Figure 4), three measurements have been conducted over three periods. The THD during the first period at point one was measured and the maximum total harmonic distortion (THD) was 10.6%. The THD during the second period at point one and the maximum total harmonic distortion (THD) was 10.7%. The THD during the third period at point one and the maximum total harmonic distortion (THD) is 10.8%

From the previous three readings it is clear that at normal load at point one the maximum total harmonic distortion of the three readings is 10.8%. Moreover, the harmonics effect appears in the current waveform as in Figure 5.

For the second point the THD during the first period indicated a maximum total harmonic distortion (THD) was 29%.

On the second measuring period the THD during the second period at point one and the maximum total harmonic distortion (THD) was 28.4%. The THD during the third time period at point two indicated maximum total harmonic distortion (THD) of 28.9%. From the previous three readings it is clear that at normal load at point two increases the harmonic flow, the maximum total harmonic distortion of the three readings is 28.9%. Moreover, the harmonics appears to distort the phase current waveform as in Figure 6.



Datablock	
Name	= Current
Date	= 24/12/08
Time	= 02:27:04
Y Scale	= 20 A/Div
Y At 50%	= 0.0 A
X Scale	= 6.7 ms/Div
X At 0%	= -13.4 ms
X Size	= 250 (254)
Maximum	= 34.3 A
Minimum	= -35.5 A
Cursor Values	
X1 :	3.2 ms
X2 :	36.7 ms
dX :	33.5 ms
Y1 :	31.9 33.9 A
Y2 :	29.1 31.5 A
dY :	-2.8 -2.4 A

Fig. 5. Current wave forms at point one

The sum of all these THD's = 83.8% is not equal the THD at point one which is 10.8%. The difference between these two values explains which is called harmonic cancellations. The phase angles of the magnetization current harmonics oppose the phase angles of the load current harmonics and such lead to harmonic cancellations. The maximum total harmonic distortion at point three is 20.6% which is less than that at point two (29%). The difference between the two values is caused also by harmonics cancellation. According to the instructions provided with the power quality analyzer manual and other standards which state that if the current THD is less than 20% the harmonic distortion is probably acceptable, the total harmonic distortion at point three (29%) was greater than 20%, so it is not acceptable and definitely will make adverse affect on the neutral line cable.

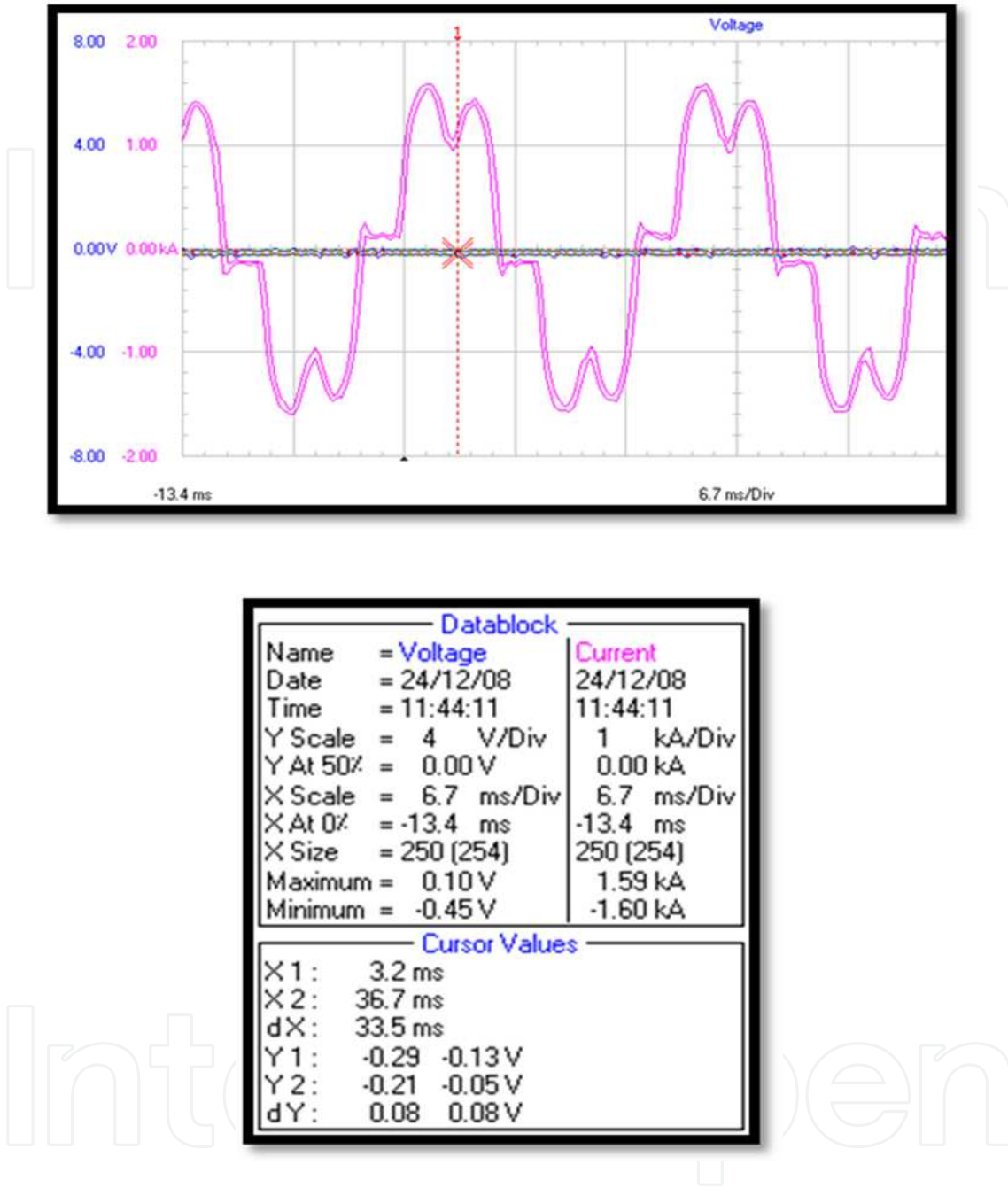


Fig. 6. Current wave forms at point two

To avoid the injection of harmonics into the system, a harmonic filter must be designed to eliminate the highest harmonics order flowing and then installed at the near bus of such produced harmonic. It is noticed in table 6 that the highest THD measured was during the period where students were using laboratories of Building 14 at point 2 with the highest harmonic is of fifth order. While table 7 illustrates harmonics produced as to the total numbers of Pc's used.

Location	Max THD in the first period	Max THD in the second period	Max THD in the third period	Crest Factor	Highest Harmonic Order
Point 1	10.6%	10.7%	10.8%	1.5-1.6	Third
Point 2	29%	28.4%	28.9%	1.5	Fifth
Point 3	19.6%	19.9%	20.6%	1.5	Fifth

Table 6. Summary of the obtained results for the three points of Bldg. 14

No. of PC's	%age Mag. of 3 rd Harmonic	%age Mag. of 5 th Harmonic	%age Mag. of 7 th Harmonic	%age Mag. of 9 th Harmonic	%age Mag. of 11 th Harmonic	%age Mag. of 13 th Harmonic	%age Mag. of 15 th Harmonic	%age Mag. of 17 th Harmonic	THD %
263	28.3A	14.8A	5.2A	0.4A	0.7A	0.1A	0.4A	0.1A	10.4
204	27.1A	13.1A	4.6A	1.4A	0.7A	0.4A	0.7A	0.1A	9.9
170	25.6A	12.5A	4.2A	1.8A	0.8A	0.4A	0.5A	0.1A	9.6

Table 7. Harmonic magnitudes for different No. of PC's at point 1

8.5 Standards and limits

International Standards have set some limits to the most equipment on the permissible harmonic content in the electrical system during operation. The following are general limits for various electrical equipments:

- Synchronous machine: permissible stator current distortion < 1.4%
- Asynchronous machines: permissible stator current distortion; 1.5% to 3.5%
- Cable: permissible core-shielding voltage distortion < 10%
- Electronic equipment: 5% voltage distortion with a maximum individual percentage of 3% depending on the equipment
- Transformer: permissible current distortion < 5% at full load [IEEE-519]

Most utilities have adopted standards to limit the harmonic content at the point of common coupling (PCC). Some of the Standards adapted around the world include:

- US/Canada IEEE 519
- Europe IEC61000 3-2, 3-4
- United Kingdom G5/4 -1
- China GB/T 14549

9. Thd theory and verification calaculations

The percentage of Total Harmonic Distortion (%THD) can be defined in two different ways, as a percentage of the fundamental component (the IEEE definition of THD) or as a percentage of the RMS (used by the Canadian Standards Association and the IEC).

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{rms,n}^2}}{I_1} \quad (9.1)$$

Where, $I_{rms, n}$ is the amplitude of the harmonic component of order n (i.e., the n th harmonic). The numerator gives the RMS current due to all harmonics and I_1 is the RMS value of fundamental component of current only. Given above is the mathematical form of the IEEE. According to IEC standards, the mathematical form of THD is given below:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_{rms, n}^2}}{I_1} \tag{9.2}$$

Where

$$I_{rms} = \sqrt{\sum_{n=1}^{\infty} I_{rms}^2} \tag{9.3}$$

Where $I_{rms, n}$ is the amplitude of the harmonic component of order n (i.e., the n th harmonic) and I_{rms} is the rms value of all the harmonics plus the fundamental component of the current. The later standard is referred in this study, because the apparatus used for analysis was based on IEC Standards.

The 3rd, 5th, 7th and 9th harmonics being the most significant, the definition of THD may be modified and written as in 9.4

$$THD = \frac{\sqrt{I_{rms,3}^2 + I_{rms,5}^2 + I_{rms,7}^2 + I_{rms,9}^2}}{I_{rms}} \tag{9.4}$$

The value of THD may be calculated for any number of computers using formula (9.3).

$I_{rms} = 308.4 \text{ A}$

RMS magnitude of 3rd Harmonic= 25.6 A

RMS magnitude of 5th Harmonic= 12.5 A

RMS magnitude of 7th Harmonic= 4.2 A

RMS magnitude of 9th Harmonic= 1.8 A

$$THD = \frac{\sqrt{25,6^2 + 12,5^2 + 4,2^2 + 1,8^2}}{308,4} = 9.36\% \tag{9.5}$$

Figure 9 is showing the magnitude of individual harmonics, when 263 PCs in building 14 were connected to the supply mains.

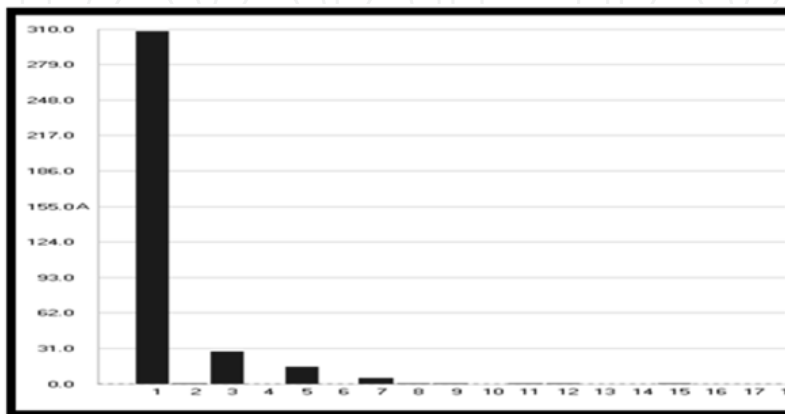


Fig. 7. Harmonic spectrums at point one when 263 PC's operating

The online value of THD was 9.6%. The percentage difference (Error) of the calculated and experimental value is 0.24%.

This difference caused by neglecting other odd harmonics such small error proves the validity of measurement using this PQA and it consequently plays a pivotal role for the accurate analysis of the odd harmonics.

Figure 8 explains the overall impact of individual harmonics cumulatively. Total Harmonic Distortion (THD) in line current is increasing when the electronic loads are increasing. Among odd harmonics only third harmonic plays active role whereas the other odd harmonics impact with increase in electronic loads is negligible.

By using linear interpolation, the relation between THD in current and the number of PC's (N) is given by the following equation:

$$I_t = 8.143 + 0.008 \times N \quad (9.6)$$

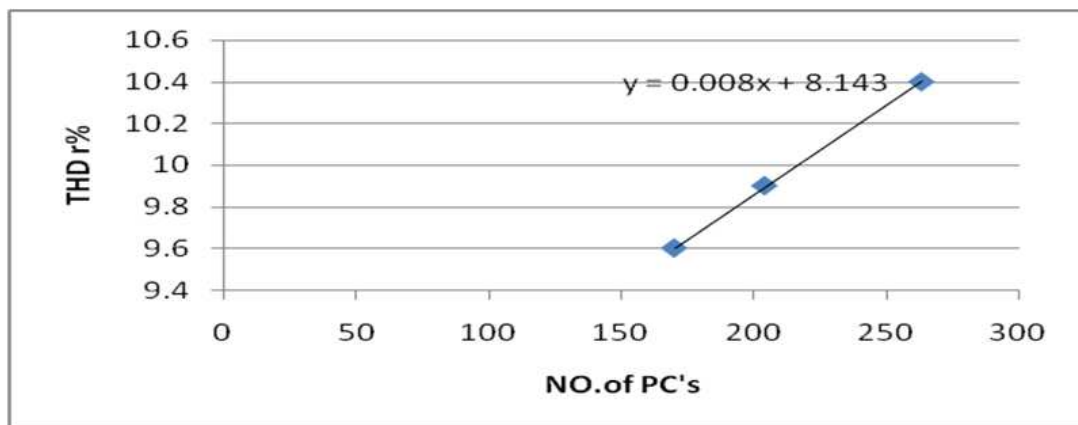


Fig. 8. THD curve vs. No. of PC's at point 1.

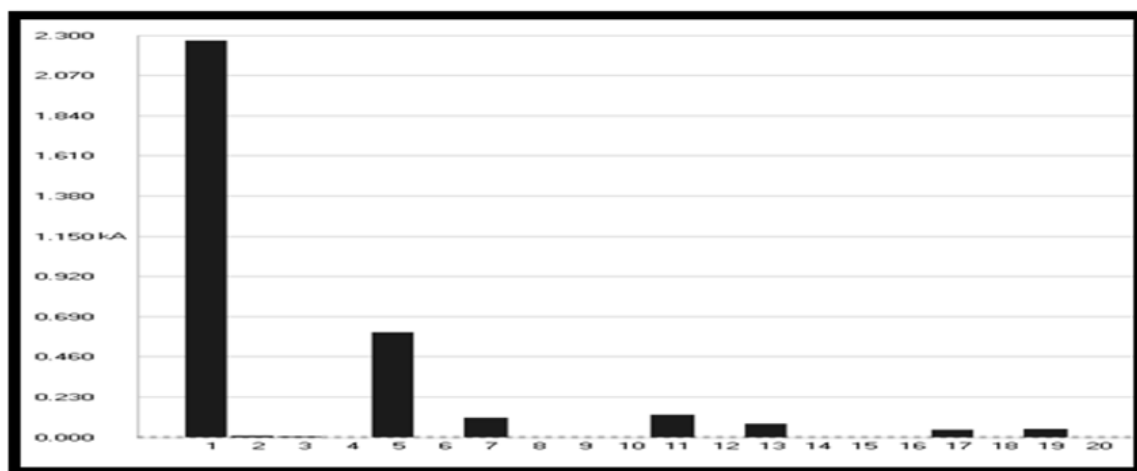


Fig. 9. Harmonic spectrums at point 2 when 263 PC's operating

The value of THD may be calculated for any number of computers with formula (9.4). Figure 9 is showing the magnitude of individual harmonics, when 263 PCs were connected to the supply mains.

$$I_{rms} = 2271 \text{ A}$$

$$\text{RMS magnitude of 3rd Harmonic} = 3 \text{ A}$$

RMS magnitude of 5th Harmonic= 600 A
 RMS magnitude of 7th Harmonic= 112 A
 RMS magnitude of 9th Harmonic= 1A

$$THD = \frac{\sqrt{3^2 + 600^2 + 112^2 + 1^2}}{2271} = 26.7\% \tag{9.7}$$

The online value of THD was 26.8%. The percentage difference (Error) of the calculated and experimental value is 0.1%.

10. Thd measurements discussion

According to the previous measurements it has been observed that the total harmonic distortion at point two (29 %) is much greater than that at point one (10.8%). Since there is no load connected between these two points except the Uninterruptible power supply (UPS), it is considered that UPS is the main reason for this difference. The UPS can be considered to fit 'in-line' between the loads and the mains power supply. In addition to providing power protection to the loads, it should also protect the main power supply itself from getting any harmonics generated by the loads themselves. However, it is again not commonly known that UPS and their design being power electronics oriented, also generate harmonic pollution. For any UPS this is typically stated as Total Harmonic Distortion (THD). Care has to be taken when comparing different THD values as these can differ when contrasting the two different types of on-line UPS (transformer-based and transformer less) and also with regard to the percentage of load applied for each measurement.

No. of PC's (N)	%age Mag. of 3th Harmonic	%age Mag. of 5th Harmonic	%age Mag. of 7th Harmonic	%age Mag. of 9th Harmonic	%age Mag. of 11th Harmonic	%age Mag. of 13th Harmonic	%age Mag. of 15th Harmonic	THD r%
263	1.6	33.7	6.4	0.1	7.6	4.4	0.1	19.7
204	1.6	33.6	4.7	0.1	7.9	3.5	0.1	20.6
170	1.4	33.5	4.3	0.1	7.8	3.5	0.1	20.6

Table 8. Magnitudes of harmonics for different numbers of PC's at point 3

Table 8 indicates the online value of THD is 19.7%. The difference of the calculated and experimental value of 0.37% as shown in table 9. This difference caused again by other odd harmonics being neglected, however, such low error proves the validity of measurement and it consequently plays a pivotal role for the accurate analysis of the odd harmonics.

Location	Calculated values	Experimental values	%age Error
Point 1	9.36	9.60	0.24
Point 2	26.7	26.8	0.10
Point 3	19.3	19.7	0.37

Table 9. Comparison of calculated and experimental values when 263 PC'S were connected

Within a UPS it is rectifier that connects to the mains power supply and converts the mains alternating current (AC) into the levels of direct current (DC) required to power the inverter and charge the battery.

For transformer-based UPS, rectifiers are typically six or twelve-pulse, dependent upon the thyristor number and configuration. A six-pulse rectifier at full load will typically generate a THD of around 29% and a 12-pulse around 8%. To reduce these values further a passive harmonic filter can be installed alongside the UPS. The obvious disadvantages of this approach being increased capital cost, wiring, installation, loss of efficiency and increased footprint. Harmonic filters can be added post-installation but further installation costs and downtime need to be planned for.

The maximum total harmonic distortion at point three is 20.6% which is less than that at point two (29%). The difference between the two values is caused also by harmonics cancellation.

11. Conclusions

The nature of such metal factories are to expand because of the high and rapid demand on steel, aluminum, etc... to keep up with the higher rates of development. As for the plant and due to presence of three arc furnaces and two ladle furnaces and adding 1 Induction Furnace in this metal facility, one expects harmonics are considerably high in the steel plant without any filtering. Also, due highly inductive load of this steel plant the Power factor needs to be corrected to match that of the utility [8].

Harmonic measurements and analysis have been conducted and are becoming an important component of the plant routine measurements and for power system planning and design. Metal plant engineers are striving to meet with utility, and IEEE standard for harmonics as well as power factor. Considerable efforts have been made by the plant engineers in recent years to improve the management of harmonic distortion in power systems and meet the utility requested power factor levels.

Results obtained from steel plant system the power factor are low at about seven buses one of them bus number 1 the utility bus were the power factor found 0.56. The power factor of all the buses ranged between 0.56 and 0.59 which considered very low for the utility power factor which is 0.93. Results obtained from the harmonic studies indicate again that many buses of the plant including the utility bus have violated the IEEE-519 1992 standard. One has to remember that using software to analyze the practical conditions it is important to understand the assumption made and the modeling capabilities, of the non-linear elements.

The authors have met with plant engineers and discuss mitigation of the harmonic level as well as improvement of the power factor. Harmonic filters were designed to suppress low harmonic order frequencies and were installed at the different buses, the filtered harmonic of this plant were mainly for the 2nd, 5th, and 7th harmonics.

The plant operations with installation of the designed filters have improved the power factors to reach 0.97. The authors highly recommend cost analysis of designed filters KVAR with harmonic and other benefits, periodic system studies especially when new equipments are added to the plant. Also power quality measurements will be necessary to double check harmonics order found through simulation.

A series of tests personal computers in some buildings at King Fahd University of Petroleum and Minerals have been investigated in order to study the influence of these computers on the line current harmonics. The following conclusions can be drawn from the results of this study.

The switch mode power supply (SMPS) used in personal computers draws a non linear current that is rich in harmonics currents. A high density of (SMPS) loads results in over loading of the neutral conductor and the overheating of the distribution transformers.

The assessment of odd harmonics in current significant in magnitudes are represented by mathematical modeling a proved theoretically the decrease in THD in current at some points when increasing the number of PC's connected to these points. On the other hand, THD increased with increase the number of PC's on the other points of these buildings. According to this study the maximum THD found was 29% in the main student lab in building 14 and it was unstable and the minimum THD was found 1.1% in building 58.

According to the instructions provided with the power quality analyzer Fluke 43 B manual which state that if the current THD is less than 20% the harmonic distortion is probably acceptable, the total harmonic distortion at point three of building 14 (29%) is greater than 20% is not acceptable and makes affect on the neutral line cable. To avoid the injection of harmonics into the system, a harmonic filter must be installed.

Due to the highly non sinusoidal nature of the input current waveform of personal computer, the high amplitude of harmonics currents are generated. These harmonics currents are of odd order because of half wave symmetry of the input current waveform. The magnitudes of the harmonics currents up to the seventh harmonics are significant.

The phase angle of the harmonics currents of the input currents of different PC's vary to cause significant current cancelation. There are some cancelations in the higher order harmonics.

The UPS (Uninterruptable power supply) in building 14 can be considered to fit 'in-line' between the loads and the mains power supply. In addition, to providing power protection to the loads, it should also protect the mains power supply itself from any harmonics generated by the loads themselves. However, it is again not commonly known that UPS themselves, by the way of their design, also generate harmonic pollution. For any UPS this is typically stated as Total Harmonic Distortion (THD). The care are has to be taken when comparing different THD values as these can differ when contrasting the two different types of on-line UPS (transformer-based and transformer less) and also with regard to the percentage of load applied for each measurement.

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According to the above results obtained from this study, THD at point 2 (29 %) of building 14 does not guarantee with IEEE 519 standers (< 20%) this well cause to reduce the life time of the transformers and cables in building 14 .

12. References

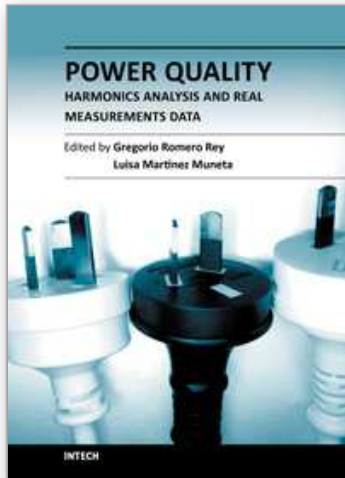
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Nowadays, the increasing use of power electronics equipment origins important distortions. The perfect AC power systems are a pure sinusoidal wave, both voltage and current, but the ever-increasing existence of non-linear loads modify the characteristics of voltage and current from the ideal sinusoidal wave. This deviation from the ideal wave is reflected by the harmonics and, although its effects vary depending on the type of load, it affects the efficiency of an electrical system and can cause considerable damage to the systems and infrastructures. Ensuring optimal power quality after a good design and devices means productivity, efficiency, competitiveness and profitability. Nevertheless, nobody can assure the optimal power quality when there is a good design if the correct testing and working process from the obtained data is not properly assured at every instant; this entails processing the real data correctly. In this book the reader will be introduced to the harmonics analysis from the real measurement data and to the study of different industrial environments and electronic devices.

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