INVESTIGATIONS OF POWER QUALITY PROBLEMS IN MODERN BUILDINGS

A thesis presented for the degree of Master of Philosophy

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ABSTRACT

This thesis presents the results of measurements made in a typical office building (Tower A) and a Residential building (Kilmorey Hall), all located in the campus of Brunel University, West London for period of one week. The collected data were statistically treated to establish the best period that characterizes the harmonic distortions and other disturbances in these buildings. The chosen period was considered as best to get the correct harmonic distortions in the day, and at a specific interval. One phase was also chosen to represent the others after some considerations.

The frequency of measurement was also noted. All the data collected were evaluated based on the limits proposed by International Standards: European, IEEE, and G4/5 Recommendations. Comparisons of the collected data were made between these two buildings. For the purpose of this project, the statistical treatment of the collected data characterizing the voltage harmonics was considered. The period of 9am to 5pm on a week day (Tuesday 26th October) was best for Tower A as it had the highest loading pattern for the week. This is a day-load establishment, because it is an office building. The period for Kilmorey Hall was Monday 1st November between the hours of 6pm up to 11pm, being considered as wholly residential building. All readings were spaced at 8minutes interval for frequency of measurement.

The methodology presented in this project is useful for quantification and qualification of the harmonic distortion of voltage and current. 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, both industrially and commercially [20]. Non- linear load is steadily increasing in residential areas also. 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 overconsumption. This could not be helping to reduce carbon emission.

Effects of Compact Fluorescent Lamps with electronic gears (CFLs) were also investigated as a rising source of harmonic production in Modern buildings.

ACKNOWLEGEMENTS

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CONTENTS

ABBREVIATIONS

AC	Current Alternating
PQ	Power Quality
THD	Total Harmonic Distortion
THDV	Voltage Total Harmonic Distortion
THDI	Current Total Harmonic Distortion
MV	Medium Voltage
PCC	Point of Common Coupling
LV	Low Voltage
CFLs	Compact Fluorescent Lamps
ASD	Adjustable Speed Drive
ATM	Automated Tele Machine
V_{rms}	Single phase supply voltage
RMS	Root Mean Square
U_{rms}	Three phase supply voltage
UPS	Uninterrupted Power Supply
PF_{true}	True Power Factor

PF	Power Factor
PFC	Power Factor Correction
PF_{disp}	Displacement Power Factor
PF_{dist}	Distortion Power Factor
DG	Distributed Generation
KVAR	Reactive Power
SMPS	Switch Mode Power Supply
EPRI	Electric Power Research Institute
IEEE	Institute of Electrical Electronic Engineering
IEC	International Electrotechnical Engineering
ANSI	American National Standards Institute
NEMA	National Electrical Manufacturers' Association
µs	microsecond
ns	nanosecond
ms	millisecond
sec	second
p.u.	per unit values
f	frequencies
f_1	fundamental frequency (50Hzs)

Chapter 1

Introduction

1.1 Overview

Almost all modern commercial buildings take their supplies at 415 volts from the secondary of the delta/ star connected 11kV/415V transformers. In recent years a large number of distorting, non-linear load 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. Although modern non-linear loads such as computer equipments are small in size (power consumption), but they are large in number. For example a 3 floor building could have as many as 300 PCs. Also the close proximity of many of these commercial buildings (Hotels, offices, departmental stores, shopping centres, and hospitals) will definitely contribute to the distortion of the electric power quality of feeder which supplies these buildings.

1.2 Why is the concern about electric power quality?

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]. Another important issue is that the electric utility is concerned about power quality issues because meeting customer expectations and maintaining customer confidence are strong motivators in particularly with the movement toward deregulation and the fierce competition between utilities.

1.3 The Main aim and objectives of this research work

With such high cost of poor power quality as shown in section 1.2, 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 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 research work is to look at the power quality problems in modern commercial 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 install correction devices could be clearly made.

In order to achieve this main aim, the following objectives are followed:

- Understanding the power quality terminology; this is covered in the literature review in chapter 2.

- Two case studies are introduced in chapters 3 and 4. The data of the power quality in a typical office building were measured and analysed in chapter 3. Some statistical investigations applied to these data are analysed. Chapter 4 contains measurements and analysis of a residential university building. The two case studies give a balance picture of power quality in modern buildings, or to be more precise, in buildings with modern loads.

- The characterisation of the data analysed in chapters 3 and 4 is presented in chapter 5 with some recommendations.

- The conclusions and future work are presented in chapter 6.

Chapter Two

Literature Review

2.1 Power Quality Problems Overview

Power is the product of voltage and current. The grid system has control over the voltage quality only and not on the current that a customer demands. The monitoring of Electric Power Quality has become an important tool to detect problems affecting electrical installation and equipments alike. Effective power quality monitoring can prevent future problems that could cause damage of equipments or premature aging of the electrical parts like transformers, circuit breakers and the wiring cables. Therefore, power quality standards concern the supply voltage being maintained within certain limits only from the Utility point of view. AC power systems are designed to operate at a sinusoidal voltage of 50Hz or 60Hz. The power frequency in Europe is 50Hz and it is 60Hz in America. Frequency variations are very rare in modern interconnected systems, but are more likely in isolated generation where the generator's governor cannot respond as quickly to the load variations. Any unacceptable deviation in the waveform magnitude, frequency or purity is regarded as a power quality problem. The current is the real vital component (since power is a product of voltage and current), there is need to address problems of current when considering power quality problems, since the voltage is usually dictated by Utility system which is beyond the control of the end-user. Poor Power Quality leads to increased electricity consumption and equipment failure. Symptoms like equipment overheating may be due to different causes like harmonics, unbalance, and overloading apart from consistent overvoltage. Focus is now on efficient operations, and reducing energy costs, which is the reason for Renewable Energy; Power Quality should be treated with the greatest attention. This chapter deals with the different types of power quality problems as they affect modern commercial buildings. There are two types of PQ variations, Disturbances and Steady State Characteristics.

2.2 Types of Power Quality Problems (Voltage Variations)

Power quality is not about harmonic only, but is about the distortion to the supply voltage and its effects on the equipment connected to it either directly or indirectly. Variation in supply voltage at the PCC is very important and critical for a consumer. There are many types of problems (disturbances) which may affect the power quality. Some of these problems are severe but rare while others could be not that critical however they are more frequent. Among the electric power quality problems, the following are distinguished: transients, harmonics, sags, swells, flicker, unbalances notches, frequency variations and high-frequency noise. Some of these power quality problems are investigated in more depth showing causes and effects of such problems and some recommendations on how to reduce/eliminate them. Variations in supply voltage outside the set limits of ± 10% are subdivided into their variation lengths as indicated in Fig. 2.1 [11].

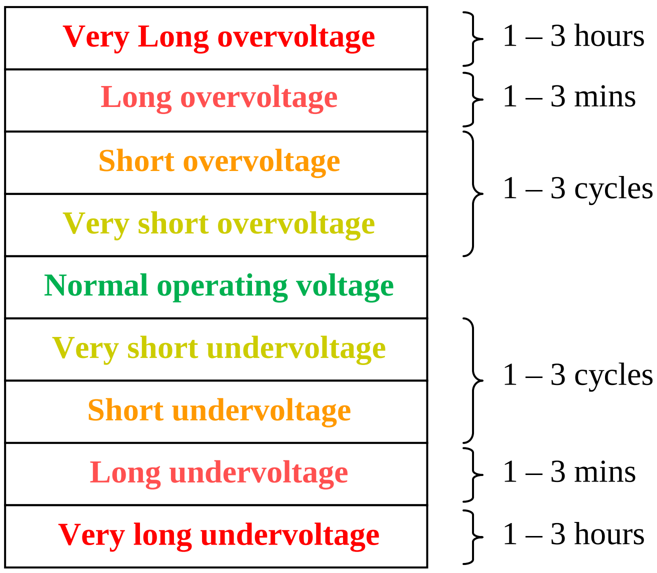
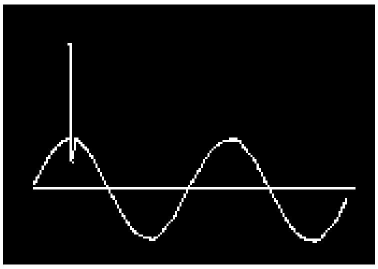


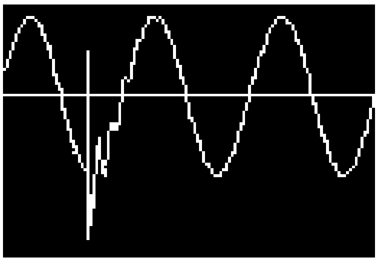
Fig. 2.1 Magnitude-duration for classification of PQ events

2.2.1 Transients

Transients are sudden and short duration disturbances which are caused by a very rapid change in the steady-state condition of voltage, current, or both, that could be unidirectional in polarity and is called impulsive transient (Fig. 2.2-a) or it could include positive and negative polarity values and this is called oscillatory transient (Fig. 2.2-b). Transients can be seen as extreme voltages which can last for very short time, usually less than 50 milliseconds [20], but are capable of causing serious damage to sensitive electronic equipments. Causes of transients include any type of switching activity which involves excessive arcing, for example, electric motors with starter contactor or closed contacts with open gaps. Transients are grouped into two types, impulsive and oscillatory reflecting the waveshape of the current or the voltage. They differ in spectral and duration.



(a) Impulsive transient



(b) Oscillatory transient

Fig. 2.2 Types of transients in voltage waveforms

Impulsive transient is usually unidirectional, sudden waveform change in the steady state of voltage and lasts for less than 3 cycles (60 milliseconds). The rise in magnitude from zero to peak value is in the order of 1.0μs and the decay duration of less than 6ms. Impulsive transient is usually expressed as, say, 1.3 × 70-μs, 4000V, where 1.3μs represents the rise time, 70μs denotes the decay time from peak to half of its peak and 4000V is the peak of its magnitude in volts. Impulsive transients (lightning) usually lead to high frequency oscillatory transients of the power system with time [9].

Oscillatory transient is the swinging of the voltage or current or both to the positive and negative magnitudes at high frequencies. Capacitor switching produces low frequency oscillatory transients in the distribution system. Ferroresonance and transformer energisation also produce oscillatory transient variations.

Typical values of impulsive and oscillatory transients are shown in Table 2.1. It can also be seen from this table that impulsive transient can occur in nano, micro, or milli-seconds, while the oscillatory transient can be in the form of low, medium or high frequency. The amplitude of the oscillatory transient is usually measured as a per unit (p.u) of the nominal voltage value, while the amplitude of the impulsive is given as a direct rms voltage or current.

(1) Impulsive	Typical Spectral Content	Typical Duration	Typical Voltage Magnitude
(a) Nanosecond (b) Microsecond (c) millisecond	5ns rise 1μs rise 0.1ms rise	< 50 ns 50ns – 1ms > 1ms	In rms voltage or current at power frequency
(2) **Oscillatory** (a) Low (b) Medium (c) High frequency	 < 5kHz 5 – 500kHz 0.5 – 5MHz	 0.3 – 50ms 20μs 5μs	 0 – 4pu 0 – 8pu 0 – 4pu

Table 2.1 Transient Categorization (1) Impulsive and (2) Oscillatory

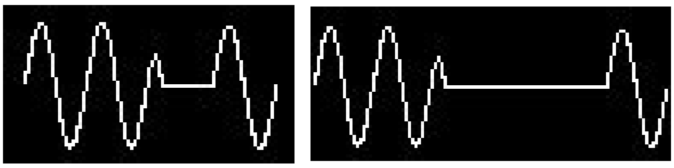
2.2.2 Short-Duration Voltage Variations

Short duration interruptions are less than 1minute, while Long duration interruptions are longer than 1minute. There are three types of short-duration variations, Instantaneous (0.5-30cycles), momentary (30cycles-2seconds), and temporary (2senconds-2minutes) as defined by IEEE-1159 [9]. Other Institutions call these types of variations ‘voltage dips’ and ‘short interruptions.’ Each of the three types is subdivided into ‘interruption’, ‘sag’ and ‘swell.’ Causes of short-duration voltage variations could include loose connections, faults and load switching [11]. All the three types are further subdivided into interruption, sag and swell, usually in the duration domain and magnitudes. Table 2.2 shows the duration of the interruption, sags and swells and how they are classified as instantaneous, momentary and temporary. In general sag can be classified as any amplitude between 0.1 and 0.9 p.u., less than 0.1 p.u is known as interruption and more than 1.1 p.u is classified as swell.

	(a) Interruption	**(b) Sag**	**(c) Swell**
Instantaneous	0.5 – 30cycles < 0.1pu	0.5 – 30cycles 0.1 – 0.9pu	0.5 – 30cycles 1.1 – 1.8pu
Momentary	0.5 – 3secs <0.1pu	30 cycles – 3secs 0.1 – 0.9pu	30 cycles – 3secs 1.1 – 1.4pu
Temporary	3secs – 1min <0.1pu	3secs – 1min 0.1 – 0.9pu	3secs – 1min 1.1 – 1.2pu

Table 2.2 Types of short duration variation

2.2.2.1 Interruption



(a) Very short interruption (b) Temporary interruption

Fig. 2.3 Interruption waveform

Interruption could be for short period (either very short or temporary), or could be for a longer period which is discussed in section 2.2.3. Fig. 2.3 shows a very short and temporary interruptions which could last for any period up to 3 seconds (very short interruption) or up to 60 seconds (temporary). Causes of very short or temporary interruptions include temporary faults that last for a short time and these usually result in computer and other electronic equipment shutting down.

2.2.2.2 Sag waveform

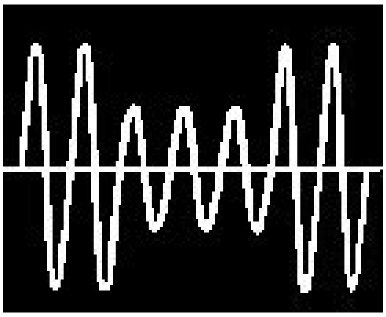


Fig. 2.4 Sag waveform

Sag is a reduction of voltage waveform at power frequency, which could be instantaneous, momentary or temporary; lasting between 0.5 cycles to 1min with a reduction in amplitude between 0.1 and 0.9 pu in rms voltage or current at the power frequency. Fig. 2.4 shows a typical sag in a voltage waveform which lasts for about 4 cycles. Sags are caused by so many factors such as loose wiring, starting heavy line loads, etc. Typical causes of sags in commercial buildings include starting up motors for lifts, and photocopiers. Sags could cause equipment tripping, dimming of lights, VDU shrinking, memory loss and data errors in the CPU of PCs. The effects of sags could be corrected by the use of power conditioners, UPS systems and voltage regulators.

2.2.2.3 Swells

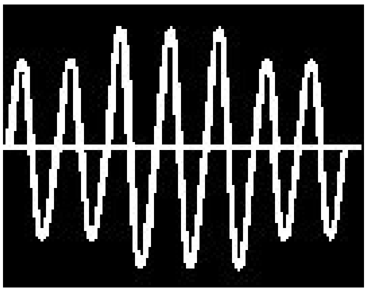


Fig 2.5 Swell waveform

Swell is the opposite of sag which is an increase of the ac voltage between 1.1 and 1.8 pu in rms voltage or current at the power frequency for duration from 0.5 cycles to 1 min. Swell can also last between 0.5 cycles to 1minute as shown in Fig. 2.5. Causes include single line to ground faults; loose wiring, sudden large load dropping, and inrush current are other forms of causes of swell. Problems caused by swell are very few, but if prolonged it becomes over-voltage. Equipment damage results if voltage rises above 6 to 10% of the normal voltage, affecting motors electronic loads, transformers and florescent lights over-humming. Lighting becomes over – bright, VDU display shrinks and data errors results. Sensitive equipments could equally shutdown. Solutions to swells also could include the use of power conditioners, UPS systems and voltage regulators.

2.2.3 Long – Duration Voltage Variations – Steady State Variations

There are three types of long duration voltage variations as classified by IEEE and IEC [25]. They are sustained interruption, undervoltages and overvoltage. The IEEE regards any interruption longer than 1minute as long duration, while the IEC takes it to be 3minutes. Mostly all long duration variations are caused by system switching operations. Two of the most common PQ standards in use today are EN 50160 [16] and IEC 61000-4 [13],

2.2.3.1 Long Duration (sustained) Interruption

Long duration interruption could last for longer than 1 minute and is usually referred to as blackout as the one shown in Fig. 2.6. When temporary interruption lasts more than 1minute to several hours it is called sustained interruption or outage or blackout. In this case the per-unit (p.u.) value of the voltage amplitude falls to zero. Uninterruptible Power Supply (UPS) and other static switches are good remedies for long duration interruptions, but these remedies are also sources of poor power quality in office buildings.

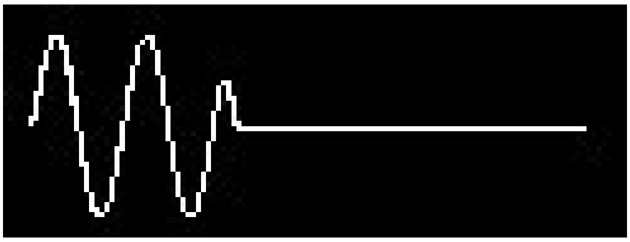


Fig.2.6 Long duration interruption

Long or sustained interruption occurs when the system fails to return automatically after interruption until it is helped by external means, for example, circuit breakers. This type of interruption is caused by forced or planned outages in the system.

2.2.3.2 Undervoltages

Undervoltage is the result of voltage reducing to 0.8 - 0.9 p.u. for more than 1minute as shown in Fig. 2.7.

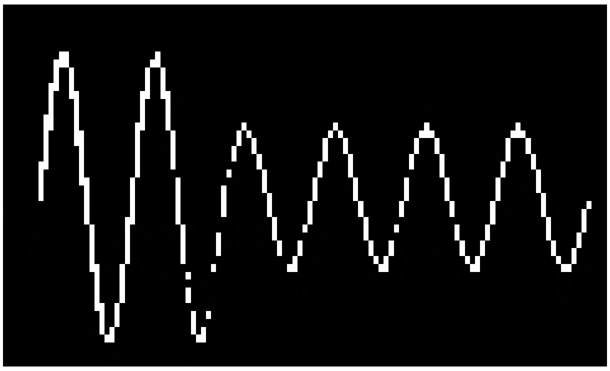


Fig. 2.7 Long-duration undervoltage.

Equipment malfunction are the usual causes of undervoltages. Prolong undervoltage can cause excessive wear on some equipments, such as motors. Undervoltage produces overcurrent which causes high losses. Utilities are usually the main cause of undervoltage, beyond the end-users' control. Causes of undervoltages include load switching on, capacitor switching off, system voltage regulation, overloaded circuits and lengthy distribution lines. Utilities try to maintain the customers' voltage at ± 5% of the supply voltage. There are always some drops in the nominal voltage as soon as loads increase, but as long as they are within the set acceptable limits, the customer has no complaints. Another source of undervoltages may be due to how far the customer is from the source of supply. Customers at the tail-end of very long distribution lines have perennial undervoltages.

2.2.3.3 Overvoltage

Overvoltage is caused by the R.M.S. voltage increasing to 1.1 – 1.2 p.u. in magnitude and is sustained for more than 1 minute. Fig. 2.8 shows such waveform. This condition may be as a result of lightning, capacitor switching on or off, or insulation failure. Overvoltage can be dangerous to both equipments and human. Overvoltage can be transient, called voltage spike, or may be permanent leading to power surge. It causes insulation breakdown, leading to short-circuits and eventual fire. Lightning causes overvoltage which is transient in nature. Voltage Spikes are caused by switching on and off heavy resistive or inductive loads. Overvoltage protection relay and zener diode are used to prevent dangerous overvoltage [16, 17]. Arcing horns and spark gaps are used to protect high voltage transformers and breakers in substations from hazardous effects of overvoltage. Gas filled tubes and surge suppressors operate on the same principle. Other Steady State Variations are discussed in the next section.

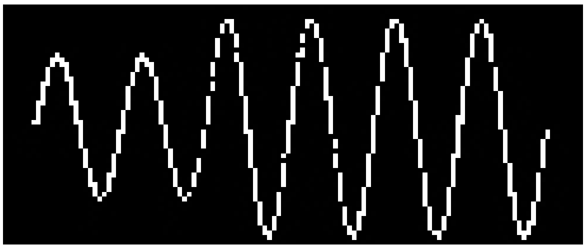


Fig. 2.8 Long Duration Overvoltage.

A comparison of the sustained interruption, undervoltage and overvoltage in terms of the duration and magnitude is summarised in table 2.3.

Type	Typical Duration	Magnitude
Sustained Interruption	> 1min	0.0pu
Undervoltages	> 1min	0.8 – 0.9pu
Overvoltages	> 1min	1.1 – 1.2pu

Table 2.3 Different types of steady- state voltage variations

2.2.4 Other Steady State Waveform Variations

2.2.4.1 Harmonics

Harmonics are made up of sinusoidal wave shapes but have different frequencies which are higher in amplitudes in comparison to the ‘fundamental’ frequency (50Hzs). The fundamental frequency is generated by all electrical utilities and this is what carries all useful power. Harmonic distortion is measured using a term called Total Harmonic Distortion (THD) of current or voltage. This gives an indication of how much distortion is present in terms of a percentage of the fundamental.

The worst waveform distortions are the Harmonics. Other forms are, Interharmonics, Notching, Noise, and DC offset. The way harmonics interfere with networks need be studied to avoid dangerous resonant frequencies with power factor correction capacitors in the network. Increased losses are also noted when harmonic currents flow in the network, which makes equipments to age faster due to insulation breakdown. Harmonic currents usually lead to voltage harmonics because of system impedances as V= iR and since current does no useful work it only leads to losses. Power factor deteriorates when harmonics are present because apparent power increases while the real useful power remains constant. Interference with control and communication systems is likely. The voltage and current quality in the steady state are determined by the different harmonics present. The sources of harmonic currents are increasing as non-linear equipments are varied and wide- spread. [35]

Harmonics formation is the summation of many frequency waveforms, Fig. 2.9 is made up of three frequencies but may contain up to 50 frequencies or more, for example, the International Standards EN50160 frequency measurement stops at 40^{th} harmonic level. All these frequencies are the odd-multiples of the fundamental as the even harmonics do not exist because they cancel out because of the natural symmetry of the ac system, except when there is a dc offset.

Each of these harmonic frequencies is sinusoidal in waveform having different cycles per second, but their summation is not sinusoidal but periodic.

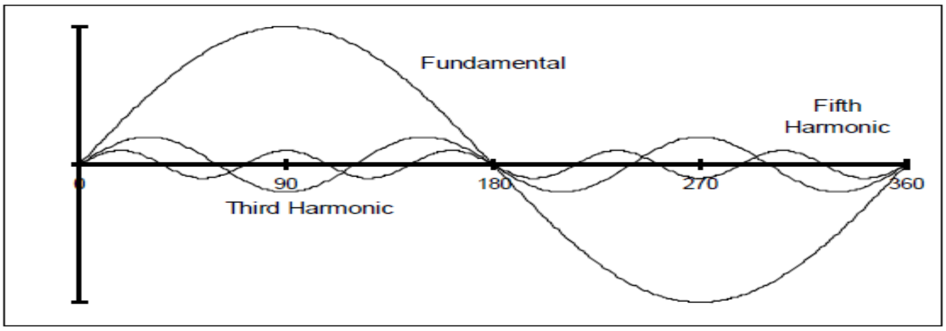


Fig. 2.9 Waveforms showing the fundamental, 3rd & 5th harmonics [48]

Most recently, non-linear loads are designed to have low distortion values. Harmonic current sources are these non-linear loads and their limit is based on the type and size of the load with respect to the source to which they are connected.

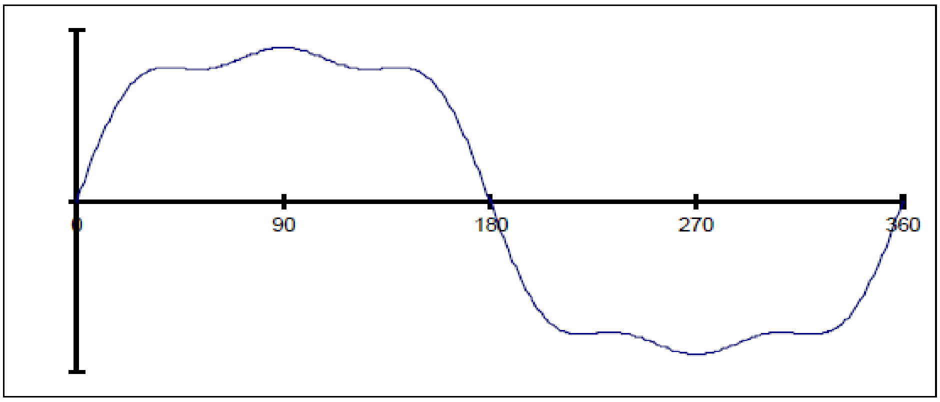


Fig. 2.10 Summation of the harmonic frequencies [48].

The sum of the harmonic frequencies, fundamental, 3rd and 5th are shown in Fig. 2.10. This is a distorted waveform and any equipment that are sensitive to distorted waveform will malfunction. The summation of the harmonic frequencies originate from the currents drawn by the non-linear load which are non sinusoidal but periodic, but the fundamental frequency is generated by the Utility (suppplier). It is this fundamental that carries all the useful power. Each harmonic waveshape is sinusoidal, having different frequency and amplitudes in comparison to the fundamental frequency (50Hz) but the summation is not. Harmonic distortion is measured, using the term known as Total Harmonic Distortion (THD) of current and voltage. This gives an indication of how much distortion is present in terms of a percentage of the fundamental.

2.2.4.2 Origin of Harmonics

The main cause of harmonics is the non-linear loads in the user's premises. The current waveshape is not sinusoidal like the supplied voltage, but periodic (Fig. 2.10). The usual element in the non-linear load is the power rectifier, which pulls current in sharp, irregular (non-linear) pulses instead of smooth linear way [33] [35]. The computer is a typical example of harmonic generator, and the computers are increasing in leaps and bonds in mordern office buildings. Other sources include fax machines, photocopiers and laser printers. All these equipments contain switch mode power supplies (SMPS) whose mode of operation entails drawing currents in pulses. Fig 2.11 shows a typical current waveform drawn by a computer power supply. A new source of harmonic generator is the Compact Fluorescent Lamps (CFLs) with electronic gear which illuminate offices better than other lamps, consumes less energy and cheaper to purchase.

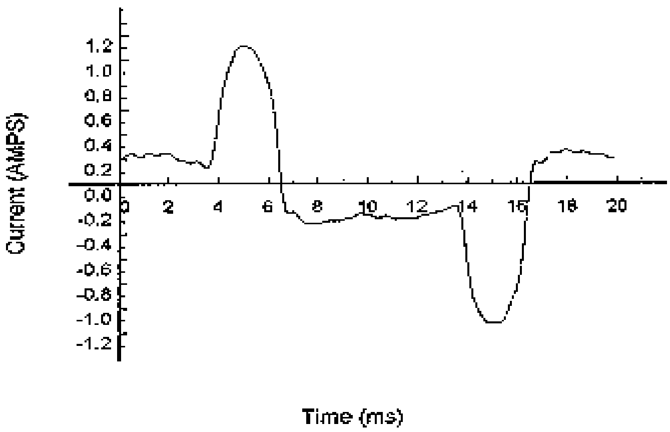


Fig. 2.11 A typical input current to a computer power supply

2.2.4.3 Effect of Compact Fluorescent Lamps (CFLs)

A well lit Modern building should be discussed at this stage. One of the major power quality problems of a modern building is the use of CFLs. The effect of other big non-linear loads has been well studied over a long time. CFLs with electronic gear are new on the scene of harmonic generators characterised by extremely distorted current with high THDI. They cause a significant distortion in electrical installations, when large quantities are installed in Commercial buildings. Their maximum permissible share of the total installed load in commercial establishment must be characterised to follow International Standards. Their maximum permissible share should not exceed the 10% limit as laid down by the International Standards. [36]. Therefore the quantity of CFLs would be restricted or the use of filters must be adopted. It is a well known fact that CFLs are long-lasting and they consume less energy than incandescent lamps with equivalent luminous output. The greatest problem that they cause for the network is voltage distortion, when used as a major source of illumination in Commercial establishments. The summation of the effect of CFLs in large group of residential homes, connected to an 11kv feeder could cause THDV higher than the accepted level of 6.5% [36]. This could be another future case study.

Generally, IEEE – 519 recommends the limits of 5% to 20% maximum harmonic distortion in % of the load current. The size of the harmonic load to the total load should be determined periodically to make sure that the International Standards are not transgressed [10, 35].

The International Electrotechnical Commission IEC 555-2 sets the highest limits on current harmonic distortion generated by equipment connected to the public supply system at 5%. [15, 32]

Power factor correction capacitors are not designed to reduce harmonic distortion. Usually specifically designed harmonic passive or/and active filters are used. The presence of high harmonic currents, in particular, the 3rd harmonic causes current increase in the neutral wire (in star connection). This could result in neutral conductor overheating if it is not sized properly. [35]

International Standards protect the Utilities, giving the limits that harmonic currents produced by the customers can be imposed on the supply. IEC 61000-3-2 [28] provides the maximum allowable limits of harmonic currents that equipment can draw with the input current.

2.2.5 Flicker

Flicker is a systematic variation of the voltage envelope as shown in Fig. 2.12. It can also be seen as a series of random voltage changes. Flicker is a type of voltage variation at the load-end, the input to a building, brought about by the rapidly fluctuating active and reactive load of the system outside of the building. Flicker is always between the ± 10% of the input nominal voltage [38].

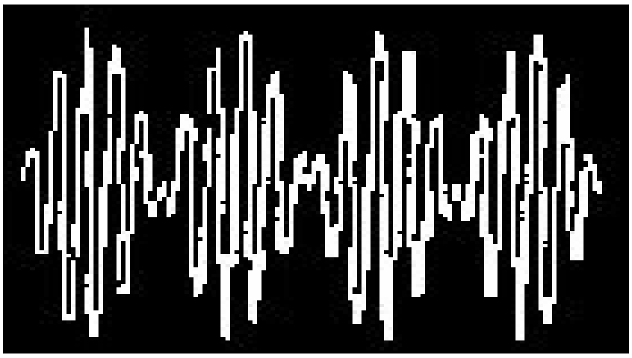


Fig. 2.12 Voltage fluctuation Flicker

There are two types of flicker, Short-term flicker (Pst) and Long-term flicker (Plt) usually differentiated by the severity and their durations. The voltage variations are caused by the instantaneous voltage drops across the resistance and the reactance of the circuitry. Usually, the equivalent resistance of the line is negligible when compared with the reactance [38 - 39].

The activation of arc furnaces, large induction machines and other large loads that produce continuous voltage impulses are the causes of the flicker. Typically, flicker occurs on systems that are overloaded, combined with considerable variations in current occurring over a short period of time.

2.3 Power Quality Problems (disturbances and steady state variation).

Most of the Power Quality problems are caused by the current waveform. Distortion in current waveforms is manifested in the quality of the voltage waveforms and as a result this causes a power quality problem. To investigate the problems of power quality, either for new design or existing system, it is necessary to evaluate the problems in the following general formation.

2.3.1 Categorising some of the power quality problems

In order to categorise a specific power quality problems the following three steps are taken:

(a) Identifying the type of problems

i. Voltage Regulation/Unbalance
ii. Voltage Sags/Interruptions
iii. Flicker
iv. Transients
v. Harmonic Distortion

(b) Problem characterization

i. Measurements/Data Collection
ii. Causes
iii. Characteristics
iv. Equipment Impacts

(c) Identify the type of solutions

i. Utility Transmission System
ii. Utility Distribution System
iii. End-Use Customer Interface
iv. End-Use Customer System
v. Equipment/Design Specifications

2.3.2 International characteristics for voltage control

The International characteristics for voltage control are a set of guidance for suppliers, consumers and manufacturers. Tables 2.4 and 2.5 refer to some of these international standards, the types of voltage variation categories, the method of characterization, the probable causes and the suggested power conditioning solutions [17, 37]

No	**Parameter**	**Supply voltage characteristics according to EN 50160**	**Low voltage characteristics according to EMC standard EN 61000**	
			EN 61000-2-2	Other parts
1	Power frequency	LV, MV: mean value of fundamental measured over 10secs. ±1% (49.5 – 50.5 Hz) for 99.5% of week -6% to + 4%(47-52Hz)for 100% of week	2%	
2	Voltage magnitude variations	LV, MV: ±10% for 95% of the week, mean 10 minutes RMS values		±10% applied for 15 minutes
3	Rapid voltage changes	LV: 5% normal; 10% infrequently Plt ≤ 1 for 95% of week MV: 4% normal 6% infrequently Plt ≤ for 95% of week	3% normal 8% infrequently Pst ≤ 1.0 Plt < 0.8	3% normal 4% maximum Pst ≤ 1.0 Plt < 0.65 (EN61000-3-3) 3% (IEC 61000-2-12)
4	Supply voltage dips	Majority: duration < 1s, depth < 60% Locally limited dips caused by load switching on: LV: 10 – 50%, MV: 10 – 15%	Urban: 1 – 4 months	up to 30% (10ms) up to 60% 100ms EN61000-6-1,6-2 Up to 60% 1000m EN 61000-6-2
5	Short interruptions of supply voltage	LV, MV: (up to 3 minutes) few tens to few hundred/year. Duration 70% of them < 1s		95% reduction for 5s EN61000-6-1, 6-2
6	Long interruption of supply voltage	LV, MV: (longer than 3 minutes) < 10 – 50/year.		
7	Temporary; power frequency overvoltages	LV: < 1.5 kV rms MV: 1.7 Uc (solid or impedance earth) 2.0 Uc (unearth resonance earth		
8	Transient overvoltages	LV: generally < 6kV, occasionally higher rise time: ms to µs. MV: not defined		±2kV, line – earth ±1kV, line – line 1.2/50(8/20) Tr/Th(µs) EN61000-6-1, 6-2
9	Supply voltage unbalance	LV, MV: up to 2% for95% of week, mean 10minutes rms values, up to 3% in some locations	2%	2% IE C61000-2-12
10	Harmonic voltage	LV, MV:	6% for 5_{th} 5% for 7^{th} 3.5% for 11^{th} 3% for 13^{th} THD < 8%	5% for 3_{th} 6% for 5^{th} 5% for 7^{th} 1.5% for 9^{th} 3.5% for 11^{th} 3% for 13^{th} 0.3% for 15^{th} 2% for 17^{th} EN 61000-3-2
11	Interharmonic voltage	LV, MV: under consideration	0.2%	

Table 2.4: Comparison of supply voltage requirements according to EN 50160[37]

2.3.3 Effects of Harmonics in Modern Buildings

Almost all Modern buildings have non – linear loads which are of the following types:

a) Fluorescent lights (CFLs with magnetic and electronic ballasts).

b) Computer power supplies with Switched Mode Power Supply (SMPS).

c) Variable speed drives as in HVAC.

d) UPS.

One of the major power quality problems in Modern Buildings is the harmonics which could take the form of current and/or voltage harmonics. Usually harmonic currents are generated by the non - linear loads connected to the system which invariably lead to voltage harmonics in the system. Majority of harmonic problems affecting a building are generated within the building. But neighbouring buildings with substantial harmonic generation can affect the harmonics of the building under consideration, hence the formulation of power quality standards evolved.

Symptoms of harmonic voltage distortions in modern buildings include:

1) Transformers may overheat without necessarily being overloaded.

2) Cables may get too hot and insulation can breakdown.

3) Induction motors may get too hot and become noisy.

4) Capacitors can overheat or form tuned circuits that resonate.

5) Circuit breakers can trip and fuses blow unnecessarily and incessantly.

6) Computers fail.

7) Metering may give false readings.

8) Electronic displays and lighting may flicker.

All these voltage distortions cause accelerated equipment ageing and metering error over a long period of high accumulated harmonic levels. Other forms of malfunctioning of sensitive electronics equipments could be caused by short bursts voltage waveforms. As mentioned earlier, power quality problems caused by an end – user can adversely affect another end – user. In order to prevent this and to set standards for sensitive electronic equipments, International Standards were set up to which power suppliers, end-users and manufacturers have to comply.

2.4 An Overview of International Power Quality Standards.

International Power Quality Standards were set up to give guidelines, and have been adopted in Europe USA and other parts of the world; the advent of deregulation which produces the 'buyers' market' climate has intensified the application of the International Standards.

Interpretation of power quality recommendations from different International guidelines has become problematic, even local benchmarking could become problematic. The methodologies employed by each Standard for the same problem mitigation differ widely. This overview tries to give comparative overview of harmonic limits in different International Standards.

Voltage quality is an indication of the quality of the supply system dictated by the supplier and the user alone controls the current consumed. Harmonic distortion is considered to be the most problematic in recent years that has taken the attention of power quality engineers because of the ever-increasing non-linear loads added to the system. These harmonic problems have led to the development of standards that Utilities and End-users are involved in the mitigation processes. The Utility is responsible for the supplied voltage, while the end-user is to control the level of harmonic currents produced from the loads into the Utility network. Differences are noticed in the ways harmonics have been treated by International Standards guidelines to minimize the harmonic effects. These guidelines have caused misinterpretations and misquotations of these standards in their specifications.

Attempts are made in this section to examine and compare the differences and similarity of the widely accepted International harmonic standards such as:

1) EN 50160 (appendix B3) [16, 24]

2) IEC 61000- 2- 2 and IEC 61000-2-4

3) IEEE 519-1992 [10]

4) ER G5/4-1

2.4.1 EN 50160

This standard covers flicker, inter-harmonics, voltage deviations and others as shown in Table 2.4 [37]. It specifies the voltage characteristics of electricity supplied by public distribution systems as input to buildings in Europe. Point of Common Coupling (PCC) is the reference point for measurement. Equipment manufacturers have also adopted the same standards to set the limits over which their equipment will operate a standard for voltage at the point of equipment connection. The complete characteristics covered by this standard are as shown in Appendix B_3. Moreover the THD of the supply voltage for all harmonics shall be less than or equal to 8%, with acceptance of 95% [Appendix B_3]. It is conventional to sum the harmonics to the 40^{th} harmonic when considering the frequency response that is 2500Hz. Detecting voltage transients require that the changes in voltage of less than one millisecond is required, therefore frequency response of at least 10 kHz is required.

2.4.2 IEC 61000-2-2; 61000-2-3; 61000-3-2 and 61000-3-4

The IEC 61000-2-2 and IEC 61000-2-3 are standards connected with the low voltage (LV) system harmonic limits.

The IEC 61000-3-2 (≤16A/phase), IEC 61000-3-4 (>16A/phase) and IEC 61000-3-12 (16A<current/phase≤75A) are different classes of standards that deal with different harmonic current levels injected by individual equipment into the public supply system. [50]

The different International Standards are compared in the following forms:

a) Scope, coverage and the maximum harmonic order (N) for respective standards.

b) Voltage distortion limits.

c) Current distortion limits.

d) Other measurement parameters (duration, h_{max}, and PCC)

2.4.3 Comparison of Different International Standards

Analyzers from different manufacturers should give the same results. The two most common PQ standards in use today are IEC 61000-4-30 and EN 50160. [49]

IEC 61000-4 sets accuracy levels, defines aggregation levels, provides measurement methods and measurement formulas are well defined.

EN 50160 provides recommended levels for different power quality parameters and the percentage of the time for which these levels must be complied with. The averaging period of 10 minutes and the 95% compliance are set for EN 50160.

2.4.3.1 Scope and coverage for respective standards.

The scope of the standards is summarized in table 2.5. The level for low voltage distribution systems is further examined in this thesis since almost all modern buildings take their supply at this level.

Standard	Area of Focus	Nominal Voltage /Nominal frequency	THD referred to Fundamental/RMS
IEEE Std 519	Non-linear loads in the supply system		$THD_{Fundamental}$ Limits applied at PCC
IEC 61000-2-2	Sets the Compatibility level for LV Distribution system	1-phase: < 420V 3-phase: < 690V Freq.: 50/60Hz	Limits applied at PCC
IEC 61000-2-4	Sets the Compatibility level for Industrial & Private distribution system	3-phase: < 35kV Freq.: 50/60Hz	PCC at the connection to the Industry or Private distribution system
EN 50160	A guide on limits for PQ both LV & MV Dist. System under steady state	LV: < 1kV MV: 1kV to 35kV Freq.: 50Hz	THD_{RMS}
ER G5/4-1	Sets the planning levels for THDV & harmonic current of non-linear loads		THD_{RMS}

Table 2.5: Scope and Coverage of Harmonic Distortions Limits for LV systems [50]

Total Harmonic Distortion (THD) is one measure of total distortion. It quantifies the thermal effect of all the harmonics. It is the RMS sum of the individual harmonics excluding the fundamental, divided by either the fundamental as used by IEEE in America, or the RMS value of the total waveform including the fundamental as used by IEC and Europe. Both definitions of THD are comparable for low harmonic frequency distortions but vary widely at high frequency harmonics.

$$I_{rms} = \sqrt{I_f^2 + 2_{nd}^2 + 3_{rd}^2 + 4_{th}^2 - - + N_{th}^2}$$

and

$$THD = \frac{\sqrt{2nd^2 + 3rd^2 + 4th^2 + 5th^2 + - - - + Nth^2}}{Irms}$$

The above definition is that of European Standards for THD. The American Standards substitutes the $I_f(I_{fundamental})$ for the I_{rms}

2.4.3.2 Evaluation of Voltage distortion

Voltage harmonic distortion could be evaluated by either using the individual voltage harmonic distortion limit, or by calculating the THD_V from the formula

$$THDv = \frac{\sqrt{\sum_{h=2}^{N} V_h^2}}{V_1}$$

or

$$THDVrms = \frac{\sqrt{\sum_{h=2}^{N} V_h^2}}{V_{rms}}$$

The total harmonic distortion THD can be referred to the fundamental quantity V_1 or the root-mean-square V_{rms}. The total harmonic distortion is defined as above with respect to maximum harmonic order 'N' listed in Table 2.6 for each standard.

Evaluation of voltage distortion can be expressed in two ways, either by individual voltage distortion or by total harmonic distortion (THDv). The THDv limits are shown in the table 2.6 using the respective harmonic limits for each standard. The IEEE 519 uses the fundamental frequency (V_1) as reference while EN 50160 and EG5/4-1 use the root-mean-square of the voltage (V_{rms}) as the reference. It should be noted that the two methods of calculating total harmonic distortions are correct and similar for small values harmonic frequencies, but not for high frequencies.

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 2.6: Comparison of Maximum harmonic level, THDv limits, & Measurement duration [50]

2.4.3.3 Evaluation of Current distortion

While the International Electrotechnical Commission (IEC) considers that controlling the limits of individual non-linear load will automatically control the total harmonic level of the summation of the system, the IEEE 519-1992 considers a single point of supply for multiple non-linear loads. The two indices for measuring harmonic content of a waveform are THD and TDD and they can be applied to either voltage or current. The IEEE 519-1992 uses the Total Demand Distortion (TDD) for calculations while the IEC uses the THDA only. THDA could be deceptive because at small currents, the THDA gives high value from its definition. The IEEE 519-1992 considers putting the current harmonic distortion limits on the customer on the basis of current distortion relative to the total load of the customer. The limits are for total customer-load and not for individual load, which makes the limits to vary depending on the ratio of short circuit current (I_{sc}) to the maximum demand load current (I_{demand}) at the PCC. Calculated values of the ratio (Isc/I_{demand}) have been made for different levels distortion [52] [Table B_{2a}]

$$\text{Ratio} = I_{sc}/I_{demand}$$

$$TDDI = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_{demand}}$$

The (h) is the Harmonic order and 'N_{th}'= 50^{th} which is taken as the maximum harmonic level considered for IEEE standard. The I_{sc} is calculated from the size of the installed transformer capacity of the customer. I_{demand} is equal to 15 or 30 minute (average) maximum demand load current at the fundamental frequency component measured at the PCC. I_{demand} is usually calculated by averaging the maximum demand current over 12-month peak demand readings. [10][51][17]

The Point of Common Coupling (PCC) as defined by IEEE is the point where a customer is tied to the Utility, where another user could also be connected, but with IEC and other standards in Europe, the PCC could be at the point of connection near the load.

2.5 Mitigation techniques of power systems harmonics

Certain types of equipments are used to reduce harmonic levels in some cases, while engineering designs are used mitigate the effects of other types as listed below:

1. Passive filters
2. Active harmonic filters
3. Hybrid harmonic filters
4. Installation of phase-shifting transformers
5. Installation of 18-pulse Variable Speed Drives (VSD)
6. Installation of line chokes (reactors) before the load
7. Installation of Drive Isolation Transformer (DIT)

The first three types will be explained in this thesis.

2.5.1 Passive Filters

The resonant shunt filter is made up of an LC branch with a frequency tuned to the frequency of the voltage harmonic to be eliminated. Fig. 2.13 is a set of passive filters designed to remove the 3^{rd}, 5^{th}, 7^{th}, and the 9^{th} harmonics (generally 5^{th} and 7^{th}). The respective resonant frequency f_r for each passive filter is equal to:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

At the specific resonant frequency f_r, the resonant shunt filter presents a low minimum impedance with respect to the resistance (R) of the reactor. Virtually all the harmonic currents (i_r) of frequency f_r injected by non-linear load are removed, and the corresponding low harmonic voltages are also removed since (v = iR). However, when the loads are not in operation, the passive filter becomes power factor correction capacitor if it is not completely isolated from the load. The passive filter then injects excessive reactive power (KVAR) causing voltage regulation problem to the network at light or no load. [43]

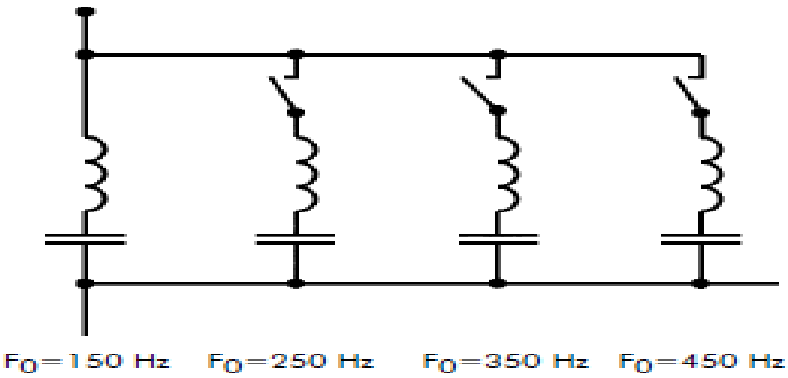


Fig. 2.13 Shunt resonant filter bank for removing specific harmonics (fo =f_r) [43]

2.5.2 Active Harmonic Filters

All active harmonic filters generate currents or voltages which are used to oppose the harmonics created by non-linear loads. There are different types of active harmonic filters, for example 'shunt' or parallel types and the series type, but the shunt types are the most commonly used. Assuming that the non-linear load produces the fundamental, the 3rd, 5th, 7th and the 9th harmonics as showed Fig. 2.14. The principle of Active filters is that the harmonics present are used to cancel themselves out. The current transformer (C.T) passes a sample of the distorted waveform to low pass filter, which removes the 50Hz fundamental component as this carries the useful power and passes the harmonics to the amplifier after inverting all the harmonics to the same value as the main line. The amplified current waveform is passed back to the main line through a transformer or an inductor (not shown in the diagram) through the magnetic flux only.

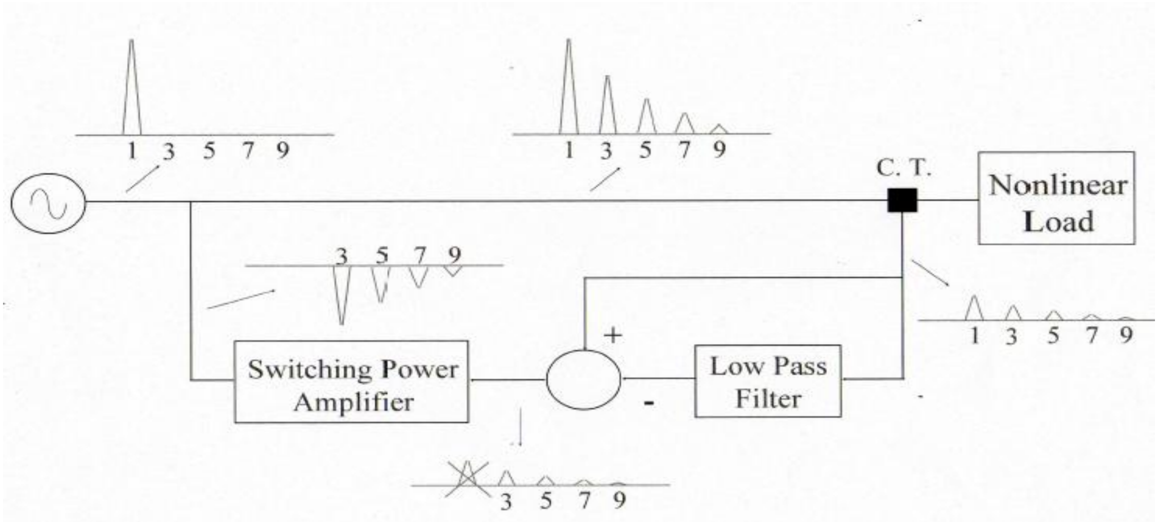


Fig. 2.14 Basic Idea of a Typical Active Filter with the frequency spectrum.

2.5.3 Hybrid 'Passive/Active' harmonic filters

The hybrid harmonic filter is a combination of passive and active harmonic filter where the passive filter part is tuned to the predominant harmonic frequency; this part supplies the requested reactive energy. The active component removes the other harmonic frequency waveforms; the combination provides the benefits over the individual filter. The installation must be designed in such a way to prevent interaction between the two different types of filters. [55], Figure 2.15 shows the harmonic filter principle where two passive filters (FP_1 and FP_2) are tuned to remove two different harmonic orders (5^{th} and 7^{th}), and the active harmonic filter part.

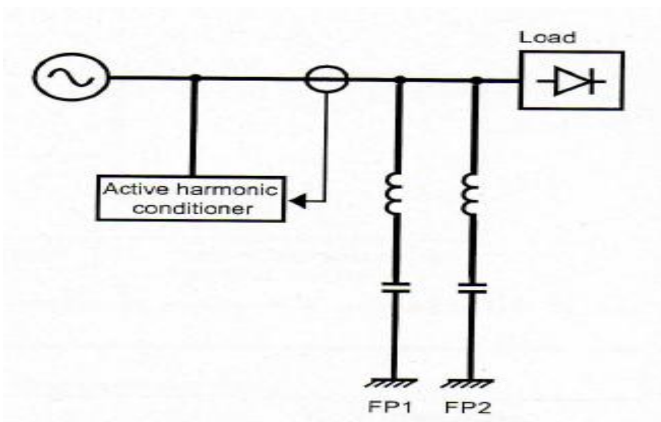


Fig. 2.15 Hybrid harmonic filter principle [55]

PQ Variation Category	Method of Characterisation	Type of Causes	Power Conditioning Solutions
Impulsive Transients	Peak magnitude Rise time Duration	Lightning Electrostatic discharge Load Switching	Surge Arresters Filters Isolation Transformers
Oscillatory Transients	Wave forms Peak magnitude Frequency Components	Line/Cable Switching Capacitor Switching Load Switching	Surge Arresters Filters Isolation Transformers
Sags/Swells Interruptions	RMS v Time Magnitude, Duration Duration	Remote System faults System Protection Mtc. (Breakers & Fuses)	Ferroresonant Transformers Energy Storage Technology(UPS/Standby supply Energy Storage Technology(UPS) Backup Generators
Undervoltages and Overvoltages	RMS v Time Statistics	Motor Starting Load variations	Voltage Regulators Ferroresonant Transformers
Harmonic Distortion Voltage Flicker	Harmonic Spectrum THD Statistics Variation Magnitude, Frequency of Occurrence, Modulation Frequency	Non-linear loads System Resonance Intermittent Loads, Motor Starting, Arc Furnaces	Filters(Active & Passive) Transformers(cancellation of zero sequence components Static Var Systems

Table 2.6 Summary of Power Quality Variation Categories (17)

2.6 Redefining types of Power Quality problems

2.6.1 Introduction

There is the necessity to reclassify the formerly known different categories of PQ problems because of the advent of distributed generation. Before the recent reclassification, all producers and consumers of electric power were guided by the same laws since the grid was uniform for all. With the advent of distributed generation (DG) where the grid is fragmented i.e. separated into different Utilities and Renewable Energy sources appear, the same type of power quality problem is called different names by manufacturers, different utilities and end users. DG is gradually taking over the functions of the unified grid, therefore a generalised set of laws and terminologies need be developed to govern all producers, manufacturers and end-users of electric power. All power electronic equipments installed to increase end-users' productivity are the major victims of power interruptions, and they are equally the source of additional power quality problems. Fully automated systems (controls and machines) depend on quality power. The usual reliability indices are no more applicable in the new system. New power quality indices must now take the place of generalised reliability indices; therefore redefinition is necessary which acts as the common laws to which all must comply with.

2.6.2 Electromagnetic Definitions of Power Quality problems

Power Quality can now be expressed in technical terms as Electromagnetic waves in the different domains [17]. Duration is normally used to identify the type of interruption. Causes of short-duration variations include loose connections, faults and load starting. Long or sustained interruption is an interruption that has to be restored manually for it to come back. These types of interruptions are caused by circuit breaker opening on fault. Technically, the 3 domains for identifying PQ problems are:-

1) Frequency domain (kHz or MHz)

2) Duration domain (ns, µs or ms) and

3) Magnitude domain(% or p.u values)

Power Quality problems are now classified into the following seven categories:

1) Transients, which can either be

   a. Impulsive, which is usually expressed in time domain of nano, micro or mini second and

   b. Oscillatory, which is normally expressed in domain of low, medium or high frequency

2) Short- Duration (interruption, sag or swell) (0.5 – 2minutes) which can be

   a. Instantaneous, (0.5 – 30 cycles)

   b. Momentary, (30 cycles – 2 seconds) or

   c. Temporary (2 seconds – 2minutes)

3) Long- Duration variation (> 1minute), which can be reclassified as

   a. Sustained Interruptions

   b. Undervoltages and

   c. Overvoltages

4) Steady State Voltage Unbalance

5) Steady-State Waveform Distortion, under which the following are grouped

   a. Harmonics

   b. Interharmonics

   c. Notching

   d. Noise and

   e. DC offset

6) Intermittent Voltage Fluctuations and

7) Variations of the Power Frequency from the fundamental frequency (50Hz)

When expressed in these three domains and categories, any power quality problem can be analysed and grouped in the classifications listed above [16, 17].

It could be seen that PQ problems are caused by the introduction and increased use of power electronics equipments in distribution networks and recently by Inverters and Converters.

Renewable Energy generation and transmission introduce more of Harmonics into the systems during their mode of operations; this is also a major PQ problem. These problems should be controlled at the source, the Utilities, the End-Users and the Manufacturers. The recent increase in non-linear loads at the Industrial and Residential levels cause abnormal increase in harmonic currents. Recently High-rise Commercial buildings are full of power electronic equipments, which are the main sources of their own power quality problems. This leads to losses of sensitive equipments and operating time. Therefore, measuring and analysing the PQ problems and mitigating techniques need be applied to these commercial buildings. These will be considered in the next part. Power Quality has become a major issue in today's electricity supply to both the power suppliers and the end-users. Power equipments have become more of power electronic devices, wide spread and still on the increase. All these devices have non-linear characteristics (drawing non-sinusoidal currents from sinusoidal voltage source and consequently affecting the source itself), which easily deteriorate power quality. IT devices, Adjustable speed drives and computes are notorious for their sensitivity to power quality because they suffer failure, mal-operation, or hardware damage during poor power quality events. But these same equipments are the major causes of power quality problems because of their non-linear characteristics.

The present day Industrial growth has witnessed massive increase in automation brought about by power-electronics equipments, for example adjustable speed drives (ASD) which cannot tolerate surges, spikes, over or under voltages and frequencies. Reliability is now in the order of sub-cycles in designing for zero down-time in service centres and industries. The suppliers, the end-users and the manufacturers of power-electronic equipments are all involved in the design. The quality and reliability of power supply have changed as civilisation tends towards power-electronics equipments. The facility manager working hard to prevent costly downtime at the load end, and the utility engineer whose work is to improve the quality of power supply at the sending end are continually looking for solutions to power quality problems. Poor power quality has bad effects on economic operations of industries because of unwanted down-time and resultant losses in production. The number of consumers with power quality sensitive processes is increasing, therefore the improvements in PQ for both the Medium Voltage (MV) and the Low Voltage (LV) grid is dependent on power electronic conversion technique. Tall modern (commercial) buildings, hospitals and ships have standby power supply, generators, which provide emergency power supply when the grid fails. These generators are subject to frequency variations which are absent in the grid. Such isolated generating systems can be characterised by the short distances between generators and loads. The major feature of the isolated generation is the 'weak grid', because the loads are usually big and ever increasing in comparison with the installed generator capacity. These situations give rise to a large voltage dip at the start of large induction loads. There is no 'infinite bus' situation, therefore the voltage and frequency cannot remain constant. The types of frequency deviations from 50HZs or 60HZs also have steady-state and non-steady-state character. The deviations should be within the limits of frequency deviations as laid down in IEC 60092-101 standard that governs such installations. The standard says that 'The long duration of frequency deviation should be less or equal to ±5% of the rated frequency, and the short duration of frequency deviation should be less or equal to ±10% of the rated frequency for isolated generation systems [22].

The economic growth of all developing countries is adversely affected by power quality problems. The commercial activities in these new mega cities are expanding at a fast rate, high rise buildings are springing up faster than envisaged. Electronic equipments multiply in all the banks and other commercial houses at a fast rate. These are major sources of harmonics, and other power quality problems such as voltage sags and short interruptions. Almost all the banks complain of incessant malfunctioning of their sensitive electronic equipments (ATMs) every day, giving rise to fraud and loss of customers' money. Almost all communication and electronic media problems usually referred to as 'Network problems' are caused by Power Quality problems. These problems have led to the special study conducted and analysed in the subsequent chapters. Power quality problems have been classified into two main groups, Steady State Variations and Disturbances. Disturbances require longer periods of monitoring, for example six months or more, but steady state variations can be conducted within a limited time frame of, say, one week. Values of voltages, currents, apparent power, active power, reactive power, voltage, transients and the Total Harmonic distortions (THDV and THDI) that form the steady state variations were taken and analysed.

2.7 Power Consumption in different types of loads

This section shows how the power consumption is dictated by both type of load and the supplied voltage.

2.7.1 Power Consumption in Passive Loads

Passive loads are resistive loads. Examples of this type of load are cookers, heaters, boilers and kettles, incandescent lights, etc, but not gas discharge (fluorescent) lights.

In this type of load the amount of power consumed (for a constant value of load) is directly proportional to (v^2). So an increase of, 10% in a supply voltage of 230V will result in an increase of power consumption of 21%, even where resistance varies or load is partially inductive or capacitive, this is still broadly true.

2.7.2 Power Consumption in Gas Discharge Lamp Loads

Examples of this type of load are fluorescent lights and high-pressure sodium lamps. Gas discharge lamps show a decrease in resistance with voltage. This is often called 'negative resistance'. It is particularly unstable, and additional components are required to limit the current. This may be a simple inductor, or may be a complex electronic circuit. While the behaviour of any one model of lamp can only be determined by measurement, the overall behaviour of a large number of gas discharge lamps is predictable. It is largely the same as for resistive loads. However, almost all designs suffer marked reduction in life with over voltage.

In this type of load the amount of power consumed (for a constant value of load) is directly proportional to (v^2). So an increase of, say, 10% in a supply voltage of 230V will result in an increase of power consumption of 21% as calculated below. The 10% increase brings the voltage to 253V

$$P = \frac{V^2}{R}$$

R is constant; therefore P is proportional to V^2

If 230V is the supply voltage, it is then regarded as 100% of supply voltage

When the upper voltage of 253V is considered, its % becomes

$$\frac{253^2}{230^2} \; x \; \frac{100}{1}$$

= 121%

This is 21% above the power consumed at 230V

The reverse is also true. If the supply voltage of 230V decreases by 10% to 207V, the consumption drops to 81% i.e. 19% lower than at supply voltage. However, the sensitivity of the load needs be considered.

2.7.3 Power Consumption in Electromagnetic Loads

Equipment with motors or transformers comes under this category. In this type of load the amount of power consumed in doing useful work is the primary factor in determining power demand and a small amount of over-voltage will result in only a slight increase in power consumption. Generally the power consumed is approximately proportional to (v). However, as voltage increases, the magnetic materials approach saturation, leading not only to increased losses in the iron core, but also to increased losses in the copper windings. At this point, the power consumption increases much more rapidly than (v^2). If the voltage rises to the level that causes saturation, the power consumed will continue to rise until catastrophic failure occurs. This applies regardless of the amount of useful work done.

Many types of mains driven motors are affected by over-voltage in another way: They commonly operate at a low percentage of full load (partly because they cannot start if the load exceeds 34% of their maximum capability). The power consumed increases with the voltage, even though there is no increase in useful work done. While they are very efficient at full load (over 90% is possible), typically, the efficiency at loads of less than 20% is very poor (under 50% is common), and most of the power drawn is attributable to losses. The power consumed by the losses increases with (v^2). In the special case of refrigeration and some types of air conditioning, additional cooling is required to cope with heat produced by over-voltage. This in turn causes increased power requirement leading to a vicious circle of decreasing efficiency. The power consumed increases more rapidly than with (v^2) for almost all levels of useful work done, and failure due to saturation is also possible.

2.7.4 Power Consumption in Active Loads

In this type of loads the amount of power consumed is delivered in response to the load demand. All types of electronic equipment or equipment with switch-mode power supplies come under this category. Examples of this type of load are computers, printers, fax machines, TV etc.

The power requirement of this type of load is the main factor in the value of the power consumed. The relationship between efficiency and applied voltage is determined by the design of the electronics. Although over-voltage results in a small increase of power consumption, other effects of over-voltage include the reduction in the lifespan of various components (e.g. capacitors). Most active loads have internal transformers which are susceptible to saturation (even if they are not operating at mains frequency), and high voltage transistors, whose losses increase with voltage faster than (v^2).

2.7.5 Summary of the Effects of Power Consumption in Different Types of Loads

There is no doubt that overvoltage will result in increased consumption of power; particularly in linear and non-linear loads (lights, heaters, office appliances, HVAC systems, computers, etc). Overvoltage decreases the lifespan of electronic component due to overheating of transformers at moderate loads and causes unnecessary excessive power consumption leading to overbilling. Overheating of conductors due to skin effect caused by harmonics at high frequencies for example 7th harmonic (350Hz) presents more reactance than the resistance of conductor. Considering the relationship between voltage level and power consumption, efforts must be made to look further than contributions of active and reactive power only, as far as the International standards indicate. It has been shown that voltage level increase can cause and do cause unwanted power consumption.

The voltage level dropping by 2% could cause power consumed to drop by as much as 3.96%. Continuous higher voltage than the normal voltage level supplied to the University could make the Institution to pay higher bills to the supply Utility. The unnecessary high increase in active and reactive power demand could be avoided.

A high tolerance for voltage level of the range of 5% as given by most International Institutions should not be the basis for maintaining a continuously high level.

2.8 Power Factor Analysis.

Voltage variation is another important characteristic derivable from the data collected. Most receiving end equipments are not very sensitive to these voltage variations as long as they are within these acceptable standards. However if the variations exceed these limits in magnitude for over 1 minute, long duration variations are considered to be present as indicated in ANSI, C 84.1[20].

$$V_{rms} = \frac{V_{max}}{\sqrt{2}} \qquad I_{rms} = \frac{I_{max}}{\sqrt{2}}$$

This statement is correct in the pure sinusoidal state.

When harmonics are involved, the equations take a new form because the harmonics are sinusoidal waveforms of different frequencies, whose summation is not sinusoidal but periodic.

$$V_{rms} = \sqrt{\sum_{h=1}^{h\max}\left(\frac{1}{\sqrt{2}}V_h\right)^2} \quad \text{and} \quad I_{rms} = \sqrt{\sum_{h=1}^{h\max}\left(\frac{1}{\sqrt{2}}I_h\right)^2}$$

$V_1, V_2 --- and\ I_1, I_2---$ are the amplitudes of voltage and current waveforms respectively.

2.8.1 Power Factor Analysis in linear loads

Linear reactive loads are inductive or capacitive and they draw current from source at source frequency of 50 Hz. For linear systems, the relative angle between the voltage and the current is represented by θ as shown in Fig. 3.14.

If the instantaneous voltage and current are represented as v_t and i_t then

$v_t = V_{max}\sin(\omega t)$ and

$i_{(t)} = I_{max}\sin(\omega t + \theta)$ then the instantaneous power (p) is

$p = v_t\, i_t = V_{max} I_{max} \sin(\omega t) \sin(\omega t + \theta)$. Therefore the

Average power $P = 1/2 V_{max} I_{max} \cos(\theta)$

$P = V_{rms}\, I_{rms} \cos(\theta)$

Where cos (θ) is the power factor (pf) in linear systems

Apparent power $S = V_{rms} \times I_{rms}$ in (KVA)

Active power $P = S\cos(\theta)$ in (KW)

Reactive power $Q = S\sin(\theta)$ in (KVAR)

Phase angle θ = power factor angle

$S = \sqrt{(P^2 + Q^2)}$

cos (θ) = displacement power factor (PF) for linear systems

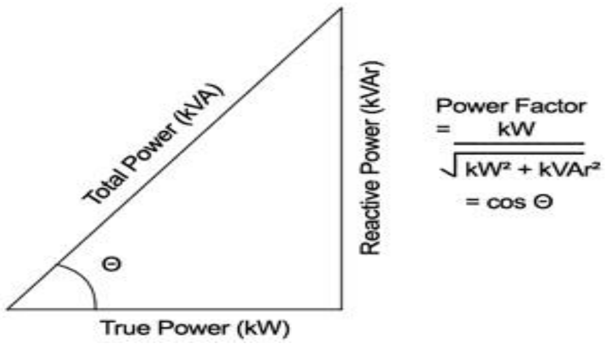


Fig. 3.14 Displacement PF for linear systems

When Reactive power (Q) is very high, PF is very low. Q must be improved upon by reducing angle θ in order to improve on the PF. Q, which is inductive, can be improved upon by adding Capacitors (capacitive loads) to the circuit. It can be seen that the bigger the inductive load the bigger the reactive power and the lower the power factor. Large inductive loads cause large lagging currents and large KVAR, thus reducing the PF. Such loads are Induction motors and Transformers. Power Factor affects the cost of electricity. The lower the PF, the more the factory pays in electricity bills to the Utility Company. Low PF causes low efficiency and therefore the power quality is said to be poor. When PF is lower than 0.94, the losses is on the high side. The use of Capacitors and Synchronous motors will improve the PF, and the load losses reduce and the bills to be paid to the Utility reduce. The carbon emission also reduces. Low PF also leads to increase in power losses and this leads to large voltage drop leading to overheating and loss of transformers and other inductive equipments.

2.8.2 Power Factor Analysis in non - linear Systems.

The modern day computers are designed to have improved PF from 0.6 or 0.65 to 0.98 by the use of Switch Mode Power Supply (SMPS). The power factor of non- linear loads is not the same as those of linear loads, as shown below. Another element is brought into the calculation as a result of the load current not being sinusoidal but periodic. The power factor is now made of two components, the true power factor (PF_{true}) and the displacement power factor (PF_{disp}).

For pure sinusoidal $PF_{true} = PF_{disp} = \cos(\theta) \leq 1$ and

For non-linear loads $PF_{dist} = \dfrac{I_1}{\sqrt{I_1^2 + I_2^2 + I_3^2 + - - - - + I_n^2}} x \dfrac{100}{1} = \dfrac{I_1}{I_{Trms}}$ where I_1 = fundamental current and I_{Trms} = rms value of total input current.

The displacement factor is for linear systems only which is equal to $\cos\theta = \dfrac{KW_1}{KVA_1}$ and

Total or PF_{true} for non – linear systems = $\frac{KW_T}{KVA_T}$ where

KW_T = total power input in kilowatts and

KVA_T = total kilo volt-amperes (rms) input.

The Distortion harmonic factor, usually called Total Harmonic Distortion (THD) is defined as

THD = $\frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + --- + I_n^2}}{I_1} x \frac{100}{1} = \frac{I_{Htotal}}{I_1}$ all of which are in RMS values.

For practical purposes Total Harmonic Distortion can be defined as

THD = $\frac{P_{Total} - P_1}{P_1}$ it is easier to measure Power than all the different types of harmonic currents and voltages.

The relationships between the load current and the supply voltage are no more uniform when non–linear loads are present because the current drawn by the load is not sinusoidal like the supply voltage but periodic.

$$\frac{P}{S} = \frac{Actual\ Power}{Apparent\ Power}$$

P represents the Actual Power and S represents the Apparent Power. It is seen that PF is a ratio, the highest value is 1. When this ratio is less than 1, the useful power is less than the apparent power. Linear loads can have PF that are as high as 0.98. This is called the *displacement power factor*. For uncompensated non-linear loads, the PF can be as low as 0.65 because of power consumed by frequencies other than the fundamental not as a result of reactive power only. This type of PF is called the *true power factor*. These affect the quality of power a consumer experiences. The apparent power is much bigger than the real power when the PF is low because of the non-linear loads. The cost of poor PF is enormous for a consumer, as he is made to pay for what he has not consumed. The current is not proportional to the applied voltage in a non-linear device, since the wave is periodic. There is no real work done when the current is not in phase with the voltage.

$S = \sqrt{(P^2 + Q^2 + H^2)}$

Where S = Apparent power in volt-amperes (KVA)

P = Active power or True power in (KW)

Q = Reactive power in volt-amperes (KVAR) which is = $(Q_L - Q_C)$, inductive

H = Distortion power in (KVA)

Power Factor = Displacement Factor × Distortion Factor i.e. $PF_{true} = PF_{disp} \times PF_{dist}$

True PF = (Displacement PF) x (Distortion PF)

Expressed in diagrammatic form the active power (P), reactive power (Q), the harmonic power

(H) and new apparent power (S) are as shown below in 3D (Fig. 3.16).

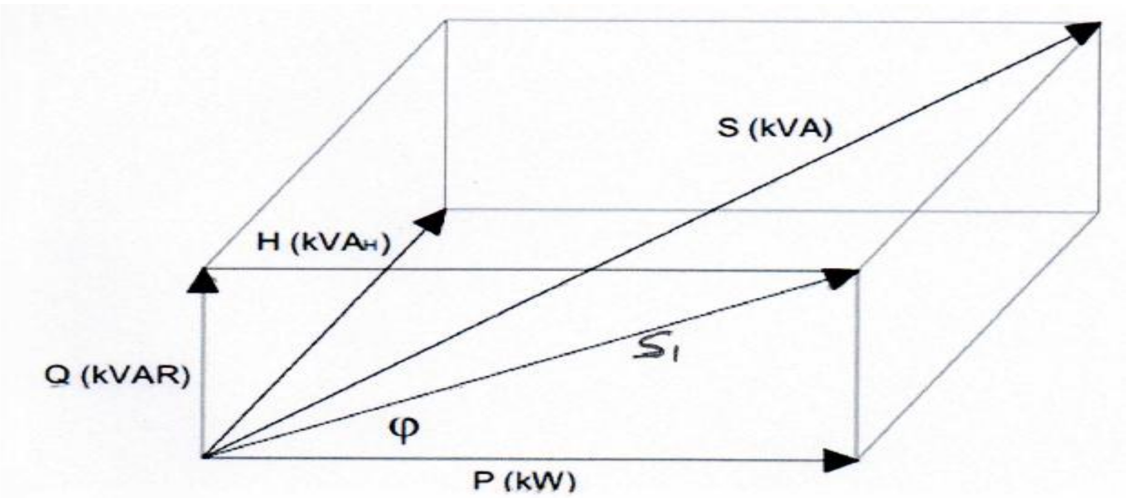


Fig. 3.16 Orthogonal Power Components.

Orthogonal relationship between the Power components for non-linear loads has an added component, the harmonic component H, also measured in kVA. H is the power component due to the nonlinearity or a periodic variation in the load. S_1 has now increased to the new and bigger apparent power, S. The new PF has decreased as a result of the non-linear loads.

Assuming the instantaneous voltages and currents of a non-linear load is represented as in Fig. 3.17, the frequency bar –chart of the fundamental and the harmonics are as shown. The upper chart represents instantaneous voltage (v) while the lower chart represents the current. The fundamentals and 3^{rd} harmonics of voltage (*v*) and current (*i*) represented in the 1^{st} and 3^{rd} positions are present. All the even harmonics have cancelled out. The 5^{th} harmonic is absent in (*v*), but present in (*i*). The 7^{th} harmonic is present in (*v*), but absent in (*i*) and so on.

'n' represents all the frequencies where both (*v)* and (*i*) are present.

'm' represents all the frequencies where (*v*) is present but (*i*) is absent.

'k' represents all the frequencies where (*v*) is absent but (*i*) present.

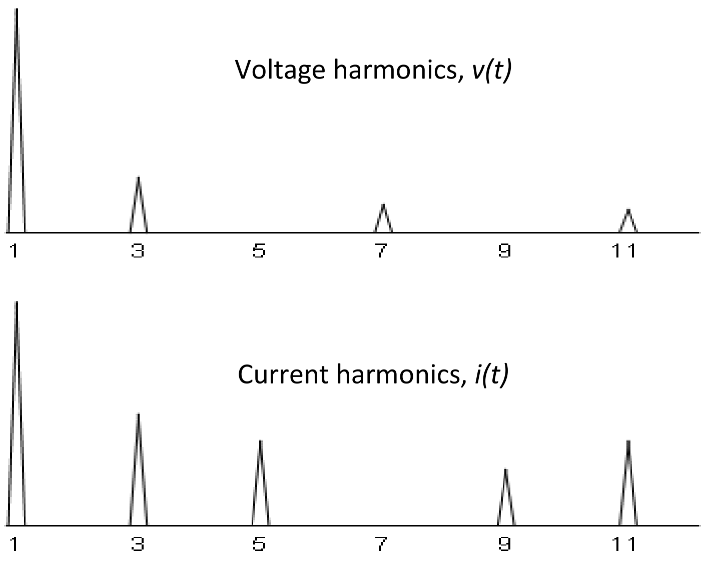


Fig. 3.17 Harmonic bar – chart of instantaneous voltages (*v*) and current (*i*)

It can be shown from Fig. 3.17 that the real power only exists if the voltage and current have the same frequency. For example the real power in this figure is delivered at the fundamental, third and the 11^{th} harmonics. Although the voltage waveform contains 7^{th}

harmonic but this is not translated into power loss since there is no equivalent current harmonic at this frequency. Expressed in mathematical waveform, the instantaneous values of the non – linear voltages and currents are as shown below:

$$v(t) = \sum^{n} \sqrt{2} V_n \sin(n\omega t + \alpha_n) + \sum^{m} \sqrt{2} V_m \sin(m\omega t + \alpha_m)$$

$$i(t) = \sum^{n} \sqrt{2} I_n \sin(n\omega t + \alpha_n + \phi_n) + \sum^{k} \sqrt{2} I_k \sin(k\omega t + \alpha_k)$$

$$Power\ Factor = \frac{\frac{1}{T}\int_0^T v\, i\, dt}{V\, I}$$

$$Power\ Factor = \frac{\sum^{n} V_n I_n \cos \phi_n}{\sqrt{(\sum^{n} V_n^2 + \sum^{m} V_m^2)(\sum^{n} I_n^2 + \sum^{k} I_k^2)}}$$

If the distortion in the supply voltage is ignored then $V=V_1$ and the PF reduce to:

$\frac{V_1 I_1 \cos\phi_1}{V_1 I} = \frac{I_1}{I}\cos\phi_1$ Since $\frac{I_1}{I}$ = Distortion Factor and $\cos\phi_1$ = Displacement Factor

Then Power factor = Distortion Factor x Displacement Factor

Distortion Factor is normally improved by active or passive filters and Displacement Factor is normally improved by capacitor compensation. The collected data shows that the power factor was between 0.92 and 0.98max. (Fig.3.15). Cost of electricity consumed in a building or factory is affected by the power factor. The lower the power factor, the more the factory pays in bills to the Utility and when the power factor is less 0.92, the losses is considered high.

2.9 Power Quality Analyzer

There are different types of instrument analyzers, beginning with simple ones like analog voltmeters to sophisticated ones like spectrum analyzers. Every instrument has its capabilities and limitations, its response to power system variations and the specific objectives of the analysis that is intended to be performed. The case study in this project made use of spectrum analyzer, the three-phase electrical networks analyser, C.A 8335 QUALISTAR PLUS, from CHAUVIN ARNOUX group as shown in Fig. 2.13 [25].

Fig. 2.13 Power quality Analyzer (C.A 8335)

2.10 Typical single-line diagram of feeder circuit

Fig. 2.14 presents a typical single-line diagram of the sectional circuit beginning from the sub-transmission station MV at 46kV to the transformer which changes the voltage down to 12kV. Another transformer located at the premises of the customer, depending on size of customer's load, steps the voltage down from 12kV to LV distribution voltage of 480volts or 415volts, 3-phase. This point is taken as the point of common coupling (PCC). Some end-users' load is big enough to take their supply at 12kV, and then the distribution from that voltage becomes the customer's responsibility.

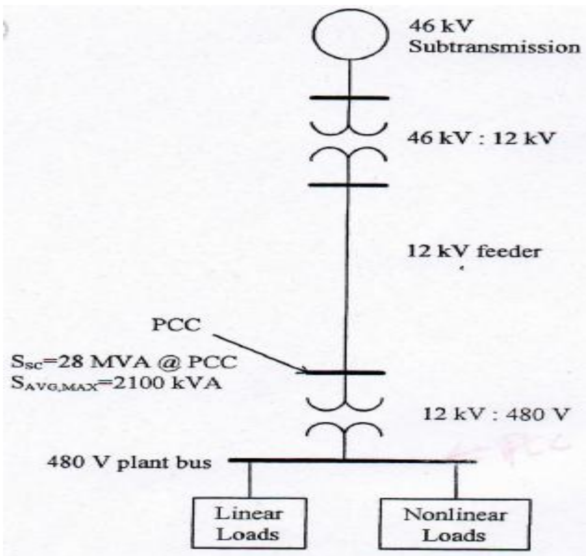


Fig. 2.14 A typical single-line diagram showing the PCC. [51]

2.11 Summary

In this chapter the importance of the power quality is identified and each of the terms is classified and discussed in some depth. Although power quality can be seen as one integrated issue but from the mathematical, prevention and correction point of views it is much easier to classify in a separate categories. Power quality has assumed a strategic issue for Utilities, End-users and Equipment manufacturer as well. Even the International Standards Organisations are involved in these problems. In this present day of economic downturn the consequences of power quality disturbances could not be taken lightly. Regular monitoring of installations and application of correct mitigation techniques should be intensified. Power quality monitoring is required now for technical reasons that is, for investment and planning. Deregulation will soon play a major role in market economic. Harmonic distortion is increasing rapidly day by day. It is not only the industrial consumers that produce harmonics, but commercial and residential consumers have joined in the same also. All modern building engineers need to study power quality problems and the mitigation technique. The energy loss due to residential load harmonics in the country can be calculated. Malfunctioning of very sensitive equipment and the loss of time and finance to put it right should also be considered. There is need to know the contribution of harmonic problems that residential load adds to the harmonic problems, (the computers and the Compact Fluorescent Lamps (CFL) and other domestic electronic load). So much advertisement on CFL's energy saving advantages is published every day without considering the power quality problems it brings along with it. Next chapter looks at the study of the power quality in an office building at Brunel University with some analysis of this study. The International Standards have been compared and for the purposes of this thesis, the EN50160 is adopted.

Chapter Three

Power Quality in Buildings (Case Studies No. 1)

Tower ‘A’ & Howell Building - Brunel University

3.1 Introduction

In Chapter 2, definitions of power quality as well as the main causes of poor power quality were discussed. In this Chapter, two buildings fed from the same LV board with the incomer breaker taken as the PCC were taken as a one of the case studies in this thesis. The two buildings are academic office/lab buildings where the maximum power consumption occurs during the day time. The power quality analyser was installed at the PCC to these two buildings and it was observed for five working days. The data were analysed based on the definitions covered in Chapter 2. Before analysing the data, some specific points related to office/lab or modern buildings in general need to be covered.

3.2 Type of loads in modern (commercial) buildings

It has been observed that the greatest power quality problem encountered in modern commercial buildings is the harmonics which is considered to be steady state variation. This is as a result of increasing number of non-linear loads connected to the circuits in the building, as earlier pointed out. Computers (the highest polluter), printers, TVs and other power electronics equipments (mostly single phase) are the main sources of such problems.

Some modern commercial buildings have more than 300 PCs. These problems are internally generated causing the neutral to carry an excessive current which burns the neutral, resulting in downtime and consequently fire outbreak. The presence of harmonics in such buildings affects not only themselves but also adjacent consumers. These buildings require power quality compensators. Traditional old cables used to have neutrals of smaller sizes because it was noted that they carry little or no currents [for balanced 3 phase loads]. The advent of massive non-linear loads has changed the design principles drastically nowadays. Neutrals are now designed to be 1.5 times bigger than the current carrying phases.

Other Power Quality problems, like Transients [impulsive and oscillatory], Short duration [instantaneous, momentary or temporary in form of interruptions, sags and swells] are mostly externally generated. Harmonics are usually internally caused by massive addition of computers and other non-linear loads, these will form the basis of PQ problems to be analysed in this report for Commercial buildings.

Harmonics is the summation of the different waveforms of currents and consequently voltages other than the fundamental (50Hz) frequency (f_1). They are multiples of the fundamental (nf_1, where n is an odd number) which when summed up together present a distorted waveform, A measure of such distortion is called total harmonic distortion – THD, which is the ratio of the sum of the total harmonics (taking angles into consideration) to the fundamental component.

For such types with high number of non-linear loads, measurements of power, line & phase currents, line & phase voltages, THD, individual current & voltage harmonics (up to 40^{th}) according to EN50160, P.F., short & long time flickers and frequency variations are necessary. Such readings were taken, analysed and compared with various standards.

3.3 Power quality in Tower A and Howell buildings

Tower 'A' is a 4 story office-building which contains a number of academic offices as well as a number of mechanical engineering and computer labs in the ground floor. The Howell building is a 3 story office building and has a number of lecture rooms and a large lecture Theatre (500 seats) in the ground floor. Both buildings have lifts and both are non-residential buildings, although staff and research students have 24/7 access to both buildings. Several power analysers could be used for monitoring the data; however the C.A. 8335 power quality analyser was selected and used for this task. Appendix 'A' shows the specifications of this type of the power analyser and the justification for its selection. The power analyser was installed for a period of one week at the distribution point of the building during the month of October 2010 (although data were collected only for five days). October is usually one of the busiest months in the academic calendar. The power, line currents, phases & 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. The incoming LV circuit breaker (shown in Fig. 3.1) is located in the control room at the ground floor directly opposite the main entrance. The measurements taken by the power analyser were discussed and analysed in details in the following sections.

Fig. 3.1 Tower 'A'/ Howell building incoming LV breaker (PCC)

3.3.1 Real, apparent, and reactive power analysis

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). The difference between the two types of powers (as shown in Fig. 3.2) is the reactive power. The measurements of the three types of powers are taken at the point of common coupling (PCC) of the two buildings. Such measurement will give good indication of the amount of power consumed and also the nature of the load at different times. This could help in improving the power consumption profile as well as deciding when power factor devices can be switched on/off as will be discussed later when the power factor are analysed in more details.

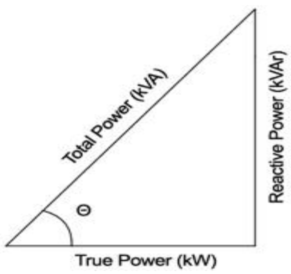
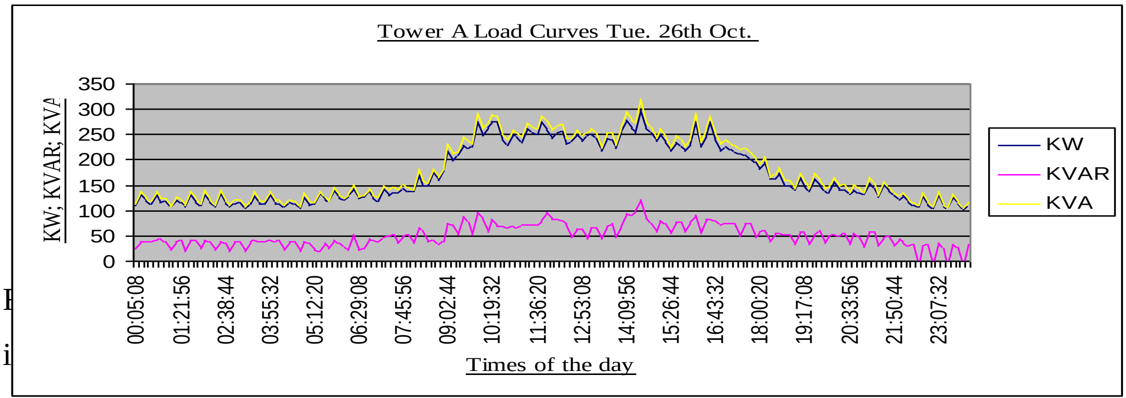


Fig. 3.2 Power triangle

Fig. 3.3 illustrates the total power consumption for a typical week day. As expected the maximum power was consumed during the peak 'academic' time which is between 10:00 am and 4:30 p.m. The figure also illustrated 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 Fig. 3.3 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.



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g

Fig.3.3 The pattern of the powers in a typical working day

3.3.2 Current Waveform Analysis

Fig. 3.4 showed 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 Fig. 3.6. 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. The graph Fig. 3.6 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 100A minimum on line A_1

of the 28th and 200A maximum on line A_3 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 116Amps, Fig. 3.5. 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 Fig. 3.6.

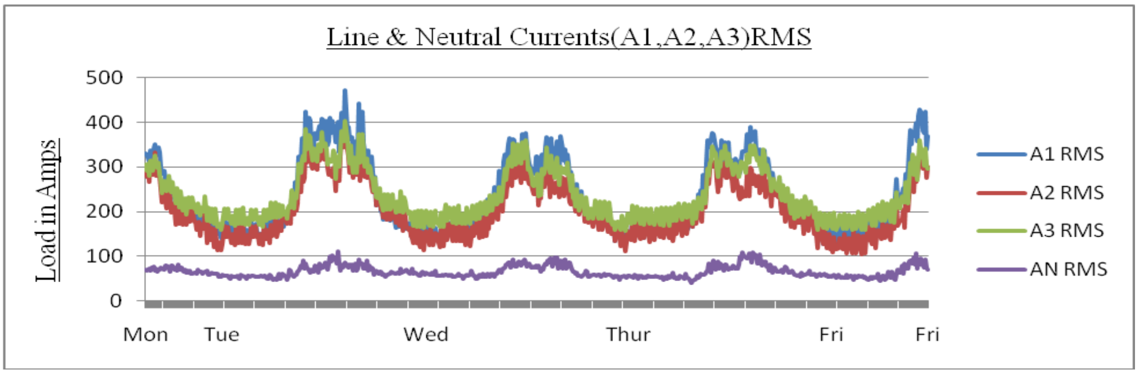

Fig. 3.4 Line and Neutral currents of Tower 'A' office building

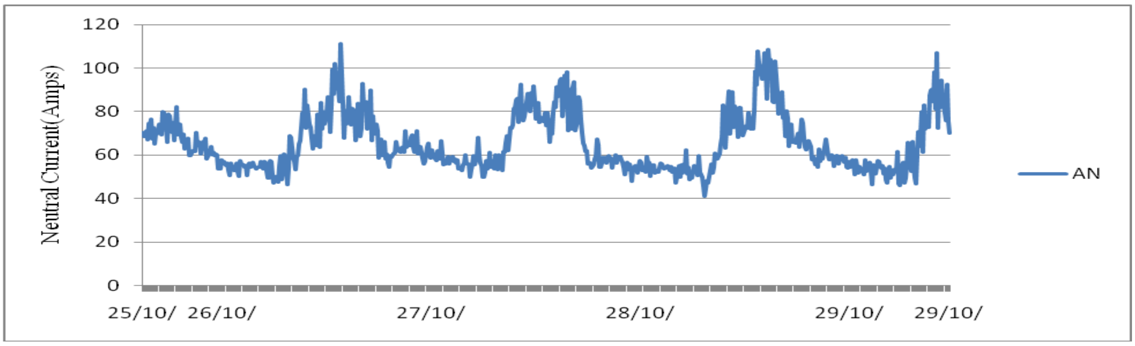

Fig. 3.5 Trend graph of RMS current in neutral of Tower A/Howell buildings.

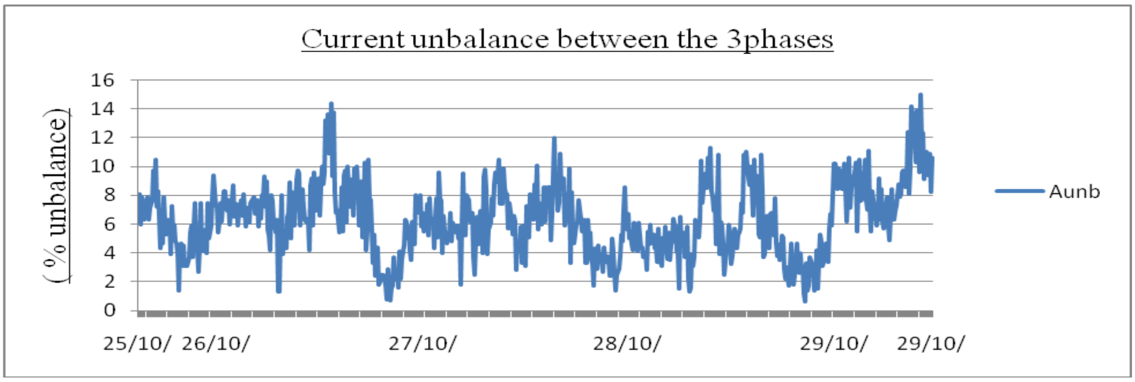

Fig. 3.6 Graph of the percent unbalance of average current Tower A/Howell buildings.

The Tuesday 26th was noticed to be the highest working day of the week (250A min on A_2 and 450A max on A_1) as shown Fig. 3.7. The neutral current was quite high (about 116A) 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. 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 to 09:02:44 (Fig. 3.7) the neutral current was not zero. This is as a result of non-linearity of the load which consists of so many PCs. Although PCs should be turned off at night but the majority of the staff/students leave them on the sleep mode. PCs still draw distorted the current in the sleep mode as shown in Fig. 3.8.

The loading between 9:11:16 and 17:09:08 was above 300A, the phase-1 load was about 400A 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 116A (Fig. 3.7)

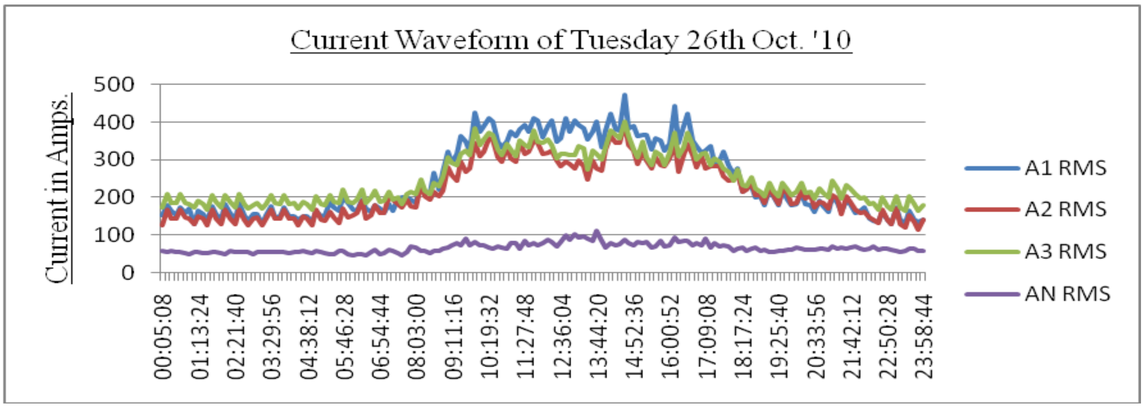

Fig. 3.7 Current waveform of Tuesday Oct. 26th

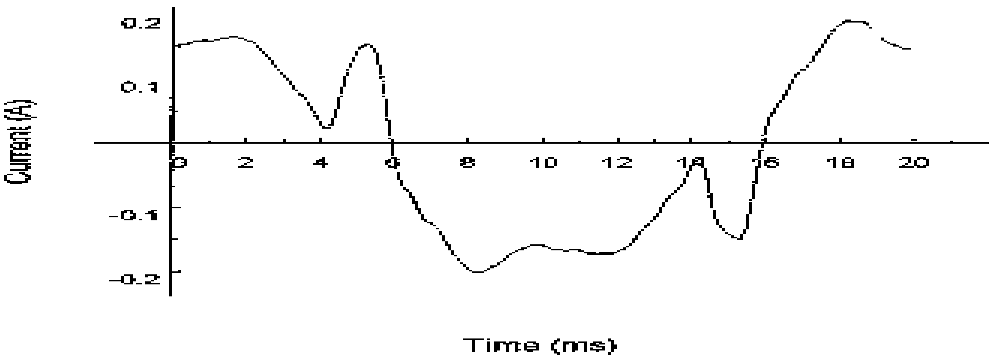

Fig. 3.8 A typical computer load current in sleep mode

The current in the neutral is originated by the 3rd harmonic (and its multiples) in the current of the phases, apart from the unbalance loading in the phases. The high neutral current caused by these harmonic distortion may be mitigated by the use of passive filters or active filters or both, if this situation causes distorbance 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.

3.3.3 Line Voltage Waveform Analysis

Supply voltage quality is considered as one of the very important topics in power quality. The supply voltage quality requirement characteristics are well stated in International Standards EN 50160, that for LV, MV voltage magnitude variations should be within ± 10% of nominal voltage for 95% of the week, mean 10 minutes RMS values [37] [16] [24]. However, within the characteristics, situation near the limit values could be unfavourable for the consumer.

Fig. 3.9 shows that the supply voltage (U_1) does not vary widely as the load current (A_1).

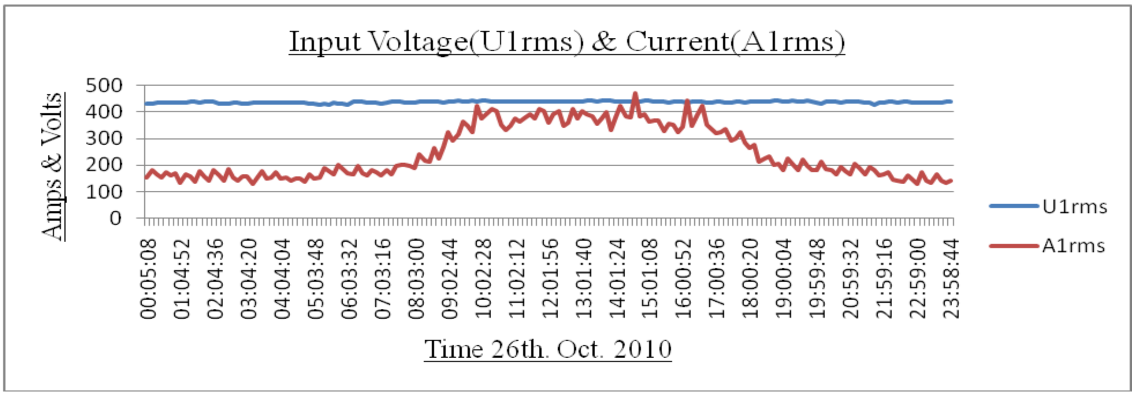

Fig. 3.9 Supplied Voltage (U_1) & Drawn Current (A_1)

The supplied line voltages (U_1, U_2, and U3) are shown in Fig. 3.10. The minimum supply voltage of 427.4 volts (U_3) occurs on 25th October, and the highest was 445.1 volts on 29th October. Though these voltages are within the ±10% of the EN50160 Standard limits [17, 23, 37], but they are consistently on the high side, which is unfavourable to the consumer. This statement is proved in the later part of this thesis. The nearer a user is to the injection substation, the higher the supplied voltage. The Uxbridge campus of Brunel University is located close to the Transmission Injection Substation, and as such, the supply voltage would be on the high side. The size of the load is also a major factor, as the load moment along the line affects supply voltage.

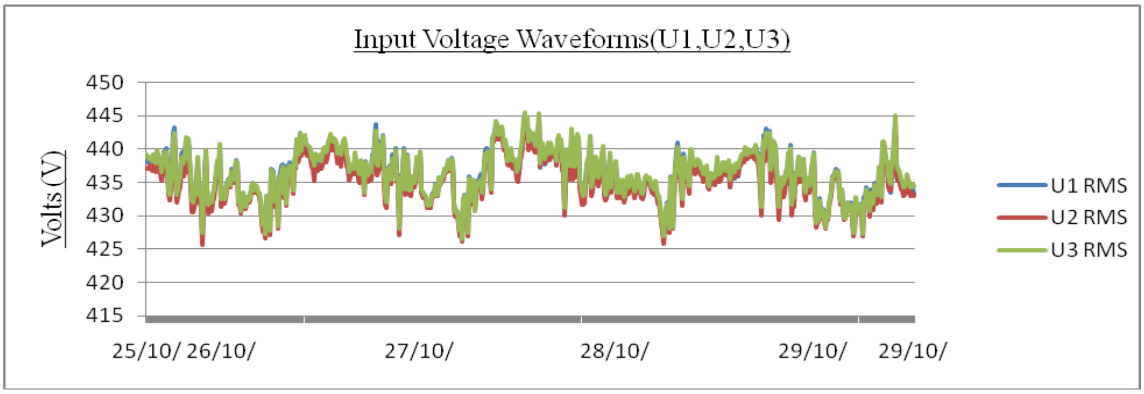

Fig. 3.10 Supply line voltages U1, U2, U3 for the week

3.3.4 Phase Voltage Waveform Analysis.

The phase voltages in Fig. 3.11 has the highest value of 257.5V (V_3rms) on the 27th and minimum of 245.9V (V_1rms) of the same day.

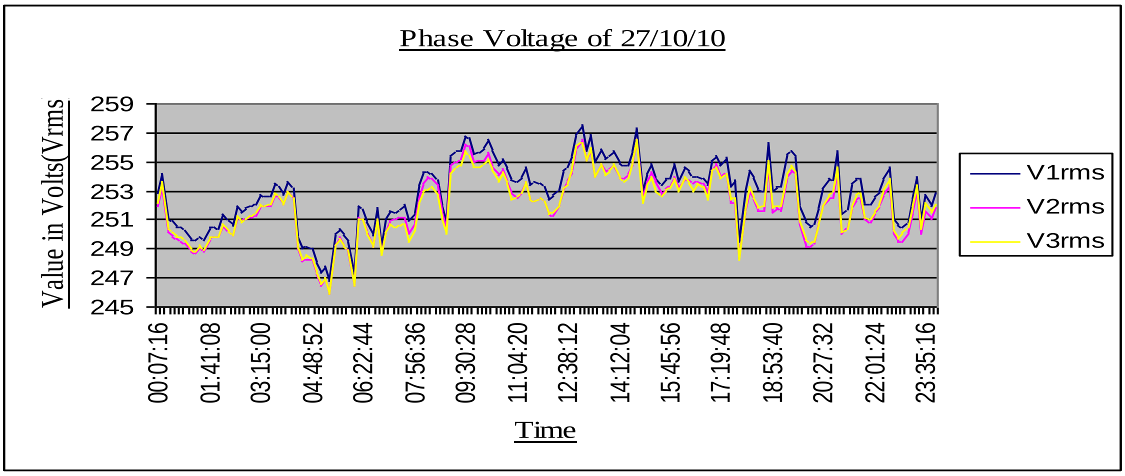

Fig 3.11 Phase voltages of Wednesday 27th Oct.2010

Customer loading also affects the voltage and current. The European Standards EN50160 [24] states that the supply voltage can remain in the range of U = (0.9 to 1.1) U_0 where U_0 = rated voltage. In practice the limits are set to +5% and -10% of the operating voltage.

The nominal voltage magnitude variation of the supply from the Utility, according to EN50160 should (±10%) i.e. (207 – 253) V of 230volts [23], [31], as noted in table 2.4, whereas the supplied minimum of 245Vrms was above the nominal permissible voltage. The supplied voltage of (245.9 – 257.5) V was continuously on the high side. Assuming the nominal voltage to be 240Vrms, the limits would be 216volts to 264volts. The supplied minimum is still higher than the nominal permissible voltage. 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.

3.3.5 Total Harmonic Distortions Voltage Waveform Analysis

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 Fig. 3.12 during the data collection period.

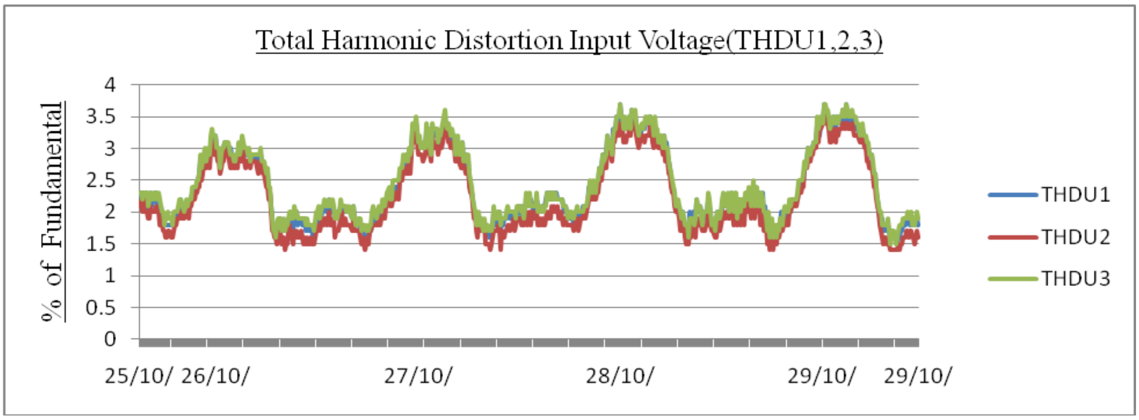

Fig. 3.12 Incomer Line THDU – Tower A

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. [16][24][37] For this period, the 7th harmonic maximum was 1.0% (5% for this limit) and the 5th harmonic level was 8.7% (6% for this limit by EN50160) on phase 1 as seen Fig. 3.11.

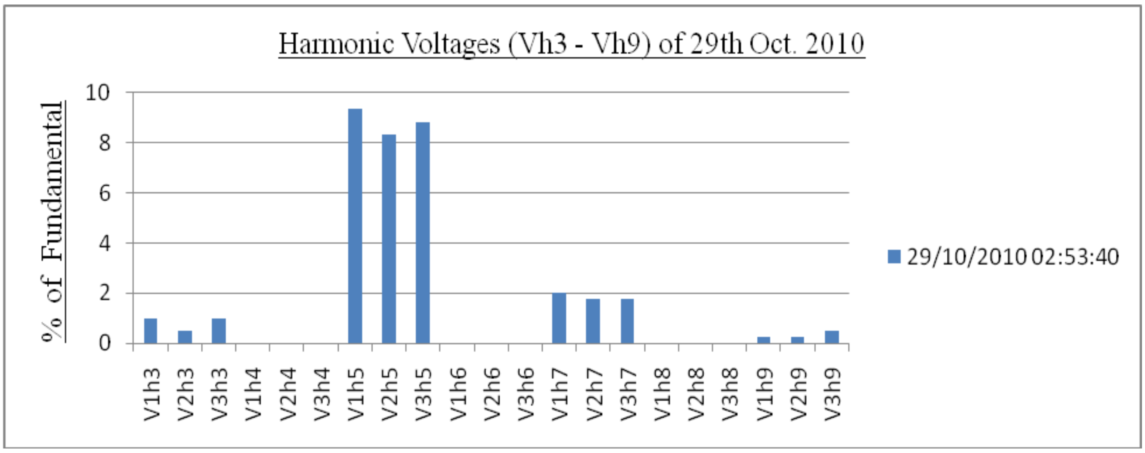

Fig 3.13 Voltage 2nd -9th harmonics at Tower A Incomer.

3.3.6 Total Harmonic Distortion Current Waveform Analysis

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 [16]. The building has many electronic types of equipment which are the main sources of harmonic distortion especially the 3th harmonic level. These are air-conditioning systems and elevator, 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 Fig. 3.12. This value has not trangressed the standard of 20% [23].

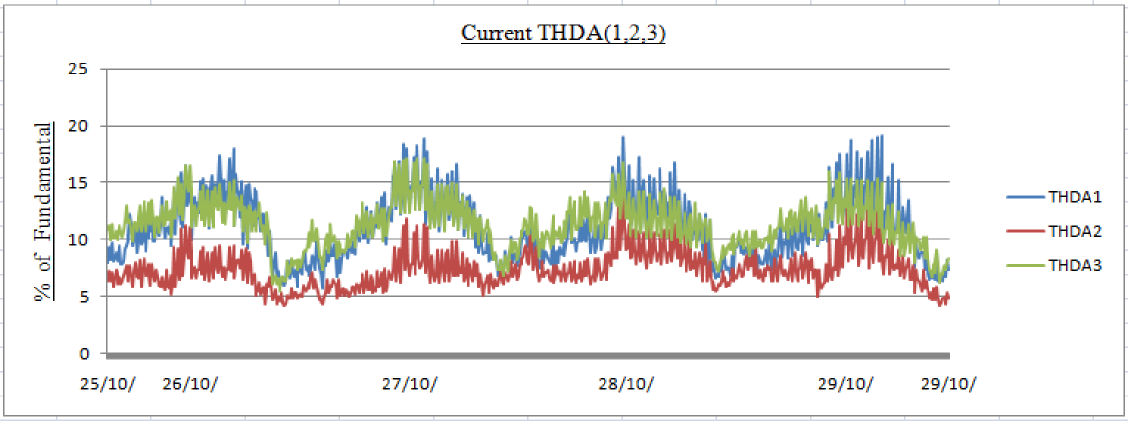

Fig. 3.14 Total Harmonic Distortions of current for Tower A

Fig. 3.13 of different odd harmonics(3rd 5th and 7th) showed that the harmonic levels are under the EN50160 standard limits, as they were less than the stipulated 20% limits. The highest level was 15.5% on A1h3 of 26/10/10 [10].

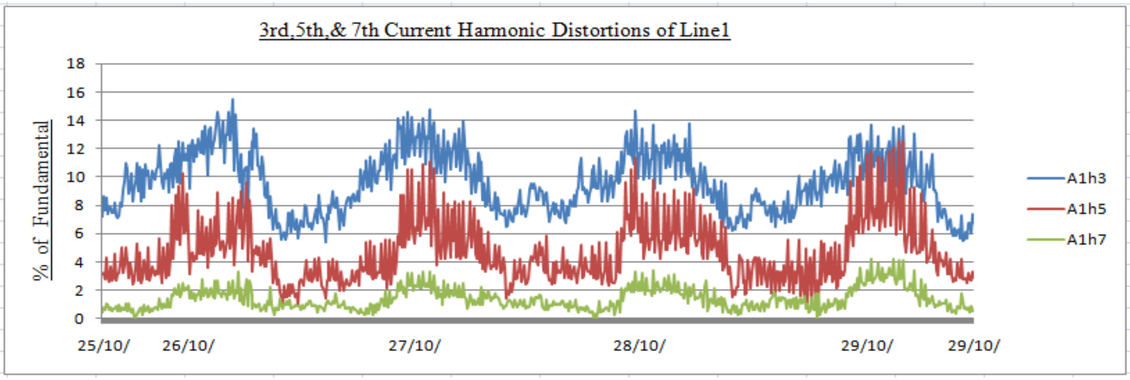

Fig. 3.15 (3rd, 5th, & 7th) Current harmonic distortion of Line1

3.3.7 The Reactive Loading of Tower 'A'/ Howell 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. Fig. 3.14 shows the period of the night that the reactive load were negative indicating that the fixed capacitors over-compensated for the inductive load.

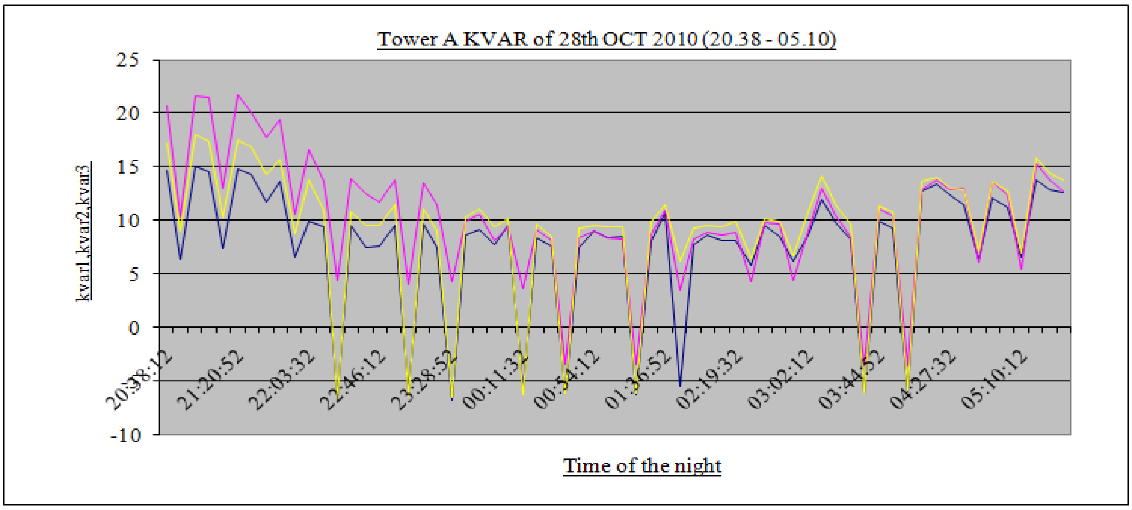

Fig. 3.16 Tower A Reactive loading of 28th October 2010

The power factor in each of the 3 phases is shown in Fig. 3.15. 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

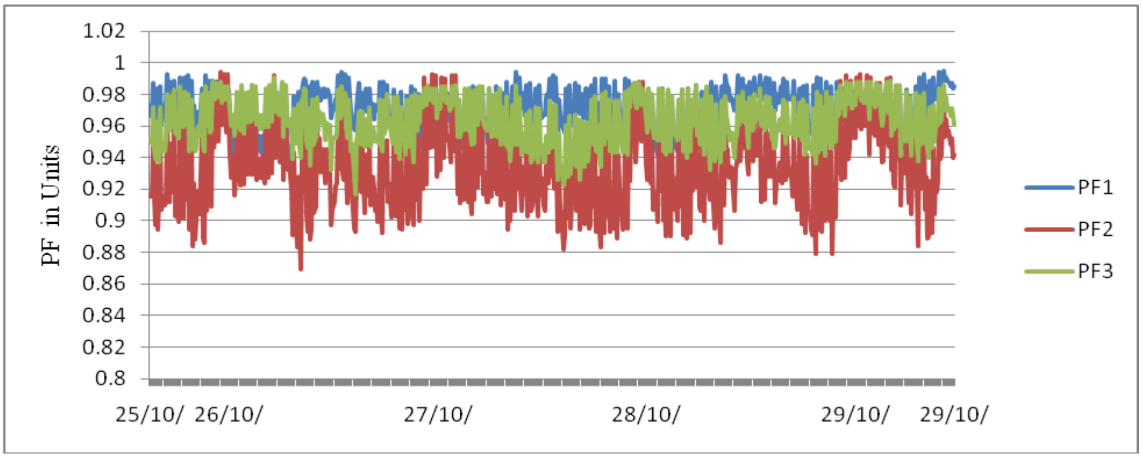

Fig. 3.17 Power Factor (PF) in all the 3 phases

3.4 Summary

In this chapter the data monitored from tower 'A' and the Howell building was analysed. Line & phase voltages, line currents, neutral current, harmonics, total harmonic distortion and power factor were analysed and were compared with the appropriate standards. Tower 'A' and the Howell building can be seen as a typical university office/lab buildings.

The power consumed in a typical day (Fig. 3.3) showed that Apparent and Real power 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 = 300KW while Reactive power = 130KVAR at 14:09:56).

The current waveform indicated that the highest current unbalance was 15% of the fundamental, the highest neutral current during the test period was 116.0Arms of Tuesday 26th Oct. The 15% unbalance is high giving rise to high neutral current. The high neutral current is the summation of unbalance in the line currents and the harmonic current caused by the non-linear load in the two buildings, which are mostly single phase loads like computers and other switch mode power supply equipments. The unbalance loading on all the three phases has made neutral current to be high (Fig 3.5). The neutral current for a balanced 3-phase and linear load should be zero. High neutral current cause overheating heating 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 (Fig. 3.12). The 3rd harmonic was the highest, 15.5% (Fig. 3.13)

The neutral current A_n was very high as shown in Fig.3.7, as the phase current was as high as 116A 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.

The supply voltage (U_1, U2, and U3) was high, as it varied between 427volts and 445volts on line 3 (U_3) 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 257.5volts highest and 245.9volts minimum on 27th October as noted in Fig. 3.9, this high voltage is unnecessary and leads to higher billing.

The THDV at the input was not high, it was 3.7% (Fig.3.10), and EN50160 puts this limit at $\leq$ 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. (Fig.3.11) 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.

Chapter Four

Power Quality in Buildings (Case Studies No. 2) Kilmorey Residence Hall - Brunel University

4.1 Introduction

In chapter 2 the power quality has been reviewed and different terminologies of power quality were introduced. International professional bodies have established standards by which PQ could be defined as mentioned earlier on. One of such bodies is the European Standard EN-50160 [24]. What may be considered as quality power to one customer may not meet the standard required by another end user. Therefore Benchmarking indices serving as metrics came to be developed. Benchmark levels for electricity suppliers, consumers and even manufacturers have been introduced. Some of these International bodies include Electric Power Research Institute (EPRI), Institute of Electrical Electronics Engineering (IEEE), International Electrotechnical Commission (IEC), American National Standards Institute (ANSI) and National Electrical Manufacturers' Association (NEMA). Quality of service is determined by first selecting the metrics to be used, deciding on what PQ data to be collected and then determining the pattern of the data with predetermined target level set by both the power supplier and the consumer. The supplier, the consumer and the regulatory agencies need to reach a compromise. Another level considered to be very important is the Performance Level introduced by a specific consumer, which is different but always higher or equal to the Benchmark values.

In this chapter, a residential case study was introduced and investigated. The case study consists of real data which was collected over a period of one week for Kilmorey Residential Hall in the same academic Institution. The building consists of equipments associated with wholly residential building, probably 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.

4.2 Line Voltage Analysis

A nominal 'rms' voltage in UK is 240V phase to neutral (V_{rms}), and 415V phase to phase (U_{rms}). The graph shown in Fig 4.1 illustrates the variation in the line voltages at different times of the test period (29^{th} Oct. – 5^{th} Nov. '10). The data were collected during the one week with a sampling period of 8 minutes. It could be seen from this graph that the voltages were not balanced. They vary from 427.0 U_{rms} on phase 1 and 445.0 U_{rms} 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 373.5V_{rms} and 435.75V_{rms} of the nominal line of 415.0 V_{rms}. The upper limit was exceeded for this building, for more than 95% of one week, the acceptance time, according to the European Standard – EN50160 as indicated in appendix B_3 [24],[16]

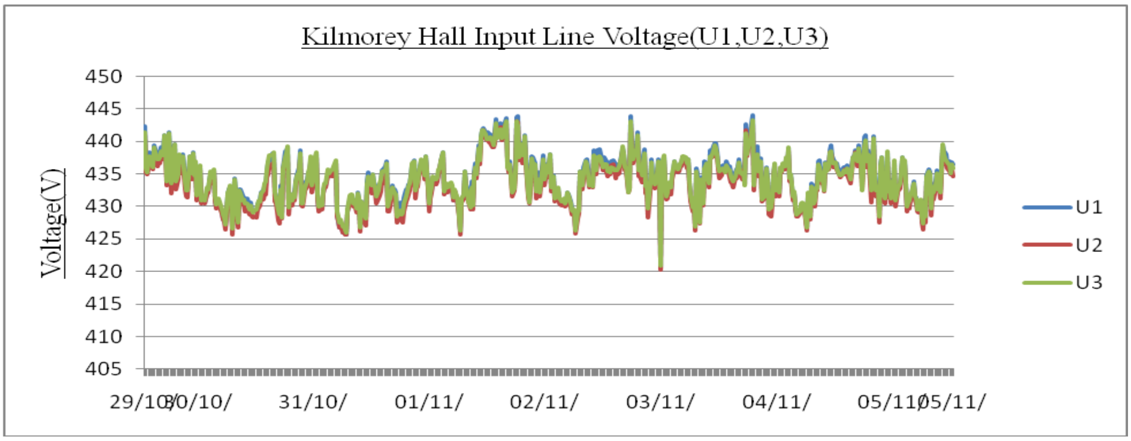

Fig 4.1 Line Voltages to Kilmorey Hall

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. Long duration variations can be overvoltage or undervoltage or sustained interruption depending on the specific circuit magnitude conditions. Short duration variations are for less than 3minutes and could be Instantaneous, Momentary or Temporary for interruption, sag or swell as defined internationally [9, 37].

Steady state variations include the normal rms voltage variation and the harmonic distortion. Voltage variations are measured, and then analysed 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 University. 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 University to the Transmission Injection Substation. The nearer a load is to the Injection Substation, the higher the supply voltage.

Kilmorey Hall of Brunel University switch room is located in a separate room adjacent to the sports building. It is from here that the Kilmorey 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, which was considered to be adequate for this investigation as seen in Fig. 4.2

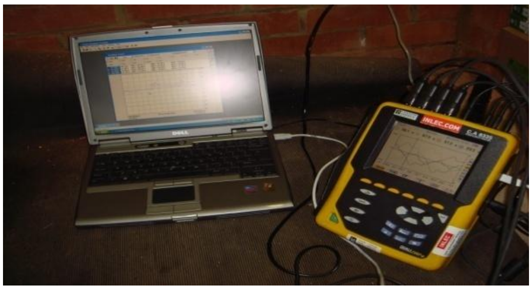

Fig 4.2 The measuring equipment and the PC connected

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 AmpFLEX, 4 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 minutes) it was seen that they rise and fall together. 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.

4.3 Current Total Harmonic Distortion (THDA).

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. Any non-linear measurements on the AC mains supply can be analysed and it will be found to comprise lots of harmonic frequencies, some predominant and some not, depending upon the nature of the circuit and the components that are connected together. The problem with harmonics is that they do not contribute any useful power. They are undesirable because they distort the fundamental sine-wave shape which the supplier are obliged to maintain and furthermore, they draw excessive currents caused by the displacement power factor plus the combined harmonic power factors. The Kilmorey Hall current harmonic distortions are as shown below. The prominent were the 3^{rd}, 5^{th} and 7^{th} harmonics, the 9^{th} and other harmonics were very small (Fig. 4.3).

The dominant 5^{th} harmonic's maximum was 20% on Sat. 31^{st} October (Fig. 4.3). The 6% compatibility limit for that harmonic order established in EN50160 standard was violated [27]. The 7^{th} harmonic was equally high. The most likely cause for this high level of 5^{th} harmonic would be the numerous electronic equipments in load. This would need further investigations because there have been complaints about some outages of this circuit breaker recently which may be due to nuisance tripping by the Residual current circuit breaker (RCCB), which operates by summing up the current in the phase and neutral conductors and if the result is not within the rated limit, the circuit breaker could trip. Even the THDA maximum was 28.4% on phase 2 of 31^{st} October and this violated the 20% established limit for the entire installation [25].

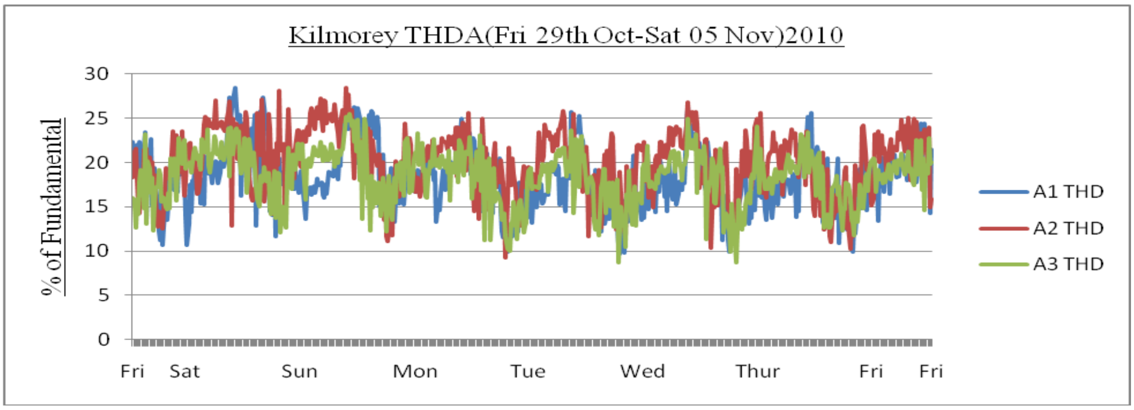

Fig. 4.2 Kilmorey THDA for 29th Oct to 5th Nov. 2010

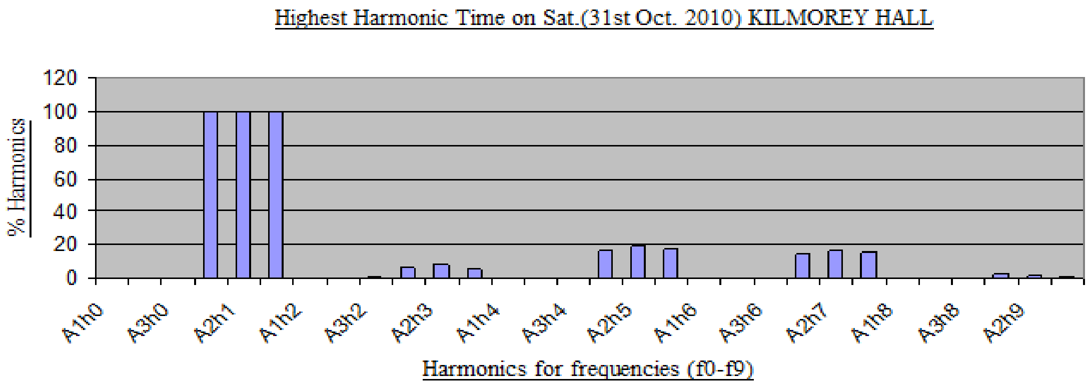

Fig. 4.3 Highest Harmonic for Kilmorey Hall on Saturday 31st October

The 3rd, 5th and the 7th harmonics are high unlike the Tower A/Howell where the 5th harmonic was the only high harmonic to deal with. (Fig.4.4) Mitigating these harmonics would require more than one passive filter and probably active harmonic filters.

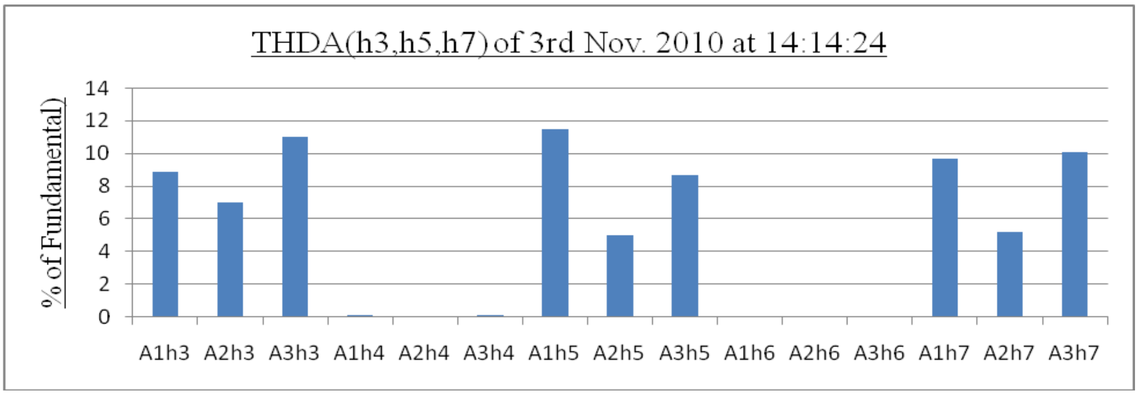

Fig. 4.4 Harmonic for Kilmorey Hall on Wednesday 3rd November

4.4 Voltage and Current Variations.

4.4.1 Voltage Variations

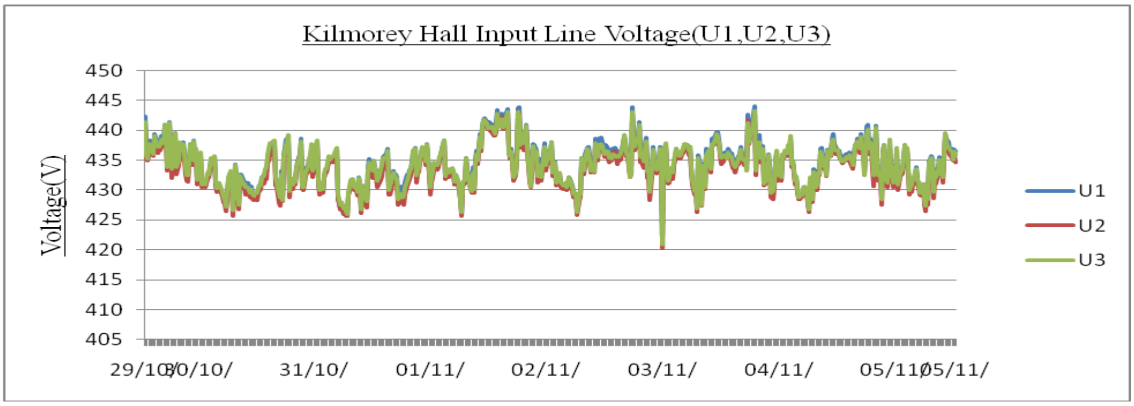

Fig. 4.5 Kilmorey Hall Incoming Line Voltages (U1;U2;U3

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 was in the range of 420V minimum and maximal value was 444.8V, Fig. 4.5). Voltage margins as set in the U.K. are ±10% of 415volts, line voltage that is from 373.5V to 435V. 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.

4.4.2 Current Variations

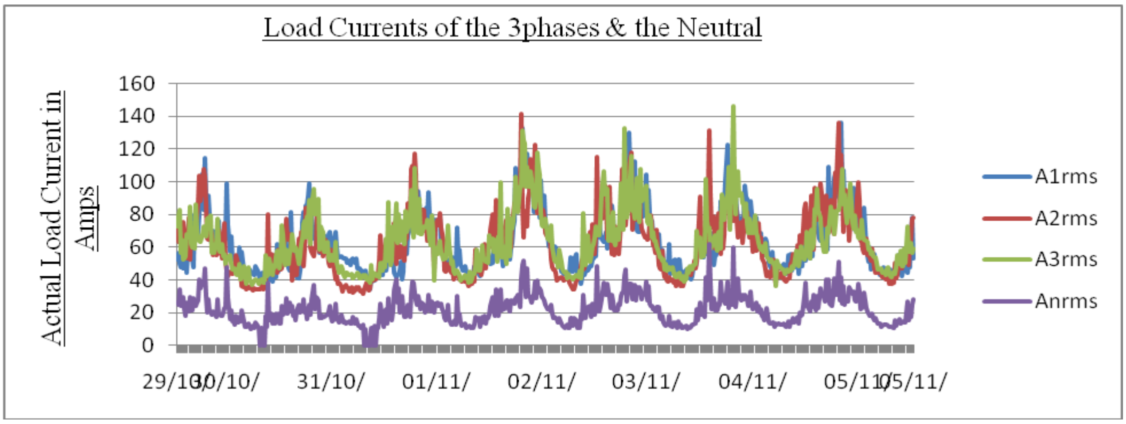

Fig. 4.6 Kilmorey Line Currents (A1;A2;A3)rms

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 Fig. 4.7. There was balanced loading on the 3 phases between 00:35:12 to 10:49:36 of 3rd Nov. But between 10:49:36 to 23:54:40 the unbalanced loading was highest, and this occured at 14:14:24 hours. The loads were A_1= 62A; A_2= 131A; A_3 = 72.1A; A_N= 62A. The neutral current (A_N) should be zero, but had a minimum of 10.1A at 09;11;12 hrs. (Fig. 4.6). The 62A on the A_N is 47.3% of the highest load current of A_1 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.

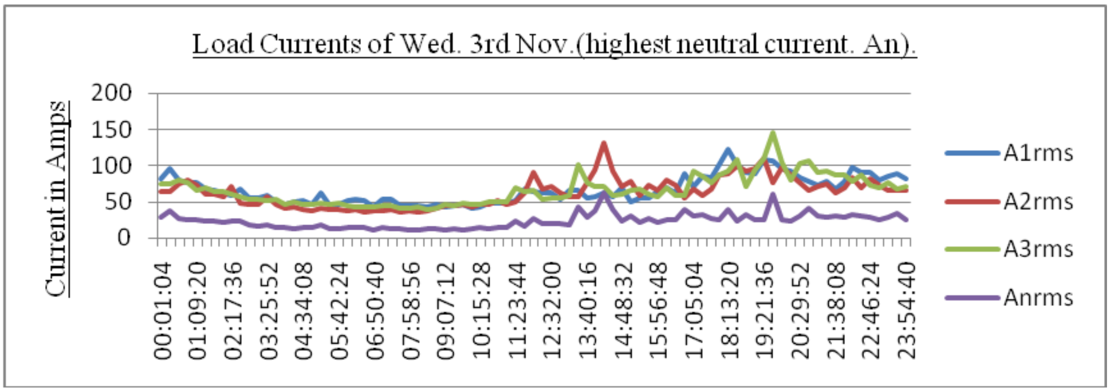

Fig 4.7 Kilmorey Hall Load Currents of Wednesday 3rd November 2010.

4.5 Active, Reactive and Apparent Power

The week's recorded data of active, reactive and apparent powers of Kilmorey Hall as shown in Fig. 4.7 showed that 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. (Fig. 4.8 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

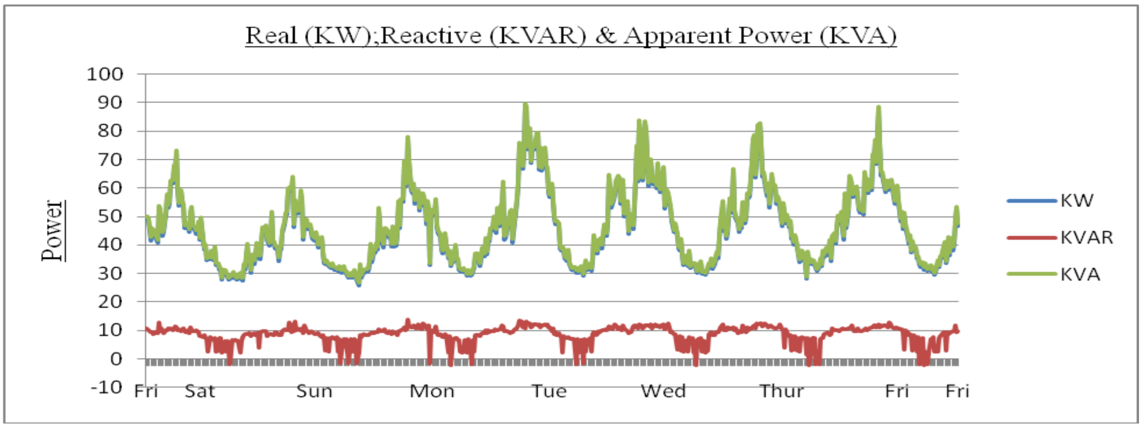

Fig. 4.8 Kilmorey Hall Loading of the week (Fri. 29th to Fri. 5th Nov)

Fig. 4.8 shows that the highest apparent load of 89.64 KVA was recorded on 01/11/10 at about 19.17.20hrs. This is a residential hall with minimum load in the morning unlike Tower A. 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.

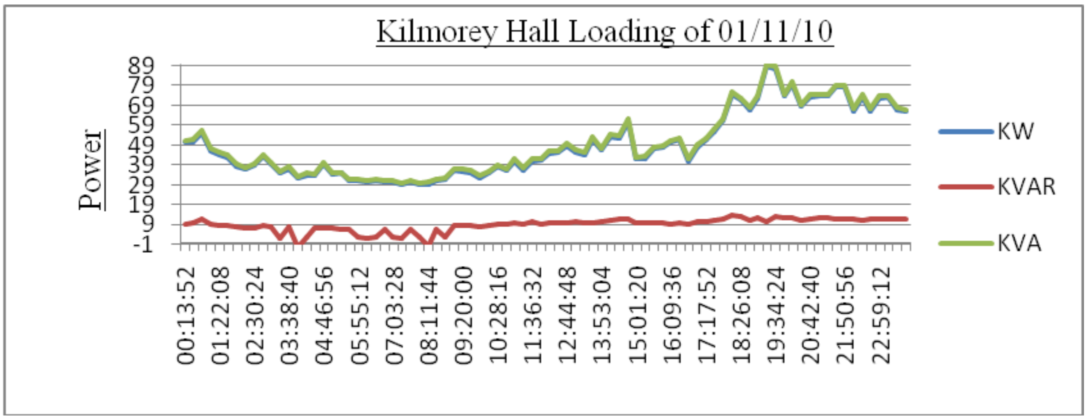

Fig. 4.9 Kilmorey Hall loading of Monday, 01/11/10

4.6 Harmonic Distortions in Kilmorey Hall load.

Some detrimental effects of harmonics are

1) Mal-operation of control devices, for example, nuisance tripping of circuit breakers, overloading of switchgear and cables, excessive currents in the neutral conductors
2) Overloading of Capacitors, thus leading to additional heating in Capacitors, Transformers, rotating machines leading to overloading of Transformers and overheating of machines.
3) Telephone interference.
4) Additional noise from motors and other apparatus.
5) Causing parallel and series resonance frequencies due to PF correction Capacitors and cable capacitance. This results in voltage amplification even at a remote location from the distorting load.

To reduce and control harmonics, the following can be applied,

1) High- pulse rectification
2) Passive, Active and hybrid filters.
3) Custom Power devices like Active Power Line Conditioners and Unified PQ conditioner. [34]

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.

4.6.1 Current harmonic distortions

The load of Nov. 3rd showed the neutral current (An) rms to be as high as the phase current (A_1) rms at 14:14:24hrs. A_1 = 61.8A; A_2 = 131.0A; A_3 = 72.0A and A_n = 62A. This high neutral current was as a result of the unbalanced loading of the phases and the presence of harmonics, especially the 5th. Fig. (4.11)

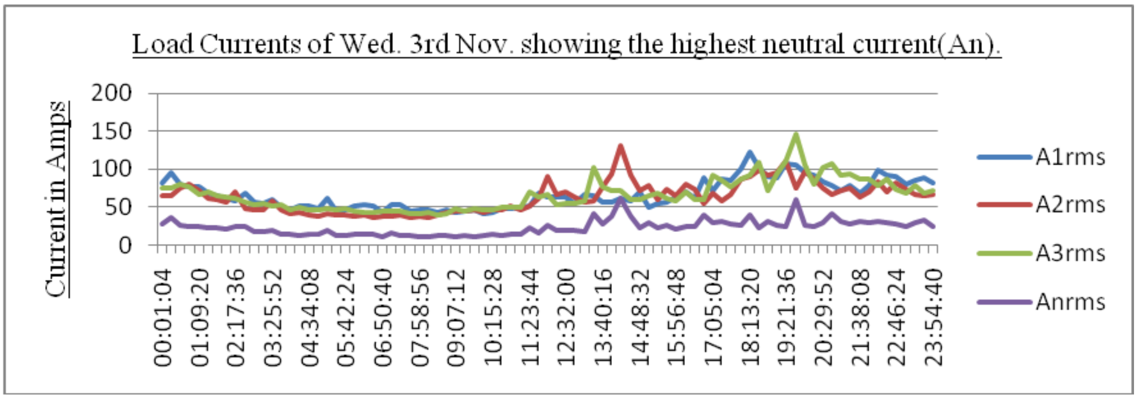

Fig. 4.10 Kilmorey Hall Load currents of 3rd November 2010

4.6.2 Voltage harmonic distortions

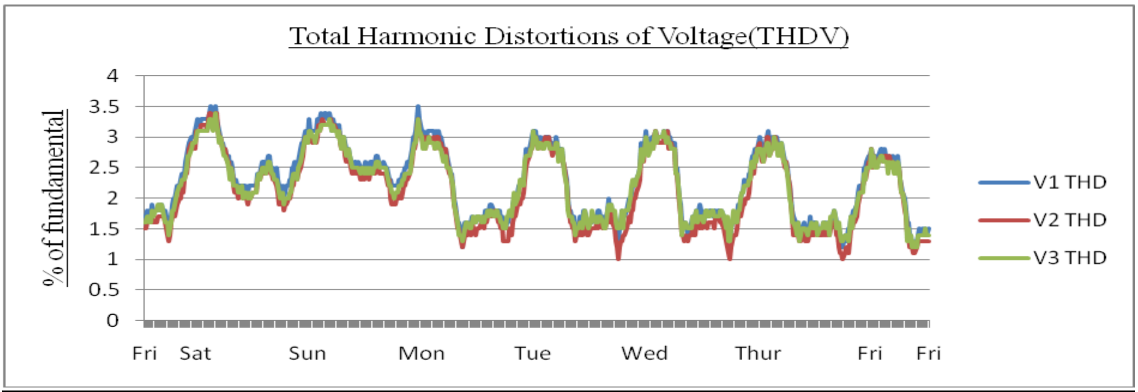

Fig. 4.11 Kilmorey Hall Total Harmonic Distortion of Voltage (THDV)

The EN50160 gives the limit of 8% for THDV for LV system, in one week monitoring period and Fig. 4.10 shows that the highest THDV was 3.5% on phase 1. Therefore the limit is not violated. [37] [Appendix B_3]

The individual voltage harmonics chart showed that the 5th and 7th harmonics are present as shown in Fig. 4.11. The highest distortion was the 5th harmonic which was 3%, and the 7th harmonic was about 0.5%. The International standard EN50160 gives the limits of 5th harmonic distortion to be 6% and the 7th to be 5%. [37], [Appendix B_4]. These limits were not violated.

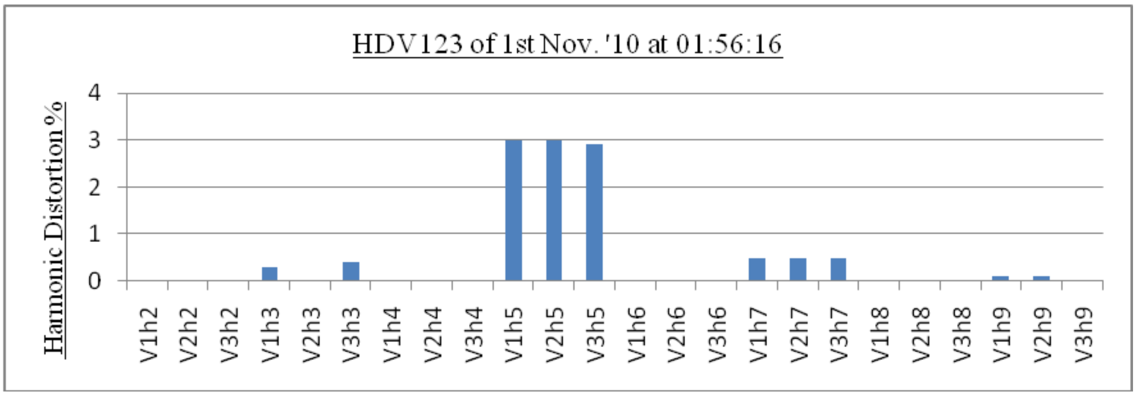

Fig 4.12 HDV_{123} of 1st Nov. '10 at 01:56:16

Mitigation measures to limit harmonic pollution include

1) Neutral up- sizing
2) Passive filter application
3) Active filter application
4) Hybrid filter application
5) Use of K- rated Transformers

4.7 Short-term Flicker of the voltage at Kilmorey Hall.

The result of the case study for Kilmorey hall (29th Oct – 5th Nov.) had its highest measured short-term flicker on the 5th of Nov as shown below in Fig. 4.11.

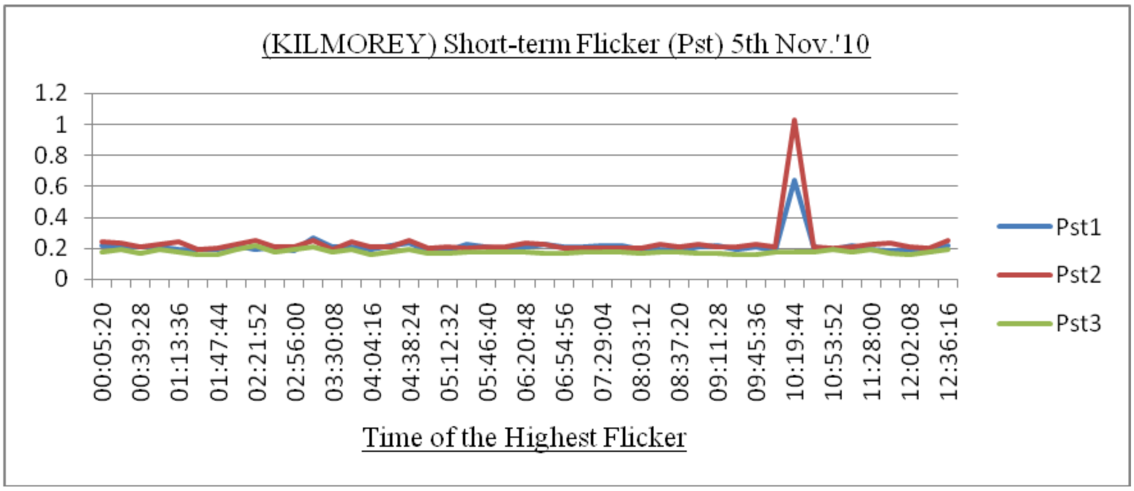

Fig. 4.11 Short-term Flicker (Pst) of 5th November 2010

At exactly 10:19:44 of the 5th of November the highest flicker was on 2nd phase (Pst_2) =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 minutes, so it has not transgressed the International limits. The International Standards [14]requires that the value of the short-term flicker severity index $Pst \leq 1.0$, and the value of the long-term flicker severity index $Plt \leq 0.65$

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%. The conditions above have assumed that the network voltage is constant at no-load without voltage fluctuation.[39, 40].

4.8 Summary

In this chapter the data monitored from 29th October to 5th November indicated that input voltage was consistently high (445.0V). 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% [27]. There was high neutral current A_N, 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 19.17hrs 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 10minutes, this has not violated the EN50160 standards on short-term flicker.

Chapter Five

Characterizing the THD of

Office (Tower A) and Residential (Kilmorey) Hall Buildings

5.1 Introduction.

Quantification and qualification of the harmonic distortion of voltage and current were carried out by statistical method of analysis, to establish the limits. Tower A, an office complex and Kilmorey Hall, a Residential Hostel are located in the same campus.

This chapter presents the results of measurement made in both buildings within one week. The statistical methods of analysis of the data allowed the establishment of the correct period to characterize the harmonic distortion. Statistical method was used because of the following reasons:

It provides other alternative methods to solving the power quality problems by correctly qualifying and quantifying the degree of distortion. The present method of applying the International Standards could not be adapted easily to measurements of harmonic distortions. The rate of increase in harmonic pollution in any electrical establishment is on rapid increase as almost all electrical appliances newly connected have one form of harmonic distortion or other thereby causing power quality problems. Statistical method would be able to cope with the volume of data involved. Therefore the statistical method could be a good alternative in characterizing the harmonic distortions in buildings. The objective of this chapter was to establish proceedings to guide efforts of measuring voltage harmonics distortions [32]. The statistical analysis helped to show that the best period to characterize the harmonic distortions for the office building like Tower A was between the hours of 08.00 hrs. - 18.00 hrs, whereas the Kilmorey Hall was best characterized between 12.00 hrs – 01.00 hrs of the second day.

5.2 Statistical Comparison of the Tower A and Kilmorey Hall.

The two buildings were compared in the following ways from the collected data:

1) Phase similarity.
2) Data frequency Acquisition Analysis.

Four different methods were employed:

a) Graphic Comparison.
b) Mean value and Standard Deviation analysis.
c) P95% Analysis. [32]

5.2.1 Phase Similarity. - Graphic Comparison.

The load curves for the two buildings are shown below in figs. 5.1 and 5.2. The Fig 5.1 has a typical office profile while Fig. 5.2 showed a typical hostel residential profile. Tuesday 26th Oct. 2010 was the highest loading day of the week for Tower A. Tuesday 2nd Nov. 2010 was chosen for Kilmorey Hall. Hours of operation of Tower A were from 08.00 to 18.00, while Kilmorey Hall had minimum loading between the hours of 04.00 to 09.00. The usual early morning peak of any residential building was absent in this case.

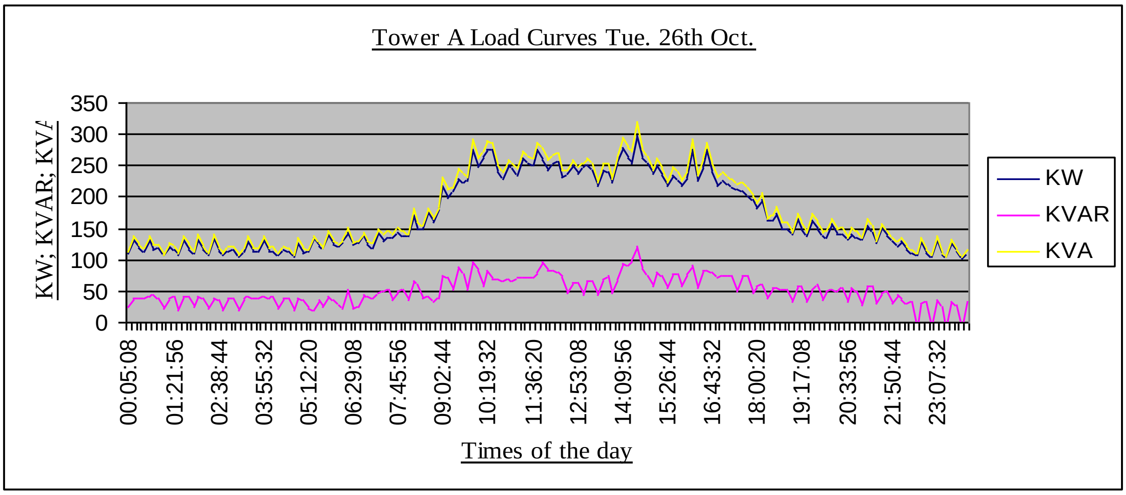

Fig. 5.1 Load curve of Tower A Lecture and Office Building

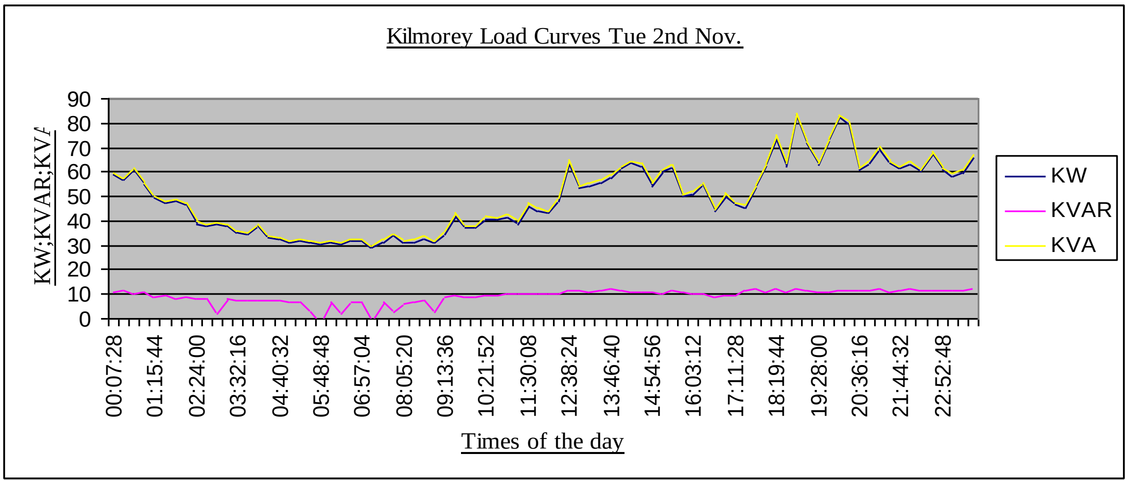

Fig. 5.2 Load curves Kilmorey Residence Hall

Fig. 5.1 shows typical day load pattern of an office building. Kilmorey Hall in Fig. 5.2 shows a mixture of day and night load pattern on a typical day. There is no phase similarity between the 2 buildings.

5.2.2 Mean Value and Standard Deviation Analysis.

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. [10, 32]

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%. [32].

The collected data was 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 5.1 for Tower A showed that the dispersion range among the phases of each day of the $THDV_1$ average values (from 2.262 to 2.118) for office Tower A on 26th was small. The Kilmorey hall's values for the Saturday 30th October (from 2.632 to 2.494) in Table 5.2 showed that the average and standard deviation values are higher than on weekdays. For both buildings, the phases V_1 and V_3 show higher THDV averages than V_2 for all the days.

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

Table 5.1 Tower A Calculated Mean and Standard Deviation values for the THDV

Days	THDV1 %	THDV2 %	THDV3 %
Sat. 30th Oct. '10	2.632 ± 0.430	2.494 ± 0.470	2.513 ± 0.418
Tues. 1st Oct. '10	2.166 ± 0.590	2.018 ± 0.608	2.094 ± 0.536
Thur. 3rd Nov. '10	2.167 ± 0.593	2.005 ± 0.634	2.125 ± 0.569

Table 5.2 Kilmorey Calculated Mean and Standard Deviation values for the THDV

5.2.3 P95% Analysis

For the THDV1 to be less than 1%, considering the 30th October which has the highest Mean and STDEV:

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

$$= \frac{1-2.632}{0.43} = -3.79$$

$$\Phi = 1-0.99992 = 0.00008$$

$$= 0.008\%$$

THD < 2% $$Z = \frac{2-2.632}{0.43} = -1.47$$

$$\Phi = 1-0.92785 = 0.07215$$

$$= 7.215\%$$

THD < 3% $$Z = \frac{3-2.632}{0.43} = 0.855$$

$$\Phi = 0.80$$

$$= 80\%$$

THD < 4% $$Z = \frac{4-2.632}{0.43} = 3.18$$

$$\Phi = 0.99926$$

$$= 99.926\%$$

THDV	< 1%	< 2%	< 3%	< 4%	< 5%
P	0.008	7.215	80	99.926	100

Table 5.3 Probability of the THDV1 less than 5%

Considering the qualitative analysis of the collected data, limits were compared with the International Standards.

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% [16]. From Table 5.3, the highest value of THDV was never higher than 8%. The THDV was under the compatibility level of 8%.

In conclusion, it was established that both buildings follow the two international standards and the limits were not trespassed.

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Chapter Six

Conclusions and Future Research

6.1 Conclusions

This thesis provided an overview for power quality problems that exist in modern (commercial and residential buildings). The consequence of electrical disturbance has become more serious considering the present economic situation. 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.

The present approach establishing a relation between voltage and power consumption both for active and reactive power is not conclusive. It was proved that power consumption figures would be significantly less at lower voltage level, but more investigations into residential, commercial and industrial loads are needed to establish this. When commercial consumers' voltage level increases significantly it produces high unwanted power consumption, because of heavy presence of passive and resistive loads. This needs further research. The theoretical proof from section 3.1.4 shows that an increase of 10% in a supply voltage of 230V increases the power consumption by 21%., and reducing the supply voltage by 10% could reduce power consumed by 19%. Keeping the voltage above the normal voltage (230V / 400V in Europe) should be avoided because of high increase in active and reactive power demand. If the international voltage range is observed and the upper limit is kept, unwanted power consumption would likely result and higher losses will also be incurred. Effect of higher voltage on load appliances in aging and insulation would need further investigation. Keeping the voltage slightly below the nominal value is acceptable.

Comparison of the commercial- office with residential buildings showed the changing load pattern of the residential having increasing harmonics and neutral currents like the office building. The thesis 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.

6.2 Future Research

There are many points which can be further investigated in this field. Some of these points are summarised below:

- The present approach establishing a relation between voltage and power consumption both for active and reactive power is not conclusive. It was proved that power consumption figures would be significantly less at lower voltage level, but more investigations into residential, commercial and industrial loads are needed to establish this. When commercial consumers' voltage level increases significantly it produces high unwanted power consumption, because of heavy presence of passive and resistive loads. This needs further research.
- Mass application of Compact fluorescent lamps with electronic gear in modern and commercial establishments is becoming as bad in generating harmonic distortions as computers and other SMPS. These CFLs cause network voltage distortion, occurring due to their distorted currents, with high level of harmonic components. Further research analyses dealing with the influence of CFLs on power systems are necessary, especially on massive residential distribution network intermingled with modern commercial buildings. The production of harmonic currents causing corresponding system harmonic voltage, mostly the triple-n harmonics could mean major power quality problems for the MV/LV sub-transmission transformers of the delta-wye types.

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Appendix A

C.A 8335

Power & Quality Analyser

The QualistarPlus C.A 8335

Power & Quality Analyser

Recorder and analyser for measurements on electrical power networks

Technical Specifications

The QualistarPlus C.A 8335 is synonymous with simplicity, performance, versatility and powerful analysis. It offers all the necessary functions with demanding specifications usually reserved for top-of-the-range laboratory instruments. This instrument is ideal for engineers and technicians seeking all the functions of an electrical network analyser in a portable, battery-powered instrument.

• Real-time display of wave forms (4 voltages and 4 currents)

• RMS voltage and currents per half-period

• Intuitive use

• Automatic recognition of the different types of current sensors

• Integration of all the DC components

• Measurement, calculation and display of the harmonics up to the 50th order, along with the phase information

• Calculation of Total Harmonic Distortion (THD)

• Capture of transients per sample (1/256th of a period)

• Display of phasor diagram
• Measurement of VA, W and var power values (total and per phase)
• Measurement of VAh, Wh and varh energy values (total and per phase)
• Calculation of the K-Factor
• Calculation of the cosϕ, displacement power factor (DPF) and the power factor (PF)
• Capture of up to 300 transients
• Flicker calculation
• Unbalance calculation (current and voltage)
• Monitoring of the electrical network with setting of alarms
• Back-up and recording of screenshots (image and data)
• Software for data recovery and real-time communication with a PC
• Recording and export onto PC

2. GENERAL SPECIFICATIONS

1.1. Casing

Casing: Rigid moulded casing over-moulded with a yellow thermo-adhesive elastomer.
Connectors: 5 voltage measurement sockets.
4 special current connectors (automatic recognition of clamp-on ammeters).
A connector for the specific mains power supply.
A connector for the USB link.
A connector for the SD memory card.
This is located in the compartment on the back of the C.A 8335, under the rechargeable batteries.
Keys: For functions, navigation and mode changes. Designed to allow use with gloves.
Metal ring: Located on the back of the C.A 8335.
It can be used to attach the instrument with a padlock.
Stand: To keep the instrument at an angle of 53° in relation to the horizontal.
Compartment: For access to the rechargeable batteries at the rear of the instrument.
Dimensions: Total: 200 x H 250 x P 67
Screen: 320 x 240 pixels, W 118 mm x H 90 mm diagonal 148 mm
Weight: 1.950 g (with rechargeable batteries)

1.2. Power supply

1.2.1. Mains power supply

Type: Specific external mains power supply: 600 VRMS category IV – 1,000 VRMS category III

Operating range:

230 V ± 10 % @ 50 Hz **and** 120 V ± 10 % @ 50 Hz

Max. power: 40 VA

1.2.2. Battery power supply

The C.A 8335 can be used without a mains power supply.

The battery also allows the Qualistar+ to be used in the event of mains power cuts.

Battery: 8 rechargeable NiMH batteries

Capacity: minimum 4,000 mAh

Rated voltage: 1.2 V per element, 9.6 V in total

Life span: at least 500 recharge-discharge cycles

Recharge current: 1 A

Recharge time: Approximately 5 hours

Operating T°: [0 °C ; 50 °C]

Recharge T° [10 °C ; 40 °C]

Storage T°: Storage for 30 days:

[-20 °C ; +50 °C]

Storage for 30 to 90 days:

[-20 °C ; +40 °C]

Storage for 90 days to 1 year:

[-20 °C; +30 °C]

1.2.3 Consumption

With 50% brightness: 300 mA

Standby mode without display: 100 Ma

Appendix B

List of International Power Quality Standards

(B_1)IEC Power Quality standards

The IEC Power Quality standards are as follows:

1. IEC 61000-4-7 Harmonic and Interharmonics measurement technique.
2. IEC 61000-4-11 Voltage sag immunity – 16 amps or less.
3. IEC 61000-4-15 Flicker measurement Standards. (formerly IEC 868)
4. IEC 61000-4-34 Voltage sag immunity – more than 16 amps.
5. IEC 61000-4-30 Power Quality measurement methods.
6. General IEC power quality standards.
    a. 61000-1-X Definitions and methodology.
    b. 61000-2-X Environment (e.g. 61000-2-4 is compatibility levels in industrial plants).
    c. 61000-3-X Limits (e.g. 61000-3-4 is limits on harmonic emissions).
    d. 61000-4-X Tests and measurements (e.g.61000-4-30 is power quality measurements)
    e. 61000-5-X Installation and mitigation.
    f. 61000-6-X Generic immunity and emissions standards.
7. IEC SC77A: Low frequency EMC Phenomena – essentially equivalent of ‘power quality’ in American terminology, subdivided into:
    a. TC 77/ WG 1: Terminology (part of the parent Technical Committee)
    b. SC 77A/WG 1: Harmonics and other low-frequency disturbances.
    c. SC 77A/WG 2: Voltage fluctuations and other low-frequency disturbances.
    d. SC 77A/WG 6: Low frequency immunity tests.
    e. SC 77A/WG 8: Electromagnetic interference related to the network frequency.
    f. SC 77A/WG 9: Power Quality measurement methods.
    g. SC 77A/61000-3-1: Electromagnetic Compatibility (EMC) – Part 3-1: Limits – Overview of emission standards and guides.

(B_2) IEEE Power quality standards

The different groups/committees in IEEE are as follows:

1. IEEE SCC-22: Power Quality Standards Coordinating Committee.
2. IEEE 1159: Monitoring Electric Power Quality. This committee is subdivided into;
    a. IEEE 1159.1 Guide for Recorder and Data Acquisition Requirements (measurements).
    b. IEEE 1159.2 Power Quality Event Characterizations.
    c. IEEE 1159.3 Data File Format for Power Quality Data Interchange.
3. IEEE P1564: Voltage and Sag Indices.
4. IEEE 1346: Power System Compatibility with Process Equipment.
5. IEEE P1100: Power and Grounding Electronic Equipment (Emerald Book).
6. IEEE1433: Power Quality Definitions.
7. IEEE P1453: Voltage flicker.
8. IEEE 519: Harmonic Control in Electrical Power Systems.
9. IEEE Harmonic Working Group.
    a. Single-phase Harmonic Task Force.
    b. IEEE P519A Guide for Applying Harmonic Limits on Power Systems.
    c. Interharmonics Task Force.
    d. Harmonics Modelling and Simulation Task Force.
    e. Probabilistic Aspects of Harmonic Task Force.
10. Surge Protective Devices Committee (having 17 Sub-committees).
11. IEEE P446: Emergency and Standby power.
12. IEEE P1409: Distribution Custom power.
13. IEEE P1457: Distributed Resources and Electric Power System Interconnection

(B_3) The Power Quality Standard EN 50160: 2000 [24]

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%

(B_4) Other new power quality standards are listed below

UIE: International Union for Electricity Applications

CENELEC: European Committee for Electrotechnical Standards.

UNIPEDE: International Union of Producers and Distributors of Electrical Energy

ANSI: American National Standards Institute. This is sub-divided into:

- i. ANSI C62: Guides and standards on surge protection.
- ii. ANSI C84.1: Voltage ratings for equipment and power systems.
- iii. ANSI C57.110: Transformer derating for supplying non-linear loads.

CIGRE: International Council on Large Electric Systems.

CIRED: International Conference on Electricity Distribution.

CBEMA/ ITIC curve.

Industry specific power quality standards include the Semiconductor Equipment Manufacturers International (SEMI) which has the sub-divisions of:

1. SEMI F46
2. SEMI F47
3. SEMI E6
4. Samsung Power Vaccine: Samsung's voltage sag immunity. Requirement is more stringent than SEMI.