LOAD HARMONIC MITIGATION:
A CASE STUDY AT UVA PROVINCIAL COUNCIL BUILDING

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Abstract

This thesis presents the application of active filters to mitigate the harmonic problems in an office building. Harmonics in electrical system induce additional heating. This causes premature aging, reduction of efficiency and life of the electrical equipments and components in the system. Harmonic problems can be caused by disturbances originating in the supply system, from customer's premises and from the nearby installations. The problem is due to the non-linear loads showing different current waveforms when supplied by a distorted or perfect sinusoidal voltage. Growing use of non-linear load equipment and technologies in commercial buildings has increased the severity of the problem.

This is common to Uva Provincial Council (UPC) building, as well, where a large number of connected computers, UPS and other peripherals are major sources of harmonics. The site measurements revealed that the non-linear loads generate TDD up to 15 % and the individual harmonic distortion up to 38 % of the fundamental. These values exceed the maximum limits prescribed by the power quality standards, lEE 519-1992.

To mitigate the harmonic effects, various available techniques are reviewed. The active power filter (APF) is selected as a solution, as it has become the popular and advantageous options among the many practices available today. The operation of common APF topologies, namely the shunt, series and hybrid APF s are discussed in detail, and shunt APF is identified as the most simple and advantageous choice for this purpose. This is followed by a review of various strategies of harmonic detection and APF controlling. After comparing the performances of these strategies with the real life applications, suitable techniques for harmonic detection and APF controlling are formulated.

Finally, a computer model of thus developed shunt active filter is simulated using MATLAB / Simulink environment.

Based on the case study, the thesis discusses alternatives and provides some practical solutions to the problem of harmonics in office buildings.

DECLARATION

The work submitted in this Dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is not being concurrently submitted for any other degree.

UOM Verified Signature

R. M. S. K. Ratnayake
Date

We endorse the declaration by the candidate

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CONTENTS

Appendix

Acknowledgement

Thanks are due first to my supervisors, Professor Ranjith Perera and Dr H. M. Wijekoon, for their great insights and perspectives. Their valuable guidance and instructions were immensely useful for my studies. Directions of them rendered me a remarkable opportunity to share their knowledge and expertise in the area of power quality.

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List of figures

List of tables

Abbreviations

ac	alternating current
APF	Active Power Filter
ASD	Adjustable Speed Drive
CEB	Ceylon Electricity Board
CFL	Compact Fluorescent Lamp
dc	direct current
HPF	High Pass Filter
HV	High Voltage
IEC	International Electro technical Commission
IGBT	Insulated Gate Bipolar Transistor
MV	Medium Voltage
MCB	miniature Circuit breaker
MCCB	Molded Case Circuit breaker
PC	Personal Computer
PCC	Point of Common Coupling
PQ	Power Quality
PWM	Pulse Width Modulation
RMS	Root Mean Square
SMPS	Switch Mode Power Supply
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
UPC	Uva Provincial Council
UPS	Uninterruptible Power Supply
VSI	Voltage Source Inverter

Chapter 1

Introduction

1.1 Background

After invention of electricity, alternative current supply was used first for lighting and afterwards for industrial loads, as well. Earlier the factories, offices and houses were supplied by radial lines with no backups, and lengthy outages were a fact of life. With the march of time and innovation of technology, electricity became a demand for greater dependability. Accordingly, utility systems developed transmission networks with primary and secondary distribution networks. So the major concern of utilities was the improvement of reliability while using the resources more efficiently and effectively.

When utility systems grew more reliable, business grew more sophisticated. In turn reliability needs were yet emphasized. Factories and other businesses began buying backup power systems as insurance against long term outages on utility systems. Utilities also went on striving to shorten outages. Until fairly recently, power quality referred to the ability of the electric utilities to supply electric power without interruption. Today both electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power.

There are completely different definitions for power quality, depending on one's frame of reference. For example equipment manufacturer may define power quality as those characteristics of the power supply that enable the equipment to work. Power quality is ultimately a consumer-driven issue, and the end user's point of reference takes precedence. Therefore, the power quality problem can be defined as "any power problem manifested in voltage, current, or frequency deviations that result in failure or disoperation of customer equipment" [1]. Simply, the ideal power supply to a low voltage customer is 230/ 400V at 50Hz with a sinusoidal wave shape.

Today the action in power electronics is shifting expectations of power quality into an entirely different dimension. The growing number of power electronics based equipment has produced an immense impact on the quality of electric power supply. Power electronics has given us many new ways to manufacture products, provide services, and utilize energy. From a power quality impact viewpoint, applications such as follows often cause for concern.

1. Switched-mode power supplies,
2. DC arc furnaces,
3. Electronic fluorescent lamp ballasts,
4. Adjustable speed drives, and
5. Flexible ac transmission components

These converter-based systems are nonlinear. The nonlinear loads change the sinusoidal nature of the ac power current (and consequently the ac voltage drop) resulting in the flow of harmonic currents in the power system [2].

Harmonic currents result in distorted voltages and currents that can adversely impact the system performance in different ways. The harmonic voltages can lead to operational and life expectancy problems for other equipment possibly not owned or operated by the same party. Both high power industrial loads and domestic loads cause harmonics in the network voltages. At the same time, much of the equipment causing the disturbances is sensitive to the Harmonic distortions. The operations of some equipment depend on an accurate voltage wave shape and they can malfunction when harmonics are present. Harmonics such as that occur in commercial buildings due to many single phase distorting loads appeared across three phase can give neutral current exceeding the active line current.

With excessive levels of harmonics there is risk of

- Overheating the neutral conductor with loss of conductor life and possible risk of fire
- Affecting the digital equipment and local area networks (LANs) if the Earthing system is poor

- Overheating the induction motor windings causing accelerated degradation of insulation and loss of life
- Extra heating of transformers leading to a reduction in their service life
- Overheating of the dielectric of transformers with a risk of explosion
- Malfunctioning of equipment trips
- Overheating of equipment and reduction in their service life

Unlike most other types of supply problems, harmonics can go unnoticed for many years unless equipment temperature or the voltage waveform is routinely monitored.

Offices located in subject premises also reported to have several of similar experiences as above, and hence identified as a location where there is a good chance of existence of power quality problems caused by harmonics.

1.2 Motivation

Over the last 20 years utilization of power electronic devices in energy conversion has increased dramatically. Power electronics technology has played a major role in creating power quality problems. The increasing number of highly nonlinear and unbalanced distorted loads leads to operational and life expectancy problems for other equipments, as well. Therefore, following the wide use of electronic appliances, harmonics has become a serious concern for electrical engineers.

When it is looked into the utility side, since its establishment in 1969, CEB has been paying much concern on improvement of reliability of the supply. However, a lesser attention has been paid for power quality improvement. Sometimes the customers are severely affected by power quality problems that exist in the system and hence the time has come to look into the power quality issues in deep.

Power quality problem can be caused by disturbances originating in the supply system, from customer's premises and from the nearby installations [1]. Responsibility for external disturbances such as outages, sags and spikes due to switching, originated in the transmission and distribution network are acceptable by the utility. For harmonic disturbances utilities are not to be blamed, but the customers themselves are also responsible for drawing excessive non-linear currents. Due to the unavailability of proper monitoring system and regulations, and due to the lack of customer knowledge, the utility as well as the customers do not work in earnest to mitigate the voltage distortions generated by non- linear load currents.

The harmonic currents produced by non-linear loads can interact adversely with a wide range of power system equipment causing additional losses, overheating, and overloading [2]. Because of adverse effects that harmonics have on customers' equipments, it is a prime importance of customers to adapt proper customer side mitigatory measures to bring down the harmonic levels in their electrical system to a favorable limit.

On the other hand, in order to avoid deterioration of the quality of power supplied to customers, regulators are going to have to expand their thinking beyond traditional reliability indices and address the need for power quality reporting and incentives for the transmission and distribution companies. Now that we are having Public utility commission as the regulatory body, empowered under Sri Lanka Electricity Act no 20 of 2009, power quality matters will be more emphasized. As the application of semiconductor devices are further advancing, there is a need of defining a suitable framework for harmonic control to ensure steady- state harmonic limits that are acceptable by both electric utilities and customers. In that case, the customer also will have to play a role to suppress their harmonic current that injected back into the distribution system.

This phenomenon is common to Uva provincial Council building at Badulla, also. A comprehensive study on power quality problems in the selected premise will be a good contribution in order to make avenue to the area of power quality research on problems originated in customer side. Therefore, being an Electrical engineer attached to Ceylon Electricity Board, I have been greatly motivated to carry out this project.

1.3 Goals of the research

The main objectives of this research are

1. to investigate the power quality of electricity supply of Uva Provincial council building,
2. to design an active filter for filtering out the harmonics injected by load of provincial council building,
3. to develop a model for active filter and simulate it using MATLAB /Simulink environment,
4. and to make an avenue to the area of power quality research on problems originated in customer side.

1.4 Scope of Work

Based on the case study, this thesis discusses the sources and effects of harmonics in power systems and some practical solutions to the problem of harmonics in office buildings. It discusses possible harmonic mitigation techniques and compares the pros and cons of various available measures. Out of the different available techniques, the active power filter compensation with relevant control method is focused in this study.

The current (first) chapter provides an introduction to the harmonic concept and defines the thesis subject. It outlines what inspired me to do this research and its aspirations. And it gives an overview of the subject and the contents of the chapters in the thesis, as well.

The second chapter discusses the fundamentals of harmonics in power systems in details together with the causes and effects therein. This chapter presents the most commonly used theory of harmonics and available harmonics standards.

The third chapter covers the practical measurements done at Uva provincial council. It compares the collected data with harmonics standards and identifies the power quality problems in the existing system.

Harmonic mitigation techniques their pros, cons and capabilities under practical situations are discussed in the fourth chapter.

The fifth chapter describes the computer modelling and controlling of a shunt active filter and simulating it with an example load under MATLAB/Simulink environment.

The sixth and final chapter provides the concluding remarks that summarize the research results and gives future work recommendations on subjects related to the thesis.

Chapter 2

Power system Harmonics & their Impacts

2.1 Introduction

This chapter basically describes what harmonics are, and introduces various terminology related with harmonics. It covers description on sources of harmonics, their effect on various electrical equipments, and the standards of harmonics.

2.2 What are harmonics?

The typical definition for a harmonic is "a sinusoidal component of a periodic wave or quantity having frequency that is an integral multiple of the fundamental frequency " [2]. Simply express, harmonics is the name given to the multiples of the fundamental 50 Hz frequency that powers our homes and businesses. Harmonics can be voltage and/or current present in the electrical system in multiples of the fundamental frequency. The even frequencies are a result of dc voltages on the busses, and the odd frequencies are a result of ac voltages. Some references refer to "clean" or "pure" power as those without any harmonics [3]. But such clean waveforms do not exist practically. Due to widespread use of electronic equipment in today's commercial and industrial environments, the actual voltages and currents in the power system are not purely sinusoidal but are periodic in the steady state. Any periodic non sinusoidal function of a fundamental frequency "f" may be expressed as the sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency. This multiple is called a harmonic of the fundamental. **Figure 2.1** Illustrates the representation of distorted waveform with a sum of sine waves.

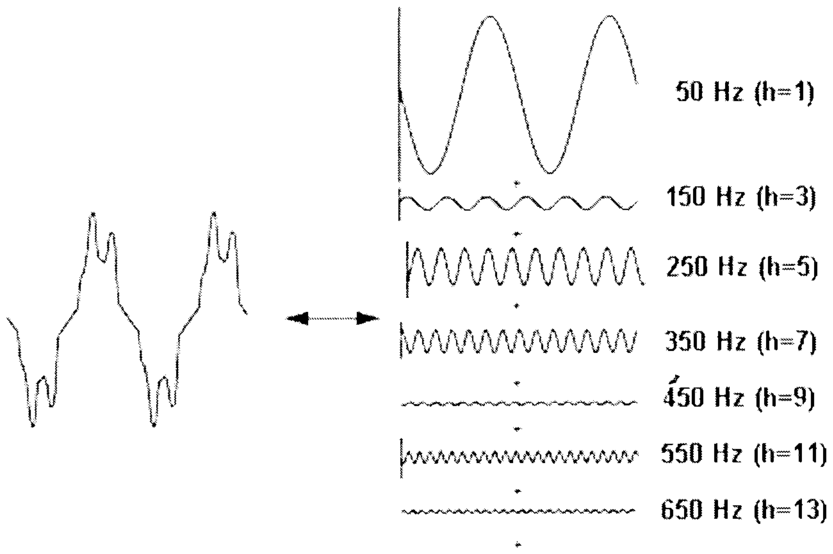

Figure 2.1 Representation of a distorted waveform

A sinusoidal voltage or current function that is dependent on time t may be represented by the following expressions:

Voltage function, $v(t) = V\sin(\omega t)$

Current function, $i(t) = I\sin(\omega t+\emptyset)$

Where $\boldsymbol{\omega = 2\pi f}$ is known as the angular velocity of the periodic waveform and $\boldsymbol{\emptyset}$ is the difference in phase angle between the voltage and the current waveforms referred to a common axis. The sign of phase angle $\boldsymbol{\emptyset}$ is positive if the current leads the voltage and negative if the current lags the voltage.

For a periodic non sinusoidal waveform the same expression may be written as,

$$V(t) = V_0 + V_1\sin(\omega t) + V_2\sin(2\,\omega t) + V_3\sin(3\,\omega t) + \ldots\ldots\ldots\ldots + V_n\sin(n\,\omega t) + V_{n+1}\sin((n+1)\,\omega t) + \ldots\ldots\ldots\ldots$$

In this expression V_0 represents the constant or the DC component of the waveform. $V_1, V_2, V_3, \ldots\ldots$ are the peak values of the successive terms of the expression. These terms are known as the *harmonics* of the periodic waveform.

2.2.1 Harmonic Number

***Harmonic number** (h)* refers to the individual frequency elements that comprise a composite waveform. For example, h=3 refers to the third harmonic component with a frequency equal to three times 50 Hz or 150 Hz. Harmonic number 1 is assigned to the fundamental frequency component of the periodic waveform and harmonic number 0 represents the constant or DC component of the waveform.

2.2.2 Odd and even harmonics

Harmonics with odd harmonic numbers (e.g. 3, 5, 7, 9, 10) are known as ***odd harmonics*** and that of with even harmonic numbers (e.g. 2, 4, 6, 8, 10) are known as ***even harmonics.*** Except in very few cases only odd harmonics are dominant in the power systems. Symmetrical waves contain only odd harmonics and un-symmetrical waves contain even and odd harmonics. A symmetrical wave is one in which the positive portion of the wave is identical to the negative portion of the wave. An un-symmetrical wave contains a dc component (or offset) or the load is such that the positive portion of the wave is different from the negative portion. Except in very few cases only odd harmonics are dominant in the power systems.

2.2.3 Inter harmonics

Voltage or current having frequency component that are not integer multiples of the fundamental power frequency are called as ***inter harmonics*** [3]. A special category of inter harmonics which are having frequency values less than the fundamental is called ***sub harmonics***. Inter harmonics, always present in the power system, have recently become of more importance since the widespread use of power electronic systems results in an increase of their magnitude.

Inter harmonics may be generated at any voltage level and are transferred between levels. Inter harmonics generated in HV and MV systems are injected into the LV system and vice versa. Their magnitude seldom exceeds 0.5% of the voltage fundamental harmonic, although higher levels can occur under resonance conditions.

The main sources of interharmonic waveform distortion are static frequency converters, cyclo-converters, induction motors, and arcing devices [4].

Table 2.1 summarizes the different forms of harmonics with respect to fundamental frequency of 50 Hz.

Frequency (*f*)	***Value of n***	***Type***
$f = 50n$	0	DC Component
$f = 50n$	1	Fundamental
$f = 50\,n$	n > 0	Harmonics
$f \neq 50\,n$	n < 0	Sub harmonics
$f \neq 50\,n$	n > 0	Inter harmonics
$f = 50n$	n > 0 ; n is odd	Odd Harmonics
$f = 50\,n$	n > 0; n is even	Even Harmonics

Table 2.1 Spectrum of harmonics

2.2.4 Harmonic phase Sequence

Traditionally, symmetrical components are used to describe three phase power system behavior. Under that concept, three phase system is transformed into three single phase systems that are much simpler to analyze. Similarly, this method can be employed for analysis of the response of power systems to harmonic currents, also.

In a balanced three-phase electrical system, the voltage and currents have a positional relationship. The three voltages are 120° apart and so are the three currents. The normal phase rotation or sequence is a a-b-c, which is counterclockwise and designated as the positive-phase sequence. For harmonic analyses, this relationship is still applicable, but the fundamental components of voltages and currents are used as reference. The fundamental frequencies have a positive-phase sequence.

The positive sequence set contains three sinusoids displaced 120° from each other with normal a-b-c phase rotation. Sinusoids of the negative-sequence set are also displaced 120° but have opposite phase rotation. The sinusoids of the zero sequence are in phase with each other.

For the fundamental frequency current components in a three-phase power system:

$$i_{a1} = I_{a1} \sin \omega t$$
$$i_{b1} = I_{b1} \sin (\omega t\text{-}120)$$
$$i_{c1} = I_{c1} \sin (\omega t\text{-}240)$$

The harmonic phase sequence can be determined by multiplying the harmonic number h with the normal positive sequence phase rotation [1]. When we apply this to third harmonics,

$$i_{a3} = I_{a3} \sin 3\ \omega t$$
$$i_{b3} = I_{b3} \sin 3\ (\omega t\text{-}120) = I_{b3} \sin (3\omega t\text{-}360) = I_{b3} \sin 3\omega t$$
$$i_{c3} = I_{c3} \sin 3\ (\omega t\text{-}240) = I_{c3} \sin (3\omega t\text{-}720) = I_{c3} \sin 3\omega t$$

The expression for the third harmonics shows that they are in phase and have zero displacement angles between the third harmonic currents, and therefore, are zero sequence.

The expression for the fifth harmonic current are

$$i_{a5} = I_{a5} \sin 5\omega t$$
$$i_{b5} = I_{b5} \sin 5(\omega t\text{-}120^\circ) = I_{b5} \sin (5\omega t\text{-}600^\circ) = I_{b5} \sin (5\omega t\text{-}240^\circ)$$
$$i_{c5} = I_{c5} \sin 5(\omega t\text{-}240^\circ) = I_{c5} \sin (5\omega t\text{-}1200^\circ) = I_{c5} \sin (5\omega t\text{-}120^\circ)$$

The expression indicates that, for the fifth harmonic the phase sequence is clockwise and opposite to that of the fundamental. Hence the fifth harmonics are ***negative sequence.***

Similar expression could be derived for the seventh harmonics and it would reveal that the seventh harmonics have same phase sequence as the fundamental, hence are called ***positive sequence*** harmonics.

Harmonic sequences for different harmonic orders are illustrated in **Figure 2.2.**

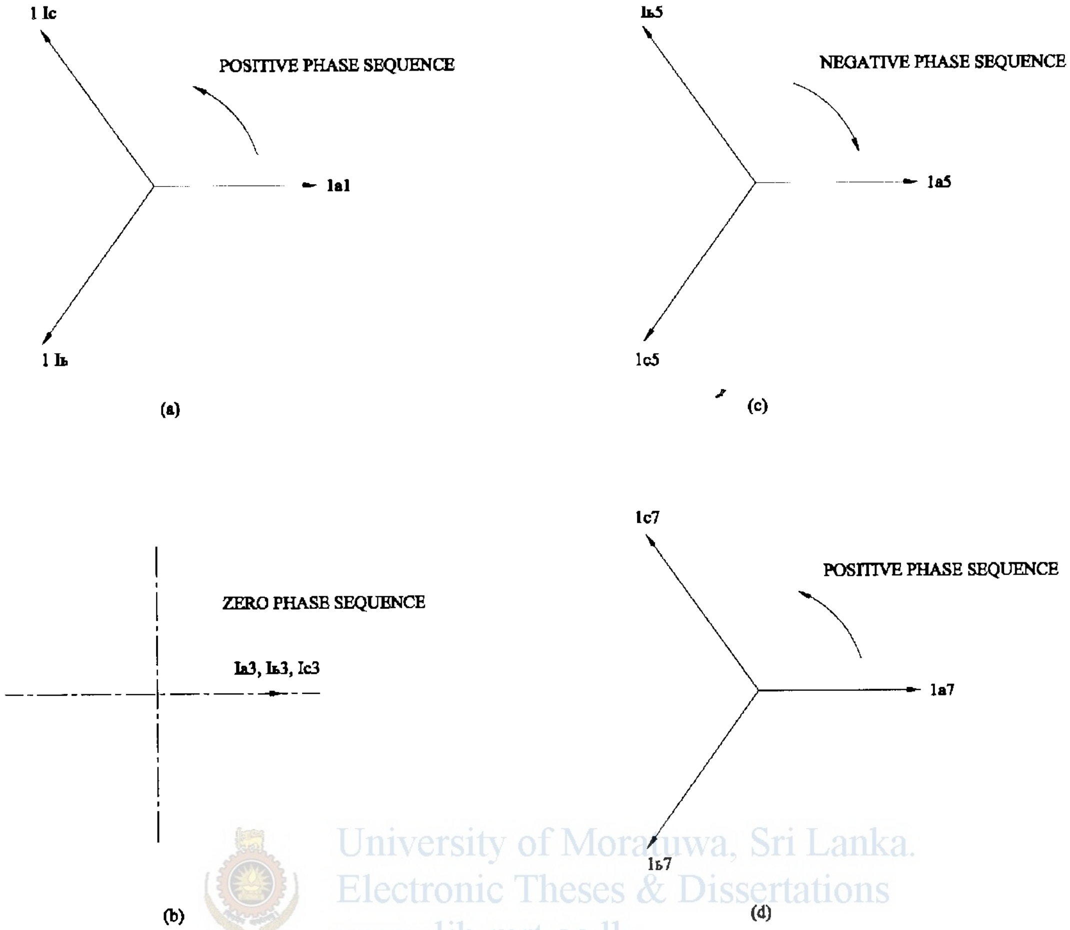

Figure 2.2 **Phase sequences of (a) Fundamental, (b) Third harmonics, (c) Fifth harmonics and (d) Seventh harmonics**

Phase sequence rotations of harmonics are summarized in **Table 2.2**

Harmonic	Fund	2nd	3rd	4th	5th	6th	7th	8th	Etc.
Sequence	+	-	0	+	-	0	+	-	…

Table 2.2 Harmonic sequencing values.

2.2.5 Triplen harmonics

Triplen harmonics are the odd multiples of the third harmonics (h=3, 9, 15, 21.....) [3]. They deserve special consideration because system response for triplen harmonics are different from others. In three phase wye circuits, triplen harmonics are accumulate in the neutral. Therefore, in grounded wye systems, triplen becomes an important issue.

2.2.6 Crest factor

The crest factor of any waveform is the ratio of the peak value to the RMS value.

$$Crest\ factor = \frac{Peak\ value}{RMS\ value}$$

Crest factor of pure sinusoidal waveform is equal to $\sqrt{2}$. Therefore, the crest factor can be used to determine the existence of distorted waveforms. The high crest factor of current waveforms in a power system is a sign of a harmonic distortion [5].

2.2.7. True power factor and displacement power factor

When harmonic currents present, the total power factor or "*the true power factor*", PF_T is given by the following expression.

$$PF_T = \frac{P}{V_{1rms} I_{rms}} = \frac{P}{V_{1rms} \times I_{1rms}\sqrt{1 + \left(\frac{\%THD_I}{100}\right)}}$$

Where, P = Real power

V_{1rms} = RMS value of the fundamental voltage

I_{1rms} = RMs value of the fundamental current component

I_{rms} = RMS vale of current

This can be given as

$$PF_T = \frac{PF_D}{\sqrt{1 + \frac{\%THD_I}{100}}}$$

Where, PF_D = displacement power factor

These expressions bring out the fact that the presence of harmonics reduces the system power factor which in turn increases the power system losses.

2.3 Harmonic indices

Two most commonly used indices for measuring the harmonic content of a waveform are the Total Harmonic Distortion (THD) and the Total Demand Distortion (TDD). Both are measures of the effective value of a waveform and may be applied to either voltage or current.

2.3.1 Total harmonic distortion

The total harmonic distortion is used to define the effect of harmonics on the power system [2]. It is used in low-voltage, medium-voltage, and high-voltage systems. It is expressed as a percent of the fundamental and is defined as

$$\mathrm{THD} = \sqrt{\frac{sum\ of\ all\ squares\ of\ amplitudeof\ all\ harmonic\ voltages}{square\ of\ the\ amplitude\ of\ the\ fundamental\ voltage}}\ .\ 100\%$$

$$= \frac{\sqrt{\sum_{h=2}^{50} V_h^2}}{V_1} * \ 100\ \%$$

Where, V_h is the single frequency RMS voltage at harmonic h, *50* is the maximum harmonic order to be considered and V_1 is the fundamental line to neutral RMS voltage.

$$THD_V = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 \ldots\ldots\ldots}}{v_1}\ .\ 100\%$$

Total current harmonics distortion is given by

$$THD_I = \frac{\sqrt{i_2^2 + i_3^2 + i_4^2 + \ldots\ldots\ldots}}{i_1}$$

Where, i_h is the RMS current of harmonic h and i_1 is the RMS value of fundamental current.

2.3.2 Total demand distortion

Current distortion levels can also be characterized by a THD value but it can be misleading when the fundamental load current is low [2],[3]. A high THD value for input current may not be of significant concern if the load is light, since the magnitude of the harmonic current is low, even though its relative distortion to the fundamental frequency is high. To avoid such ambiguity a total demand distortion (TDD) factor is used instead [3]. TDD is defined as:

$$\mathrm{TDD} \quad = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_L} * 100\ \%$$

$$TDD = \frac{\sqrt{i_2^2 + i_3^2 + i_4^2 + \ldots\ldots\ldots}}{i_L}$$

I_L is the peak, or maximum, demand load current at the fundamental frequency component measured at the point of common coupling (PCC). This factor is similar to THD except that the distortion is expressed as a percentage of some rated or maximum load current magnitude, rather than as a percentage of the fundamental current. Since electrical power supply systems are designed to withstand the rated or maximum load current, the impact of current distortion on the system will be more realistic if the assessment is based on the designed values, rather than on a reference that fluctuates with the load levels.

2.4 How harmonics generate in power systems?

The objective of the electric utility is to deliver sinusoidal voltage at fairly constant magnitude throughout their system. This objective is complicated by the fact that there are loads on the system that produce harmonic currents. These currents result in distorted voltages and currents that can adversely impact the system performance in different ways.

As the number of harmonic producing loads has increased over the years, it has become increasingly necessary to address their influence when making any additions or changes to an Installation.

To fully appreciate the impact of these phenomena, there are two important concepts to be considered with regard to power system harmonics. The first is the nature of harmonic-current producing loads (non-linear loads) and the second is the way in which harmonic currents flow and how the resulting harmonic voltages develop.

2.4.1 Linear and non-linear loads

A linear element in a power system is a component in which the current is proportional to the voltage. In general, this means that the current wave shape will be the same as the voltage as shown in **Figure 2.3.** Typical examples of linear loads include motors, heaters and incandescent lamps.

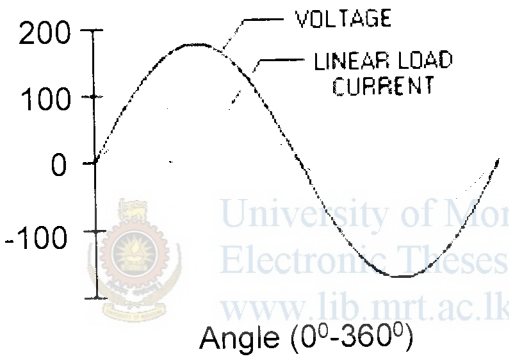

Figure 2.3 Voltage and current waveforms for linear loads

Harmonic distortion is caused by non-linear devices in the power system. A nonlinear device is one in which the current is not proportional to the applied voltage. Typical examples of non-linear loads include power supplies with rectifiers, UPS units, discharge lighting, adjustable speed motor drives, ferromagnetic devices, dc motor drives and arcing equipment. **Figure 2.4** illustrates this concept by the case of a sinusoidal voltage applied to a simple nonlinear resistor in which the voltage and current vary according to the curve shown. While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a different wave shape.

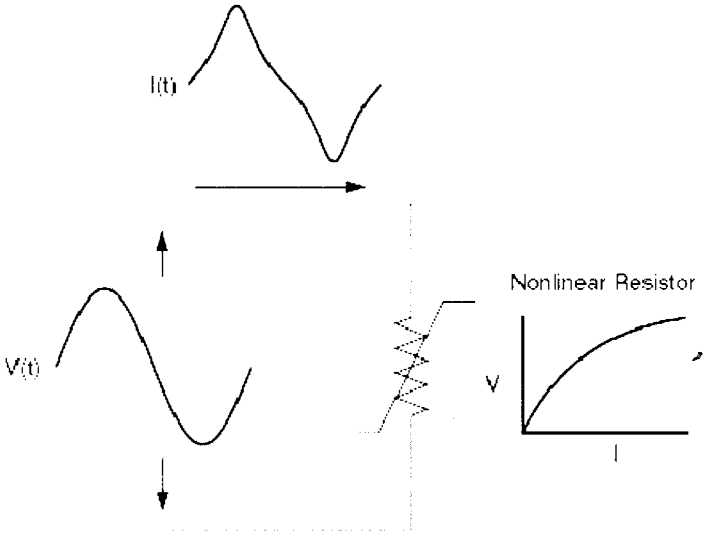

Figure 2.4 Current distortion caused by nonlinear resistance.

So in case of nonlinear loads current and wave form shapes are not same as shown in Figure 2.5.

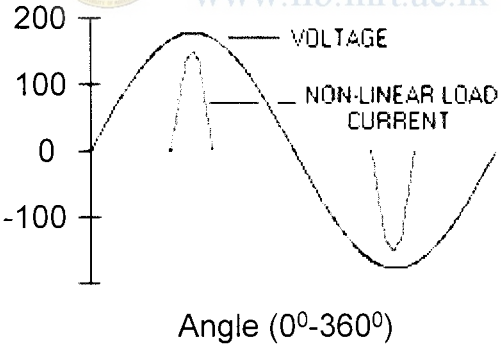

Figure 2.5 – Voltage and current waveforms for non-linear loads

This phenomenon is the source of most harmonic distortion in a power system. The sinusoidal components are integer multiples of the fundamental where the Fundamental is 50 Hz. The only way to measure a voltage or current that contains harmonics is to use a true-RMS reading meter. If an averaging meter is used, which is the most common type, the error can be Significant.

2.4.2 Harmonic current flow

When a non-linear load draws current, it passes through all of the impedance that is between the load and the system source as shown in **Figure 2.6** As a result of the current flow, harmonic voltages are produced by impedance in the system for each harmonic.

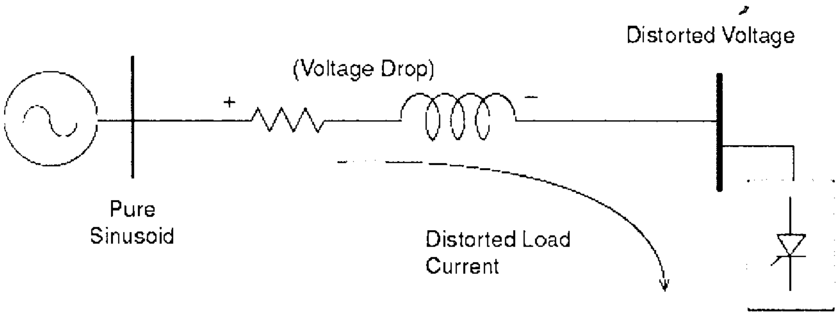

Figure 2.6 Harmonic currents flowing through the system impedance result in harmonic voltages at the load

Addition of these voltages to the nominal voltage produces voltage distortions. The magnitude of the voltage distortion depends on the source impedance and the harmonic voltages produced. If the source impedance is low then the voltage distortion will be low. If a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the voltage can increase dramatically [1].

2.5 Harmonic sources

2.5.1 Fluorescent lamps

Lighting typically accounts for 40 to 60 percent of a commercial building load. As fluorescent lights are a popular choice for energy savings, fluorescent lighting is used more than seventy five percent of commercial floor spaces.

Fluorescent lights are discharge lamps; thus they require ballast to provide a high initial voltage to initiate the discharge for the electric current to flow between two electrodes in the fluorescent tube. Once the discharge is established, the voltage decreases as the arc current increases. There are two types of ballasts, magnetic and electronic. Magnetic ballast is simply made up of an iron-core transformer with a capacitor encased in an insulating material. Electronic ballast employs a switch-mode–type power supply to convert the incoming fundamental frequency voltage to a much higher frequency voltage.

The current THD of standard magnetic ballasts is about 15 percent [6]. As a comparison, electronic ballasts, which employ switch-mode power supplies, can produce double or triple the standard magnetic ballast harmonic output. But most electronic ballasts are equipped with passive filtering to reduce the input current harmonic distortion to less than 20 percent.

2.5.2 Adjustable speed drives

Common applications of adjustable-speed drives (ASDs) in commercial buildings are in elevator motors and in pumps and fans in ac systems. An ASD consists of an electronic power converter that converts ac voltage and frequency into variable voltage and frequency. The variable voltage and frequency allows the ASD to control motor speed. This involves generation of harmonics [3].

2.5.3 Switch mode power supplies

Switch-mode power supplies are now almost universally employed in Personal computers, printers, copiers, and in most other single-phase electronic equipment. The key advantages are the light weight, compact size, efficient operation, and lack of need for a bulky transformer.

All variable frequency drives cause harmonics because of the nature of the front end rectifier design [6]. It feeds a capacitor that supplies the voltage to the electronic circuitry. Since the load is a capacitor as seen from the power system, the current to the power supply is discontinuous. That is, current flows for only part of the half-cycle. **Figure 2.7** shows the current wave form of such a power supply.

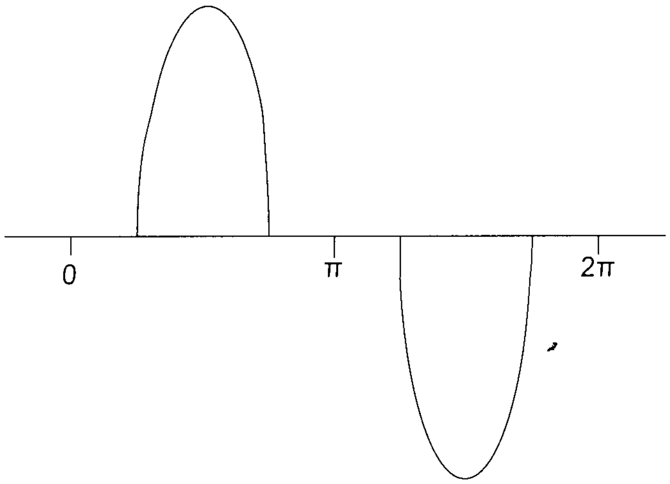

Figure 2.7 **Current Wave of Switch Mode Power Supply**

A distinctive characteristic of switch-mode power supplies is a very high third-harmonic content in the current. The increasing application of switch-mode power supplies causes concern for overloading of neutral conductors. This leads to neutral and transformer overheating problems.

2.5.4. Pulse Width Modulated (PWM) Drive.

This dc link drive has a diode rectifier that gives it a high displacement power factor. It has a large capacitor on the dc link to regulate the voltage. Therefore, at light loads, the current only flows if the voltage output of the diode rectifier is above that of the capacitor. So, at light loads, the current in the ac circuit is discontinuous. It is similar to the switch mode power supply except that it is a three-phase circuit high in fifth harmonic current. As the load on the drive increases, the current becomes continuous.

2.6 Effects of Harmonics

Harmonics can cause a variety of problems to any user of electric power. For large users, the problems can be intense. The degree to which harmonic can be tolerated is determined by the susceptibility of the load to them [2]. Even in the case of the least susceptible equipment, harmonics can be harmful. In the case of an oven, for example, they can cause dielectric thermal or voltage stress, which causes premature aging of electrical insulation.

Unlike most other types of supply problems, harmonics can go unnoticed for many years unless equipment temperature or the voltage waveform is routinely monitored. The danger is the not knowing the effect of harmonics until failure occurs. The detailed study on how harmonics can interact within a power system and how they can affect power system components is important for preventing failures. As the affects of harmonics and appropriate solutions vary depending on the power supply, the installation and the components, they need to be addressed separately. The effects of harmonics on some common power supply components are discussed in the following.

2.6.1 Motors

Motors are typically considered to be linear loads; however, when the source voltage supply is rich in harmonics, the motor will draw harmonic current [2]. The typical result is a higher than normal operating temperature and shortened service life. A major effect of harmonic voltages and currents in motor is the heating due to iron and copper losses at the harmonic frequencies. The harmonic components thus affect the machine efficiency, and can also affect the torque developed. Harmonic currents in a motor can give rise to a higher audible noise emission as compared with sinusoidal excitation.

The harmonics also produce a resultant flux distribution in the air gap, which can cause or enhance phenomena called cogging (refusal to start smoothly) or crawling (very high slip) in induction motors [1].

Harmonic pairs, such as the fifth and seventh harmonics, have the potential for creating mechanical oscillations in a motor-load system. The resulting mechanical oscillations can cause shaft fatigue and accelerated aging of the shaft and connected mechanical parts. Different frequency harmonic currents can cause additional rotating fields in the motor. Depending on the frequency, the motor will rotate in the opposite direction (counter-torque). The fifth harmonic, which is very prevalent, is a negative sequence harmonic causing the motor to have a backward rotation, shortening the service life.

Harmonics currents can induce additional heating in the stator windings, thus adding to the temperature rise. The resultant effect of the harmonics is reduction in efficiency and life of the machinery.

2.6.2 Transformers

The effect of harmonics on transformers is twofold. Current harmonics cause an increase in copper losses and stray flux losses. And voltage harmonics cause an increase in iron losses [2]. The overall effect is an increase in the transformer heating. Of the transformer, the upper limit of the current distortion factor is 5% at rated current [7]. The recommended practice suggests that the maximum withstand voltage in the steady state: 5% at rated load and 10% at no load. The harmonic currents in the applied voltage must not result in a total RMS voltage exceeding these ratings.

It should be noted that the transformer losses caused by both harmonic voltages and harmonic currents are frequency dependent. The losses increase with increasing frequency and, therefore, higher frequency harmonic components can be more important than lower frequency components in causing transformer heating.

2.6.3 Power Cables

Because harmonic frequencies are always higher than the 50Hz fundamental frequency, “skin effect” also becomes a factor. Skin effect is a phenomenon where the higher frequency causes the electrons to flow toward the outer sides of the conductor, effectively reducing the cross-sectional diameter of the conductor and thereby reducing the ampacity rating of the cable. This effect increases as the frequency and the amplitude increase. As a result, higher harmonic frequencies cause a greater degree of heating in conductors [2].

2.6.4 Neutral Conductors

On balanced three-phase systems with no harmonic content, the line currents are 120 degrees out-of-phase, canceling each other and resulting in very little neutral current. However, when there is distortion in any one of the phase currents, the harmonic currents increase and the cancellation effect is lessened. The result is typically a neutral current that is significantly higher than planned. The triplen harmonics (odd multiples of three) are additive in the neutral and can quickly cause dangerous overheating. In theory, the maximum current that the neutral will carry is 1.73 times the phase current[3]. If not sized correctly, overheating will result. Currents higher than the normal neutral current will cause voltage drops between neutral and ground which are well above normal.

2.6.5 Switchgear and Relaying

False tripping of circuit breakers is also a problem encountered with the higher frequencies that harmonics produce [2]. Peak sensing circuit breakers often will trip even though the amperage value has not been exceeded. Harmonic current peak values can be many times higher than sinusoidal waveforms.

As with other types of equipment, harmonic currents can increase heating and losses in switchgear, thereby reducing steady-state current carrying capability and shortening the life of some insulating components. Fuses suffer a derating because of the heat generated by harmonics during “normal” operation.

2.6.6 Capacitors

Power factor correction capacitor failure in many cases can be directly attributed to harmonic content. The reactance of a capacitor bank decreases with frequency. Hence at high frequencies, capacitors appear as extremely low impedance values and are more susceptible to harmonics. This effect increases the heating and dielectric stresses.

Inductive reactance varies directly with frequency ($X_L = 2\pi fL$). Parallel resonance between the capacitor bank and the source impedance can cause system resonance resulting in higher than normal currents and voltages. High harmonic currents have been known to overheat correction capacitors, causing premature failure and sometimes resulting in explosion.

Most harmonic problems result when the resonant frequency is close to the fifth or seventh harmonic [2]. These happen to be the largest harmonic amplitude numbers that adjustable speed drives create. When this situation arises, capacitor banks should be resized to shift the resonant point to another frequency

2.6.7 Electronic Equipment

Power electronic equipment is susceptible to disoperation caused by harmonic distortion. This equipment is often dependent upon accurate determination of voltage zero crossings or other aspects of the voltage wave shape. For electronic equipment that relies on the zero crossing of the sinusoidal waveform, such as clock timing devices, heavy harmonic content can cause a zero crossing point offset.

Other types of electronic equipment can be affected by transmission of ac supply harmonics through the equipment power supply or by magnetic coupling of harmonics into equipment components. Computers and allied equipment such as programmable controllers frequently require ac sources that have no more than a **5%** harmonic voltage distortion factor, with the largest single harmonic being no more than **3%** of the fundamental voltage [2]. Higher levels of harmonics result in malfunctions of the equipment that can, in some cases, have serious consequences. With high level of harmonics, instruments can give erroneous data or otherwise may perform unpredictably. Perhaps the most serious of these are malfunctions in medical instruments.

2.6.8 Communication equipment

Noise can be picked up in communication equipment and telephone systems when harmonics at audio or radio frequencies are inductively or capacitively coupled into communication or data lines. The presence of harmonic currents or voltages in circuitry associated with power conversion apparatus can produce magnetic and electric fields that will impair the satisfactory performance of communication systems.

2.6.9 Meters

Metering and instrumentation are affected by harmonic components, particularly if resonant conditions exist. Averaging type current meter give incorrect reading when harmonics present. Induction disk devices, such as watt-hour meters, normally see only fundamental current. However, phase imbalance caused by harmonic distortion can cause erroneous operation

2.7 Harmonics standards

There are two distinct sets of standards that can be applied to limit the amount of harmonics in power systems. The first has been introduced by the International Electro technical Commission (IEC). That is a series of limits appropriated for application *at the terminals* of any particular nonlinear load. The philosophy of the IEC limits specified by IEC/EN 61000-3-2 is based on the presumption that limiting harmonic production from every piece of equipment will effectively limit any combined effects.

The second is favored by the IEEE and the basis for IEEE 519-1992 is a series of limits that is appropriate for application at a single more central point of supply to multiple nonlinear loads [2]. IEEE limits are somewhat more restrictive consider the use of both voltage and current harmonic limits. IEEE 519 attempts to propose steady state harmonics limits that are considered reasonable by both the electrical utilities and customers. It divides the responsibility for limiting harmonics between both end users and utility.

The underline philosophy is that

- Customers should limit harmonic currents
- Utilities should limit harmonic voltages

These limits for voltage and current harmonics are dependent on several variables and concepts defined as follows:

PCC: Point of common coupling.

The harmonic current and voltage limits are applied at the PCC. This point is defined as the point in the utility service to a particular customer where another customer could be connected. It is defined as the electrical connecting point or interface between the utility distribution system and the customer's electrical distribution system.

I_{SC}: Available short circuit current.

I_{SC} is the available short circuit current at the point of common coupling. The I_{SC} is determined by the size, impedance, and voltage of the service feeding the PCC.

I_L: Maximum load current

I_L is the maximum demand load current (fundamental frequency component) measured at the PCC. It is suggested that existing facilities measure this over a period of time and average it. IEEE recommendation is to calculate the average current of the maximum demand for preceding 12 months.

2.7.1 Harmonic limits for consumers

This section describes the current distortion limits that apply to individual consumers of electrical energy. Table 2.3 lists the harmonic current limits based on the size of the load and size of the power system to which the load is connected. The ratio $\mathbf{I_{SC}/I_L}$ is the ratio of the short-circuit current available at the point of common coupling (PCC), to the maximum fundamental load current.

As the size of the user load decreases with respect to the size of the system, the percentage of harmonic current that the user is allowed to inject into the utility system increases. This protects other users on the same feeder as well as the utility, which is required to furnish a certain quality of voltage to its customers.

I_{SC}/I_L	<11	11<=H<17	17<=H<23	23<=H<35	35<=H	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20
Even harmonics are limited to 25% of the Odd harmonic limits above						
Where I_{SC} = Maximum short circuit current at PCC I_L = Maximum demand load current(Fundamental frequency component)						

Table 2.3 Current Distortion Limits for General Distribution Systems (120V through 69000 V) [2]

2.7.2 Harmonic limits for utility

This standard [2] specifies the quality of electrical power that the producer should furnish to the consumer. The distortion limits recommended in this section establish the maximum voltage distortion at the point of common coupling (PCC) with each consumer. The limits are given in Table 2.4. Electric utilities are responsible to maintain voltage harmonics and THD of voltage within the prescribed limits.

PCC Voltage	Individual Harmonic Magnitude (%)	THD_V (%)
< 69 kV	3.0	5.0
69-161 kV	1.5	2.5
>161 kV	1.0	1.5

Table 2.4 Voltage distortion limits [2]

Chapter 3

Provincial Council Building

3.1 Introduction

This chapter describes the available power supply at Uva provincial council building and site measurement carried out therein. Due to the limitations of measuring instruments available, the measurement could only be taken at low voltage level. The data logged during the measurement are filtered to obtain only the data pertinent to harmonic distortions. Finally in this chapter, the collected data is analyzed and compared with the harmonic standards to identify the power quality problems in the existing system.

3.2 Background

The site selected for this case study, Uva Provincial Council (UPC) building is a major office building in Badulla. It is a five storied building having about 75,000 square feet in floor area. Provincial Council, several other ministries, secretariats, auditorium, etc. are housed in this building. Electricity supply to this building is fed from Badulla 132kV/33kV Grid substation and the installed capacity is 400kVA.

It is expected to add an extension to the building in near future with the expansion of ministries. In that case, same substation can be utilized to cater the addition, as it has excess capacity.

The loads under investigation included many nonlinear loads such as

1. Various types of single phase and three phase air conditioners (28 Nos.)
2. Large number of computers, printers and other related peripherals (215 Nos.)
3. Large number of UPSS
4. Lighting load consists of Fluorescent lamps, CFLL (almost all the indoor lamps consist of fluorescent or CF bulbs)

They were fed from separate plug-in-unit and supplies were distributed from MCCB to individual MCB board as shown in **Figure 3.1**. In order to have full load and part load conditions measurements of harmonics were taken under both working and non-working hours. The parameter studied included power factor, voltage and harmonics.

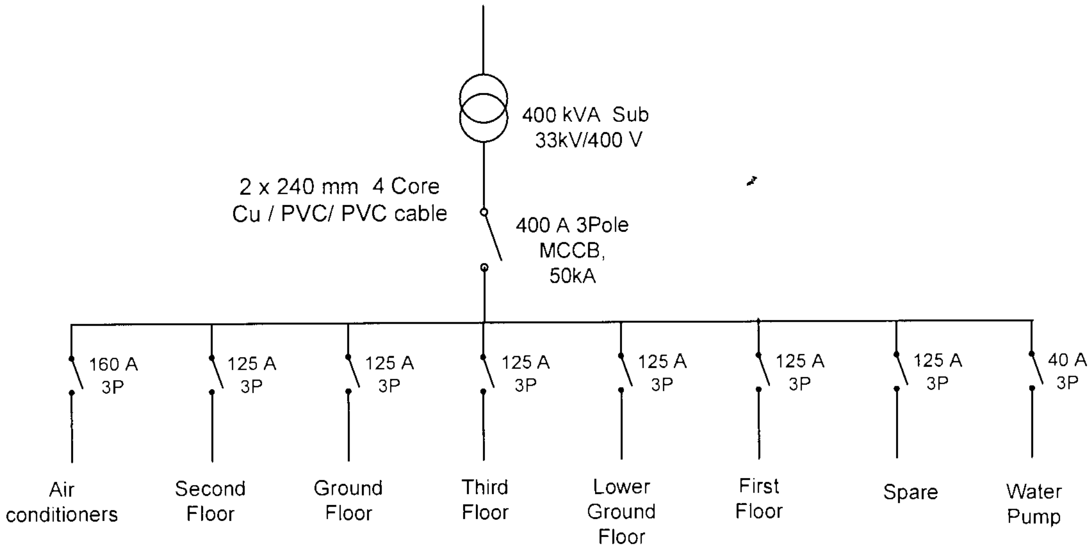

Figure 3.1 **Single line diagram of Electricity distribution system**

The occupants often complain on power supply issues such as frequent failures of equipment, specially the UPSs, equipment malfunctioning, shorter life spans of bulbs and computers, nuisance computer shut down, nuisance tripping, etc. These adversely affect the day to day work of the various offices located in this premise.

Exact records on past failures and defects are not available. But the work superintendents \ technical offices claim that in some months five to six numbers of UPSS become faulty; hundreds of bulbs have to be replaced. Suspecting these are due to the low quality of supply, they have complained to CEB several times on these issues. As a response, after an inspection they have been told that these are not due to the supplier side faults.

3.3 Data logging

3.3.1 Location for data logging

Objective of data logging is to investigate the overall quality of the facility. Therefore, the Point of Common Coupling (PCC) was selected for monitoring the power quality. So the data logging was done on the secondary side of the supply transformer. It was useful to record the quality of power supply to the facility as well as the effects of major loads within the facility.

3.3.2 Instruments used

Instruments used for measurements are Kew Snap digital clamp meter, APR4u4i Disturbance Recorder/Network Analyzer and POWERmonic data logger. The measurements were carried out at low voltage level.

The digital clamp meter is capable of measuring currents in the range of 0 to 400A in a frequency range of 40 Hz to 1 kHz at an accuracy of 0.1 A. It is able to measure current in two modes, *"peak"* and *"RMS"*. The peak mode shows the current's crest value divided by the square root of two. The other mode shows true RMS current value.

Network analyzer is a product of Soule of France. This is a clamp type power meter which is capable of measuring power, voltage, current, power factor and harmonics and their integrated values of low voltage three phase four wire power lines. It uses a high capacity signal processor and it is capable of real time analysis of mains network.

The other instrument was the POWERmonic20 three phase data logger, which incorporates three-phase three channel voltage logging and three phase four channel data logging. It logs RMS voltages and currents, harmonic voltages and currents and power factor for each phase.

3.4 Measurement and data analysis

Some of the data logged during the measurement are shown below.

3.4.1 Frequency Variation

According to EN 50160, Power frequency of supply should be within ±1% of nominal frequency (49.5 - 50.5 Hz) for 99.5% of week. **Figure 3.2** shows very slight variance in power frequency but it is within the acceptable range. In general, utilities maintain very close control of the power system frequency, hence variations are rear.

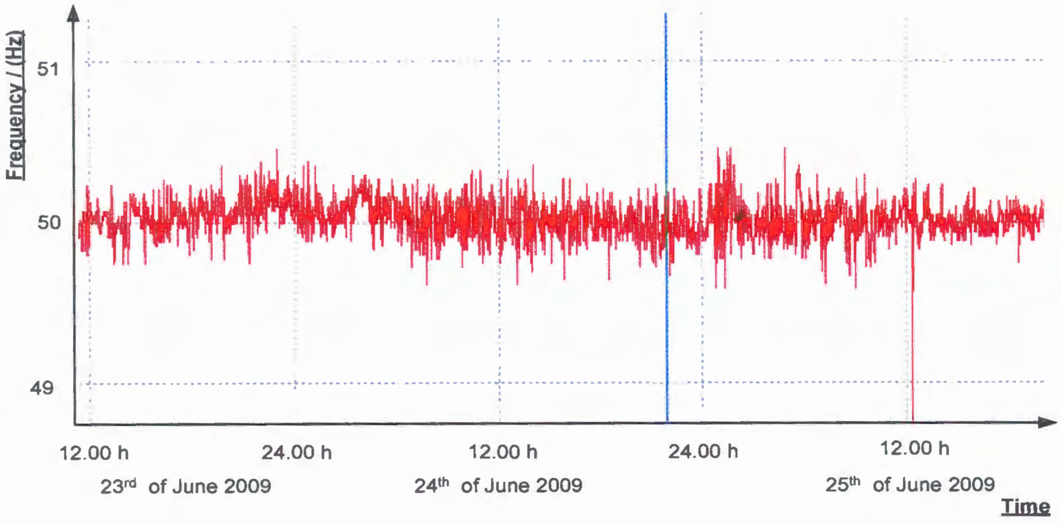

Figure 3.2 **Graph of Frequency**

3.4.2 Supply voltage variation

According to the local steady state voltage regulations, maximum allowable voltage tolerance is 6% of the nominal voltage. **Figure 3.3** shows that the supply voltage to UPC building exceeds the upper boundary value of tolerance, 244 V

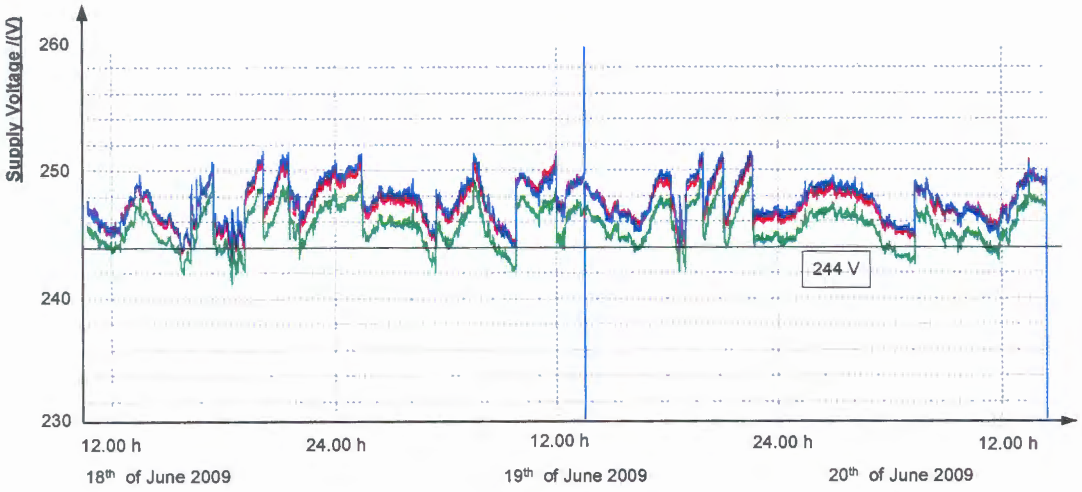

Figure 3.3 **Graph of Three Phase Voltage**

It was found that incorrect tap settings on transformers can cause for system over-voltages. Over-voltages may cause equipment failure. Sustained overvoltage on transformers, cable, bus, switchgear, CTs, PTs and rotating machinery can result in loss of equipment life.

3.4.3 Load Current variation

Figure 3.4 shows that the maximum RMS current is around 200 A, and the phases are balance in average.

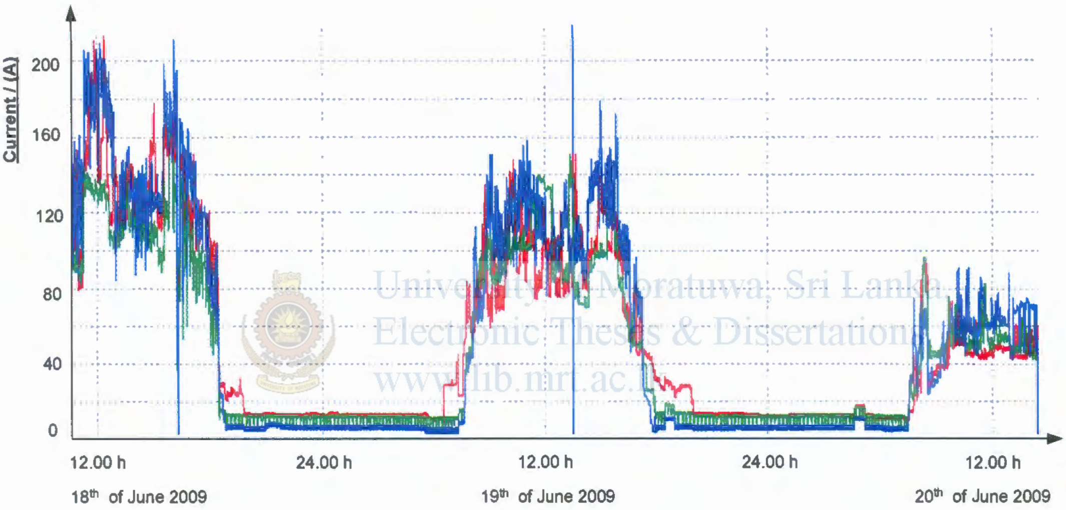

Figure 3.4 **Graphs of Three Phase Currents**

3.4.4 Current measurement

The measured supply currents in both modes on three days at around 14.00 hour are shown in **Table 3.1**. The peak mode of this meter shows the current's crest value divided by √2 , that is the equivalent RMS value.

Phase	Phase R / (A)		Phase Y / (A)		Phase B / (A)		Neutral / (A)	
Mode	**Peak**	**RMS**	**Peak**	**RMS**	**Peak**	**RMS**	**Peak**	**RMS**
Day 1	88.0	68.0	58.8	63.5	80.2	60.6	53.0	33.5
Day 2	80.5	68.0	58.0	62.0	111.0	83.0	64.0	38.0
Day 3	117.0	97.0	93.0	96.0	140.5	105.5	85.0	54.5

Table 3.1 Current measurements

So, if the current waveform is sinusoidal, readings in different modes should be equal. Varied readings in two modes indicate the existence of distorted current waveforms in the electrical system of Uva provincial council building.

$$Reading\ in\ peak\ mode = \frac{Crest\ value}{\sqrt{2}}$$

$$Crest\ factor = \frac{Peak\ value}{RMS\ value}$$

Therefore, $$Crest\ factor = \frac{\sqrt{2} \times Reading\ in\ peak\ mode}{Reading\ in\ RMS\ mode}$$

In a perfect sine wave, the crest factor is 1.414. The calculated crest factors of each instance are shown in **Table 3.2** and they are found to be much higher than 1.414. It indicates the existence of harmonics.

Phase	Phase R / (A)	Phase Y / (A)	Phase B / (A)	Neutral / (A)
Day 1	1.83	1.309	1.87	2.23
Day2	1.67	1.322	1.89	2.38
Day 3	1.71	1.37	1.87	2.21

Table 3.2 Crest factors of current waveforms

3.4.5 Voltage harmonic distortion

Figure 3.5 shows the variation of THD of voltage over three working days. As discussed in chapter 2.7.2, for voltages less than 69 kV, the maximum limit for voltage THD is 5%. Graph shows 3.5 % peak. It shows the voltage THD is well within the limits, and complies with the standards.

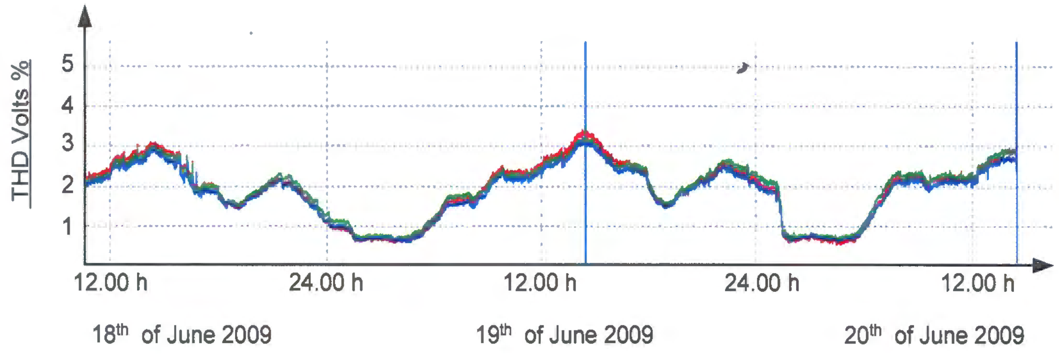

Figure 3.5 **Graph of Percentage THD of Voltage**

However, voltage harmonic spectrum registered at a worse case is shown in **Figure 3.6**. The third harmonic component and THD logged at this instance are as high as more than 6 % of the fundamental voltage, and hence they exceed the prescribed limits given in Table 2.4.

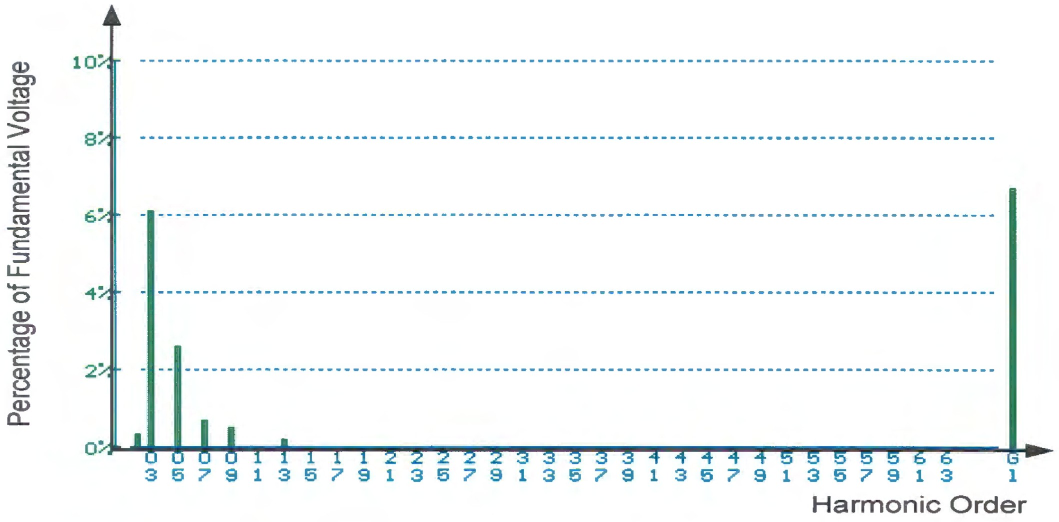

Figure 3.6 **Individual voltage harmonics**

3.4.6 Current harmonic distortion

Figure 3.7 shows the three phases THD of current. In the day time average of THD is around 25 % but during the night when fundamental current value is lower, current THD increases.

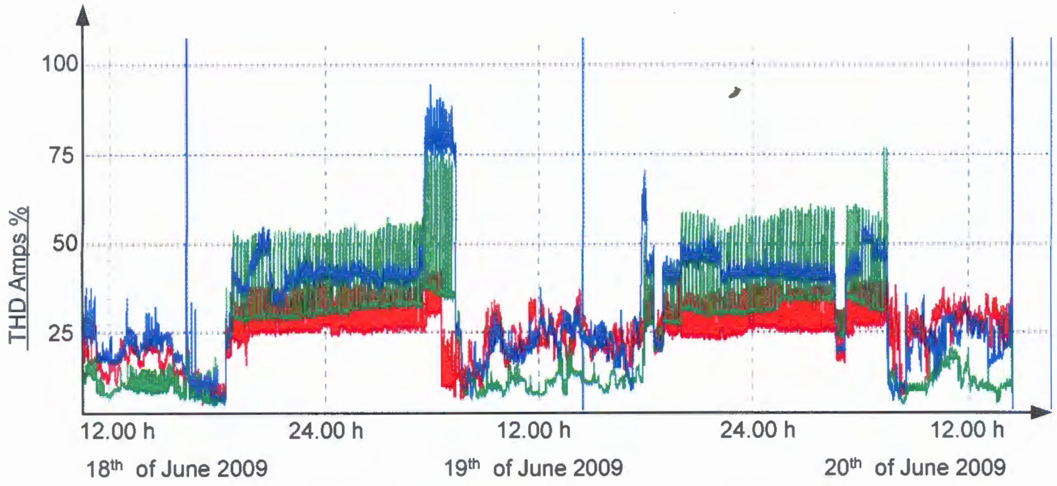

Figure 3.7 **Graph of Percentage THD of Current**

$$THD = \frac{\sqrt{i_2^2 + i_3^2 + i_4^2 + \ldots\ldots\ldots\ldots}}{i_1}$$

where, i_h is the RMS current of harmonic h and i_1 is the RMS value of fundamental current. IEEE standards specify the limitations on TDD, not on the THD. TDD is given by

$$TDD = \frac{\sqrt{i_2^2 + i_3^2 + i_4^2 + \ldots\ldots\ldots\ldots}}{i_L}$$

Where, i_L is the peak, or maximum, demand load current at the fundamental frequency component measured at the point of common coupling (PCC).

From the above two equations it can be derived that

$$TDD = THD \times \frac{RMS\ value\ of\ fundamental\ current}{RMS\ value\ of\ maximum\ demand\ load\ current}$$

So, using the logged data (of which a sample is given in the appendix) TDD can be calculated, and thus calculated TDD variation against time is shown in **Figure 3.8.**

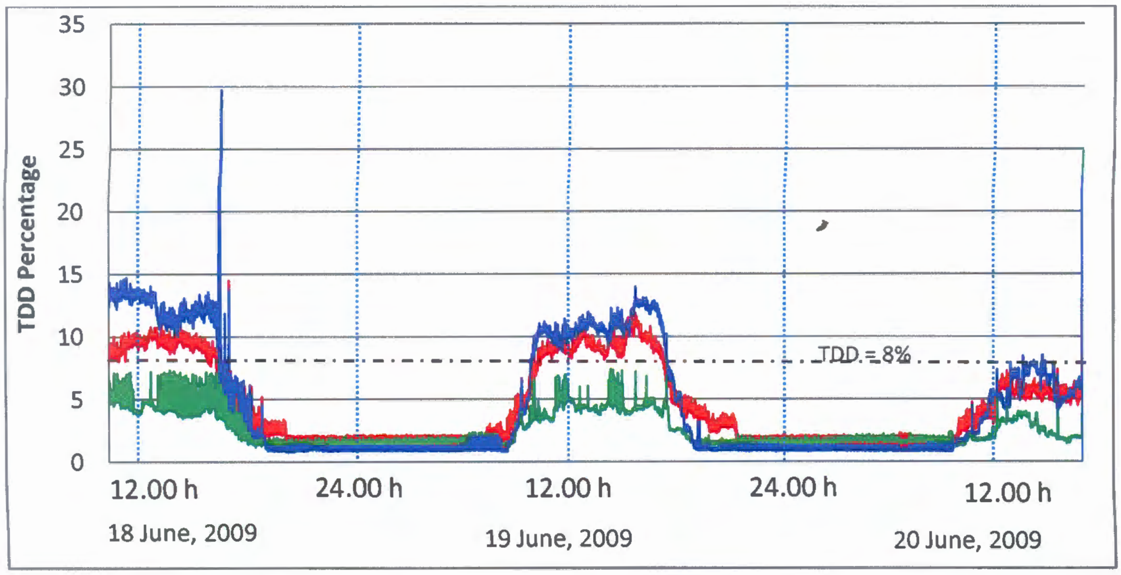

Figure 3.8 **Graph of TDD**

As discussed in chapter 2.7.1, limitations of Harmonic current distortion depends on the ratio of I_{SC} / I_L, where I_{SC} is the short circuit current at PCC and I_L is the maximum demand load current at the PCC.

I_L was calculated as the average of the maximum monthly demand currents for the previous 12 months period. Billing information pertaining to the previous year is given in the Appendix.

Average of Maximum kVA reading = 200 kVA

Hence, Average of Max. demand load current, $I_L = \frac{200 \times 1000}{\sqrt{3} \times 400}$

$$I_L = 288.7 \text{ A} \qquad (3.1)$$

Figure 3.9 represents the single line diagram of feeding system of UPC building. X_s, X_f and X_t denote the short circuit impedance of 33kV bus, the feeder impedance and the transformer impedance, respectively. The fault current at 33kV bus at Badulla grid substation was ascertained as 8.2 kA.

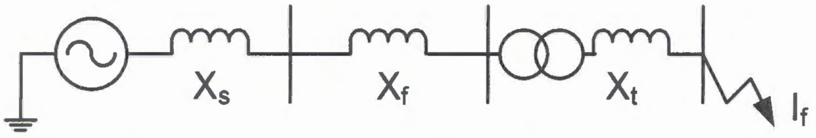

Figure 3.9 Line diagram of feeding system of UPC building

The distribution transformer is 33kV/ 400V , 400 kVA. Assume the transformer percentage leakage reactance as 7 % . Resistances of the feeding path are assumed to be negligibly low.

Select S_{base} = 400kVA and V_{base} = 33kV.

$$X_{33} = \frac{33 \times 10^3}{\sqrt{3} \times 8.2 \ x\ 10^3} = 2.32\,\Omega \qquad (3.2)$$

Consider a 33 kV Racoon feeder of 1 km length. For Racoon, reactance is taken as j0.353 Ω/km.

$$X_f = 0.353 \times 1 = 0.353\,\Omega \qquad (3.3)$$

Similarly, $X_{t,pu}$ = 7% = 0.07 pu

$$Z_{base} = \frac{V_{base}^2}{S_{base}} = \frac{33^2}{400} \times 1000$$

$$= 2722.5\,\Omega$$

$$X_t = 0.07 \times 2722.5 = 190.575\,\Omega \qquad (3.4)$$

Total impedance = 2.32 + 0.353 + 190.575

= 193.248 Ω

Hence the fault current at primary side of transformer,

$$I_{f,33} = \frac{33 \times 10^3}{\sqrt{3} \times 193.248} = 98.59\text{ A}$$

Secondary side,

$$I_{f,400} = 98.59 \times \frac{33000}{400} = 8133.6 \text{ A}$$

Therefore Short circuit current at PCC, I_{SC} = 8134 A (3.5)

Equations (3.1) and (3.5) give the Short-circuit ratio as,

$$\frac{I_{SC}}{I_L} = \frac{8134}{288.7}$$

$$= 28.17$$

This result relates to the 20 < $\mathbf{I_{SC}/I_L}$ < 50 raw of the Table **2.3.** Abstract of relevant rows are shown in **Table 3.3.**

I_{SC}/I_L	**<11**	**11<=H<17**	**17<=H<23**	**23<=H<35**	**35<=H**	**TDD**
20<50	7.0	3.5	2.5	1.0	0.5	8.0
Even harmonics are limited to 25% of the Odd harmonic limits above						
Where I_{SC} = Maximum short circuit current at PCC I_L = Maximum demand load current(Fundamental frequency component)						

Table 3.3 **Current distortion limits for 20 < I_{SC} / I_L < 50**

When we compare TDD graph shown in **Figure 3.8** with the above standards, it is obvious that TDD exceeds the prescribed limit of 5 %, considerably.

Figure 3.10 shows the harmonic spectrum of current recorded at a worse case. The 3rd, 5th, 7th and 9th order current harmonics take significantly high values. Comparison of these individual harmonics with the standard is shown in **Table 3.4.** It shows that the logged values are well above the prescribed limits.

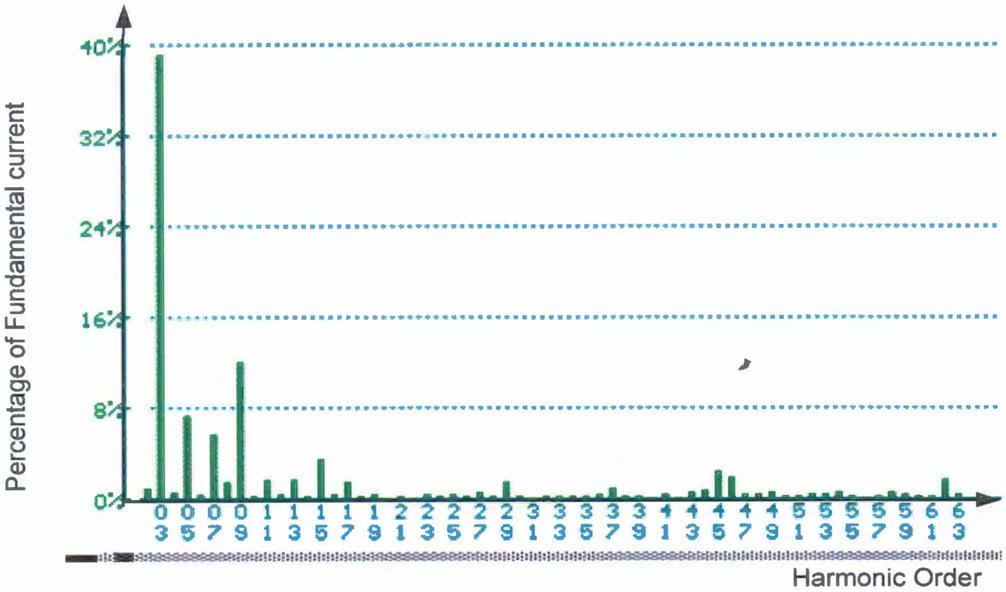

Figure 3.10 **Individual current harmonics**

Harmonic Order	Prescribed Limits / (%)	Logged percentage current harmonic distortion /(%)
3rd	7	38
5th	7	7
7th	7	6
9th	7	12
11th	3.5	2
13th	3.5	2
15th	3.5	4

Table 3.4 **Comparisons of individual Current Harmonic distortion with prescribed limits**

3.4.7 Power factor variation

There is only a slight variation between true power factor and the displacement power factor hence both show almost same variation. Average power factor is about 8.5 lagging. Part of the logged true and displaced power factor values are given in the

Appendix. Even due to a slight variation of power factor, at high load current considerable power loss in the range of 1 kW can be observed.

3.5 Identifying problem category

When the above graphs and logged data are compared with the power quality standers, it is clear that the dominant power quality problem category in Uva Provincial Council is Harmonic Distortion. Other than that an over voltage condition has been observed throughout the measurement.

When the collected data is compared with standards [2], it reveals that

- TDD is greater than the prescribed limit.
- Some Individual current harmonics exceed the prescribed limits.
- Sometimes the Individual voltage harmonics percentage exceeds the prescribed maximum limit of 3%
- THD of voltage is usually within the limits.

Indices	**Maximum limit (%)**	**Measured values**
Induvidial Voltage Hoarmonic percentage	3.0	6 % maximum at the worse cases
Total Voltage Harmonic Distortion	5.0	Within limits
Total demand distortion	8.0	Up to 15 %
Individual Current Harmonic distortion (for 20 $<I_{SC}/I_L < 50$)	7 for order < 11	Exceed the prescribed limits (Up to 38 %)

Table 3.5 Comparison between Standard limitations and Measurements

Chapter 4

Harmonics Mitigation

4.1 Introduction

There are many methods and techniques for mitigating the harmonics. All of them have advantages as well as disadvantages and involve investment in equipment and/or alteration of the feeding system. Selection of the best solution depends on the total load, type of the installation, the allowable harmonic distortion level and other related factors inherent to the location. [5]

First, an attempt can be made to reduce harmonics disturbances by altering the systems that distributes harmonics. Under that concept varied solutions are identified. The most obvious way is to minimal use of nonlinear loads or use of less polluting equipment. Next step is to reduce the impedance of the network through the alteration of the installation or of certain equipment. Finally, solutions can be chosen based on filtering equipments.

4.2 Reducing harmonic currents in load

This involves restricting the harmonic generation within the installation. As a general rule, if the total rectifier loading (i.e. variable speed drives, UPS, PC, CFL etc.) on a power system comprises less than 20% of its current capacity then harmonics are unlikely to be a limiting factor [8]. This concept has focused the interest in less disturbing equipment. One choice is to minimal use of non- linear loads. Another method is to replace the power electronic devices with improved ones in such a way that they emit fewer harmonics to the system.

Using such equipment or replacing the present equipment with such devices is impracticable because

- Replacing equipment incur much cost.
- Purchasing such equipment is difficult because present day market in Sri Lanka is not concerned on such improved features.

- To identify needed quality equipment require expertise knowledge.
- Replacing all such equipment in non economical and not productive

So, there is little that can be done with existing load equipment to significantly reduce the harmonic currents.

4.3 Structural Alterations

This involves the structure modification by feeding system reinforcement [15]. The aim is to upgrade the distribution network for increasing short-circuits level and thereby to improve the PQ indices. The increase of short circuit level diminishes the effect of THD at nonlinear loads feeding points. The diminishing is obtained by the reduction of total impedance upstream of the load.

Change of current harmonics spectrums depends only on the load type connected to the buildings distribution networks and the supply voltage harmonics. Therefore, in this case any attenuation of the current harmonics level cannot be expected but its dominance can be reduced.

The methods of feeding structure alteration are complicated. And it incurs a great cost. Usually it's beyond the control of customers. What customer can do is to request resizing of the transformer, but it requires much investment.

UPC is having a transformer of 400 kVA whereas the average maximum monthly demand is in the range of 200 kVA. And the feeder length to the transformer is very short. Therefore, resizing of transformer and further improvement of feeding system may not be justifiable.

4.4 Filtering techniques

The filtering technique is a successful harmonic distortion reduction method used in existing installations, especially where the distortion has gradually increased. Further, it is a global solution for new installations, as well. As UPC building is also expected to be expanded with added new loads, this may be a suitable methodology for control harmonics. There are two principal filtering techniques: passive filtering and active filtering.

4.4.1 Passive filtering

The passive filtering is the simplest conventional solution to mitigate the harmonic distortion. Usually, they consist of inductance, capacitance, and resistive elements. So high power applications need to have big capacitors and Inductors.

Passive filters have traditionally been used to absorb harmonics generated by large industrial loads, primarily due to their simplicity, low cost and high efficiency. In passive filters, the flow of the undesired harmonic currents into the power system is prevented by the usage of a high series impedance to block them or by diverting them to a low impedance shunt path. These two methods represent the concept of the series and the shunt passive filters, respectively.

Series passive filters are connected in series with the load. This filter consists of parallel inductance and capacitance as shown in **Fig. 4.1.** The filter is tuned to provide high impedance at a selected harmonic frequency. This impedance blocks the flow of harmonic current at the tuned frequency only. At fundamental frequency, the filter is designed to yield low impedance, thereby allowing the fundamental current to flow. For blocking multiple harmonics, multiple series filters are needed.

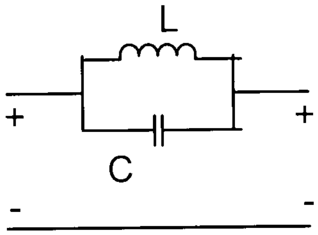

Figure 4.1 Series Passive Filter Configuration

A shunt filter offers very low impedance path at the frequency to which it is tuned and it shunts most of the harmonic current at that frequency. **Figure 4.2** shows common types of passive filters and their configurations [3]. The single-tuned filter is the most common and economical type of passive filter [9]. This filter is connected in shunt with the power distribution system. So, harmonic currents are diverted from their normal flow path through the filter.

Another popular type of passive filter is the high-pass filter (HPF). A HPF allows a large percentage of harmonics above its designed frequency to pass through it. HPF generally takes on one of the three forms, as shown in **Figure 4.2.** The first-order, which is characterized by large power losses at fundamental frequency, is rarely used. The second-order HPF is the simplest to apply while providing good filtering action and reduced fundamental frequency losses [9]. The filtering performance of a third-order HPF is superior to that of the second-order HPF, but it is not commonly used for low-voltage or medium-voltage applications due to the economic, complexity, and reliability factors.

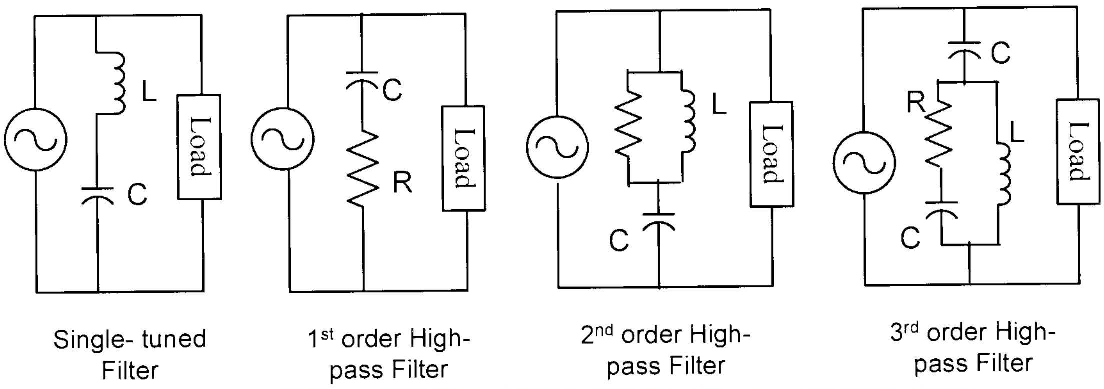

Figure 4.2 Common types of passive filters

Although simple and least expensive, the passive filters have several shortcomings. The filter components are very bulky. Furthermore the compensation characteristics of these filters are influenced by the source impedance. As such, the filter design is heavily dependent on the power system in which it is connected to. Passive filters are known to cause resonance, thus affecting the stability of the power distribution systems.

4.4.2 Active filtering

The advantage of active filtering is that it automatically adapts to changes in the network and load fluctuations. They can compensate for several harmonic orders, and are not affected by major changes in network characteristics. Active power filter (APF) s eliminate the risk of resonance between the filter and network impedance [10]. The basic principle of APF is to utilize power electronic technologies to produce specific currents components that cancel the harmonic currents components caused by the nonlinear load. **Figure 4.3** shows the components of a APF system and their connections. The information regarding the harmonic currents and other system variables are passed to the compensation current/voltage reference signal estimator.

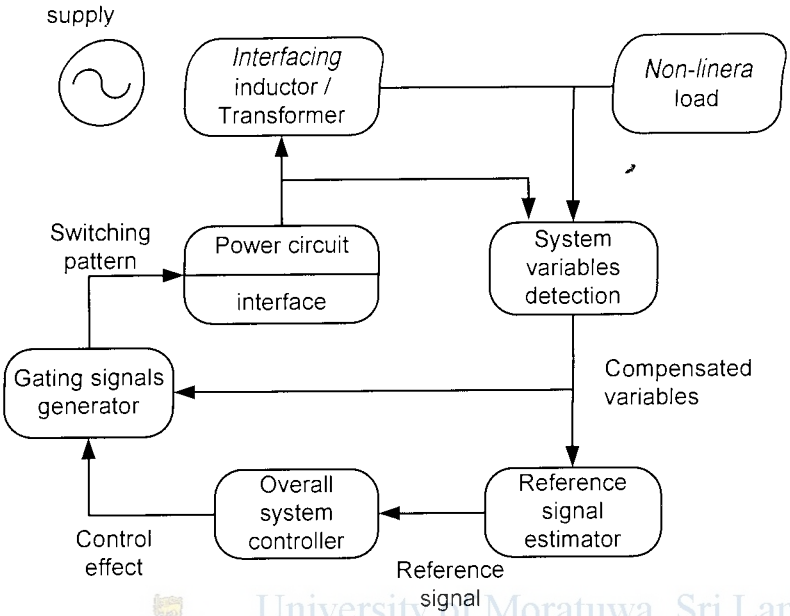

Figure 4.3 **Block diagram of general APF**

The compensation reference signal from the estimator drives the overall system controller. This in turn provides the control for the gating signal generator. The output of the gating signal generator controls the power circuit via a suitable interface. The power circuit in the generalized block diagram can be connected in parallel, series or parallel/series configurations depending on the interfacing inductor/transformer used.

APFs have a number of advantages over the passive filters. First of all, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the APFs performances are independent on the power distribution system properties [11]. Another advantage is that it takes very little space compared with traditional passive filters. Hence APF was preferred to employ in mitigating the harmonics presence at UPC building.

4.5 APF Configurations

APF can be connected in several power circuit configurations as illustrated in the block diagram shown in **Figure 4.4**. They can be classified based on the type of converter, topology, control scheme, and compensation characteristics [12]. In general, they are divided into three main categories, namely shunt APF, series APF and hybrid APF.

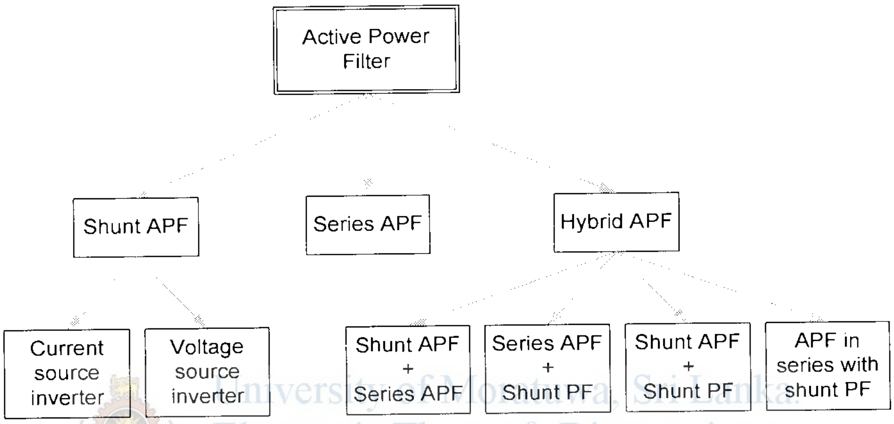

Figure 4.4 **Divisions of Active power Filters**

4.5.1 Shunt active power filter

This is widely used configuration in active filtering applications [13]. A shunt APF consists of a controllable voltage or current source. The voltage source inverter (VSI) based shunt APF is by far the most common type used today, due to its well known topology and straight forward installation procedure. **Figure 4.5** shows the principle configuration of a VSI based shunt APF. It consists of a dc-bus capacitor (C_f), power electronic switches and interfacing inductors (L_f).

Shunt APF acts as a current source, compensating the harmonic currents due to nonlinear loads. The operation of shunt APF is based on injection of compensation current which is equals to the distorted current, thus eliminating the original distorted current.

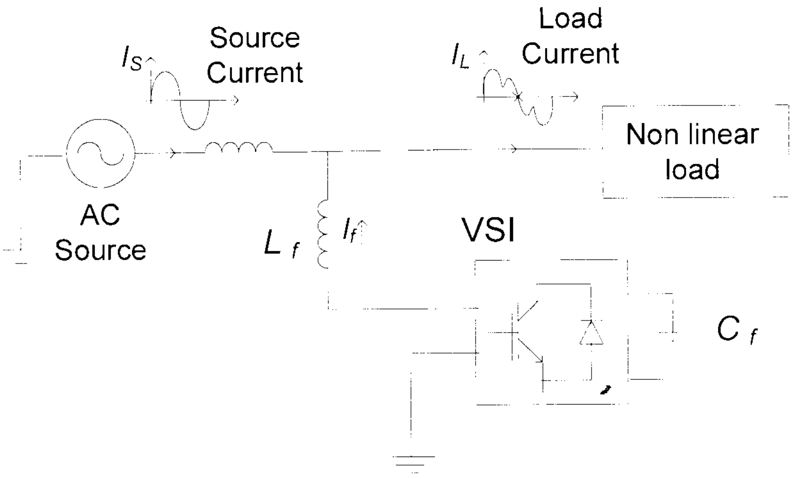

Figure 4.5 Configuration of Shunt APF

This is achieved by "shaping" the compensation current waveform (I_f), using the VSI switches. The shape of compensation current is obtained by measuring the load current (I_L) and subtracting it from a sinusoidal reference. The aim of shunt APF is to obtain a sinusoidal source current (I_s) using the relationship:

$$I_s = I_L - I_f$$

Shunt APFs have the advantage of carrying only the compensation current plus a small amount of active fundamental current supplied to compensate for system losses. It can also contribute to reactive power compensation. Moreover, it is also possible to connect several shunt APFs in parallel to cater for higher currents, which makes this type of circuit suitable for a wide range of power ratings [10].

4.5.2 Series active power filter

The series APF is shown in **Figure 4.6.** It is connected in series with the distribution line through a matching transformer [12]. VSI is used as the controlled source, thus the principle configuration of series APF is similar to shunt APF, except that the interfacing inductor of shunt APF is replaced with the interfacing transformer.

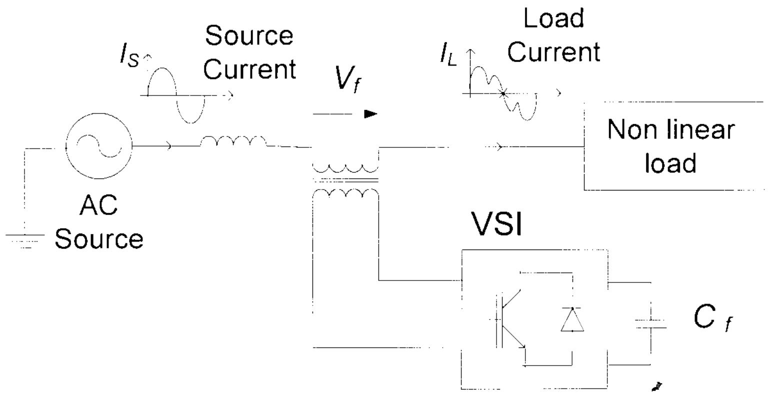

Figure 4.6 Configuration of Series APF

The operation principle of series APF is based on isolation of the harmonics in between the nonlinear load and the source. This is obtained by the injection of harmonic voltages (v_f) across the interfacing transformer. The injected harmonic voltages are added /subtracted, to/from the source voltage to maintain a pure sinusoidal voltage waveform across the nonlinear load.

Series APFs are less common than the shunt APF . This is because they have to handle high load currents. The main advantage of series APFs over shunt one is that they are ideal for voltage harmonics elimination.

4.5.3 Hybrid active power filter

They are typically the combination of basic APFs and passive filters. Hybrid APFs, inheriting the advantages of both passive filters and APFs, provide improved performance and cost-effective solutions. The idea behind this scheme is to simultaneously reduce the switching noise and electromagnetic interference [14]. The main objective of hybrid APF therefore, is to improve the filtering performance of high-order harmonics while providing a cost-effective low order harmonics mitigation.

Hybrid Active filtering is a relatively new technology. So, further research and development are needed to make this technology well established.

4.6 Selection of suitable configuration of APF for UPC building

When selecting the suitable technique the objectives addressed are as follows.

- Bringing down of harmonic levels below that specified by the standards.
- Reducing the overall system voltage total harmonic distortion.
- Solution should withstand future load alterations, easily.
- It should be a long term solution to the harmonic problems
- The solution should be low in maintenance.

When we consider the different configurations of APF and their applications, shunt active power filters are found to be widely used to compensate current harmonics, reactive power and load current unbalance [16]. The series connected active power filter is more preferable to protect the consumer from an inadequate supply voltage quality. This is specially recommended for compensation of voltage unbalances and voltage sags from the ac supply. Logged data revealed the requirement of current harmonics reduction. Therefore, a shunt active filter is selected to compensate harmonics in UPC building.

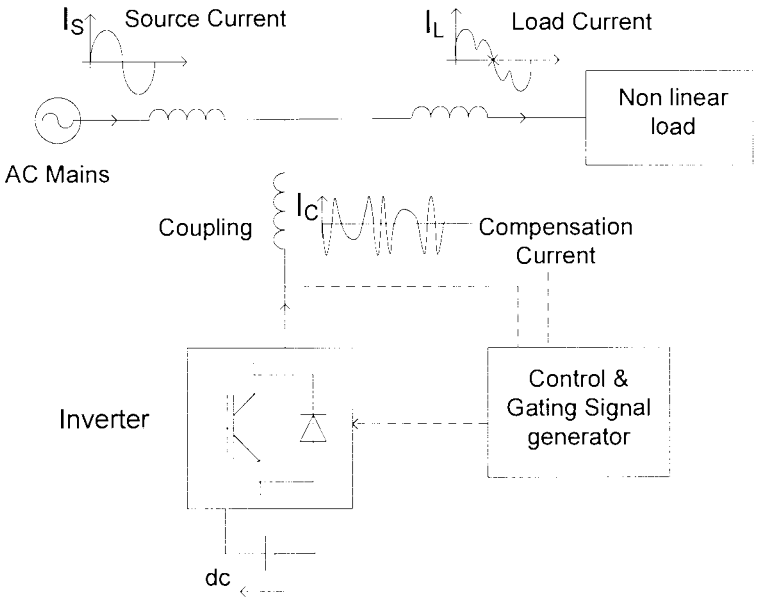

Figure 4.7 Component of Shunt Active Filter

Figure 4.7 illustrates the basic components of a shunt APF. This consists basically of a control and gating signal generator and a voltage source inverter controlled in a way that it acts like a current source.

4.6.1 Classification of APF

Various types of shunt active filters have been proposed by many researches. Those can be classified according to their power circuit, the control strategy and the harmonic detection method [14]. The main purpose of the active filters installed by individual consumers is to compensate for current harmonics and / or current imbalance of their own harmonic-producing loads.

4.6.2 Classification by Power Circuit

There are two types of power circuits used for active filters: a voltage-fed PWM inverter and a current fed PWM inverter. These are similar to the power circuits used for ac motor drives. They are, however, different in their behavior because active filters act as non-sinusoidal current or voltage sources. The voltage fed PWM inverter is advantageous because the voltage-fed PWM inverter is higher in efficiency and lower in initial costs than the current-fed PWM inverter [14]. So, majority of active filters, which have been put into practical applications are adopted the voltage-fed PWM inverter as the power circuit.

Considering these facts voltage fed PWM inverter is selected for the shunt APF.

4.6.3 Classification by method of harmonic detection

The control strategy of active filters has a great impact on the compensation objective, required kVA rating of active filters, and also on the filtering characteristics in transient state, as well as in steady state.

APF controller determines the harmonics that are to be eliminated. For that it is required to detect the essential voltage /current signals to gather accurate system variables. The voltage variables to be sensed are ac source voltage, dc bus voltage of the APF, and voltage across interfacing transformer. Typical current variables are load current, ac source current, compensation current and dc-link current of the APF. Based on these system variable feedbacks, reference signals estimation in terms of voltage/current levels are estimated in frequency-domain or time-domain. As illustrated in **Figure 4.7** an inverter is then used to generate and inject the compensation current I_c into the power line.

There are mainly two types of control strategies: Frequency domain control based on the **Fourier analysis** and the Time domain control based on the Akagi-Nabae theory [10], [17]. Many methods are available for harmonic determination in both of above control strategies. Some of them are shown in **Figure 4.8.**

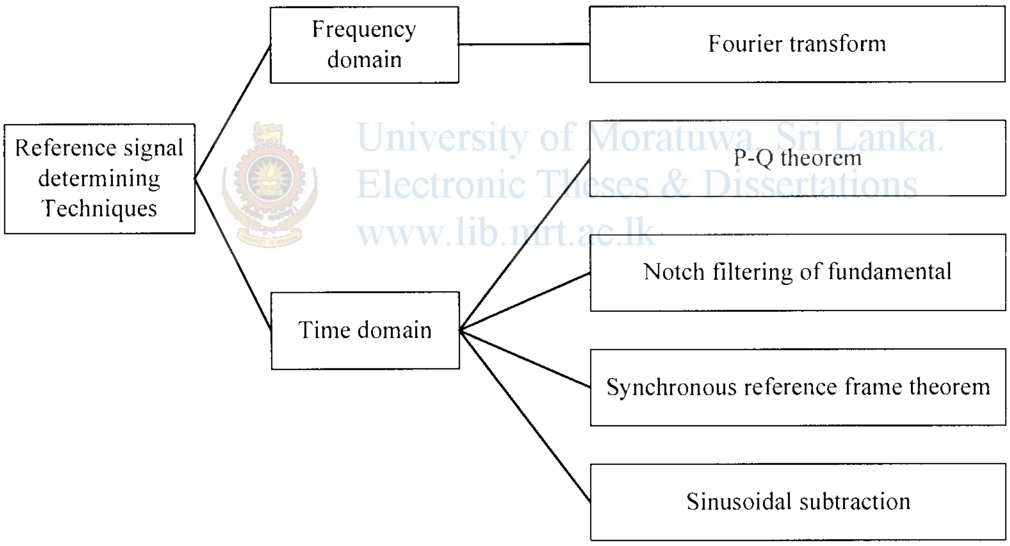

Figure 4.8 Harmonic determination methods

Each of these methods has pros and cons which depend on the situation. Summary of performance of harmonic determination methods is shown in **Table 4.1** [17]. The notch filtering of fundamental and P-Q (Instantaneous reactive power) theorem are the common methods that are being successfully used in modern APF controllers. As the notch filtering of harmonic detection shows better performance [18] in all the aspects, it is selected to use with APF for modeling and simulation.

Property	**Notching Filter**	**IRPT**	**SRF**	**Sine subtraction**	**FFT**
Steady state quality	Good	Poor	Good	Excel	Excel
Transient response quality	Good	Excel	Good	Good	Excel
Transient response speed	Good	Good	Good	Poor	Poor
Requires voltage	No	Yes	No	No	No
Requires balanced 3	No	Yes	Yes	No	No
No. of filter stages	3	2	3	3	0

Table 4.1 Summary of the performance of harmonic determination methods

4.6.4 Classification by control technique

The aim of APF control is to generate appropriate gating signals for the switching transistors based on the estimated compensation reference signals. The performance of an APF is affected significantly by the selection of control techniques [18]. Therefore, the choice and implementation of the control technique is very important for the achievement of a satisfactory APF performance.

Variety of control techniques such as linear control, digital deadbeat control, hysteresis control [10],[19], etc. are available for APF applications.

As shown in **Figure 4.9**, the linear control of APF is accomplished by using a negative-feedback system. In this control scheme, the compensation current (I_f) or voltage (V_f) signal is compared with its estimated reference signal (Ref_i, or Ref_v,) through the compensated error amplifier to produce the control signal. The resulting control signal is then compared with a saw-tooth signal through a pulse width modulation (PWM) controller to generate the appropriate gating signals for the switching transistors. The frequency of the repetitive saw-tooth signal establishes the switching frequency. This frequency is kept constant in linear control technique. As shown in **Figure 4.10**, the gating signal is set high when the control signal has a higher numerical value than the saw-tooth signal and via versa.

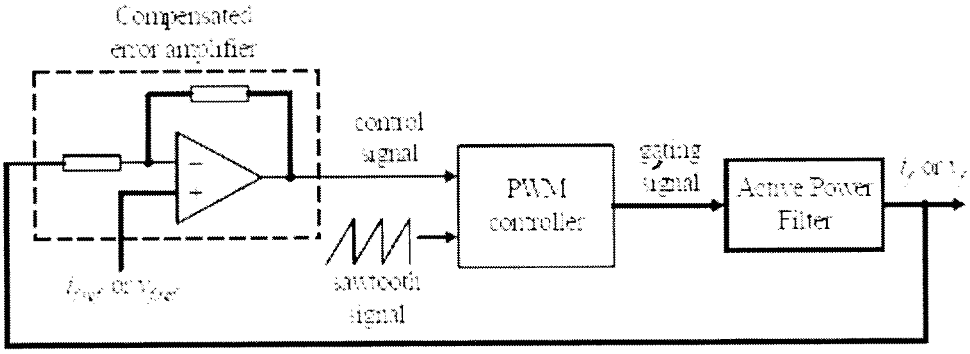

Figure 4.9 Block diagram of linear control techniques.

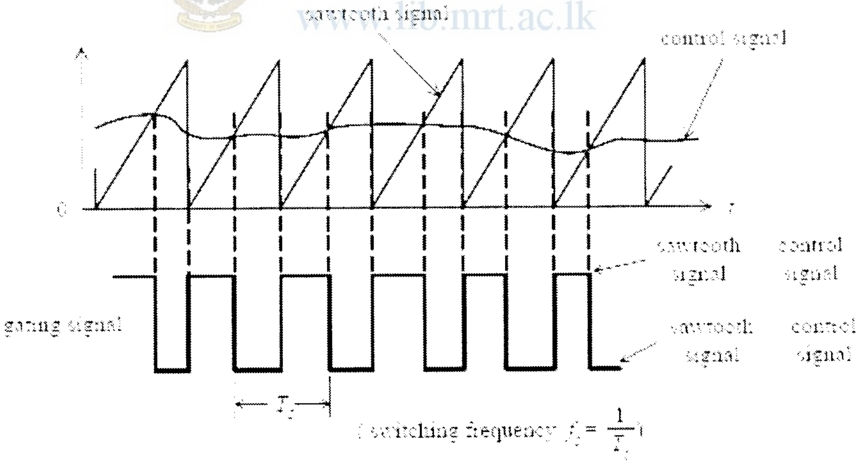

Figure 4.10 Gating signal generation by linear controller

Depending on the compensation signal there are two types of controllers: voltage-fed PWM inverters and current-fed PWM inverters. In current-fed PWM controllers the output is primarily determined in terms of current. Therefore current-fed inverter tends to be unsuitable for certain types of loads whereas the voltage-fed inverter operates quite satisfactorily. Voltage –fed inverters are high efficient and lower in initial cost. Current- fed inverters are heavier due to the inductors and incur high cost. Therefore, Voltage-fed PWM inverters are popular choice in modern APF.

The other type, Hysteresis Control Technique exhibits several unsatisfactory features. The main drawback is that it produces uneven switching frequency. Consequently, difficulties arise in designing. Furthermore, there is possibly generation of unwanted resonances on the power distribution system. Besides, the irregular switching also affects the APF efficiency and reliability [10].

Considering the above facts, voltage-fed PWM linear control is considered further in modeling the APF.

According to the above discussion the suitable filter for this purpose is the Active Shunt Filter which incorporates voltage fed PWM inverter type power circuit. Notch filtering harmonic detection and voltage-fed PWM linear controlling are the other encompassed features.

4.7 Location for harmonic mitigation

Harmonic currents flowing in internal circuits overload the conductors and transformers. This affects the equipment, as well. Transporting of real power along with the added harmonic components cause additional losses and reduce power factor. Therefore, harmonic elimination at the source of harmonic generation will always be the best location for installing harmonic filters. However, this leads to installation of many small filtering devices. The expected economy of a large scale filter suggests that the best location is where several distorted currents are combined, such as a load centre. The number and size of the harmonic filters will also affect internal losses of the filter and operating cost. Further, when determining the filtering locations, special wiring- related conditions such as neutral overloading and cancellation should also be considered. Therefore, in depth studies are required in order to find the best location for the filtering device.

Chapter 5

Simulation

5.1 Introduction

Chapter 2 discusses the fundamentals of power system harmonics and their effects on power system components, and the chapter 4 deliberates the various harmonic mitigation techniques. The latter chapter discussed the operating principles and the design methods of active filters, and developed a method for configuration of suitable APF to be used in UPC building.

This section describes the modeling of the active filter and simulation of an example load using in MATLAB/Simulink environment.

Simulation is a powerful tool that can be used to reduce development time. It ensures the proper fulfillment of critical steps of the design, as well. In the process of designing the shunt active filter, simulation allows us to study of its behavior under different operation conditions. It permits the tuning of some controller parameters together with the optimization of the active filter component values.

5.1.1 Simulation softwares

Nowadays a lot of softwares are available for simulating power systems. Some of them are dedicated to simulation of detailed behavior of power electronics based on specific circuit library, such as PSCAD (Professional's tool for Power Systems Simulation), CASPOC (Power Electronics and Electrical Drives Modeling and Simulation Software), PSPICE (Design and simulate analog and digital circuits), PSIM (simulation software designed for power electronics, motor control, and dynamic system simulation) and so on. Other software enables an efficient control development based on specific system libraries or toolboxes such as MATLAB/ Simulink. MATLAB/Simulink comprise of a range of blocksets such as communications, control, power system and fuzzy logic etc.

5.1.2 MATLAB /Simulink software

MATLAB is a high-level language oriented toward engineering and scientific applications. It has evolved over a period of more than eighteen years to become a flexible, powerful and simple language. It has served as an effective platform for more than twenty toolboxes supporting specialized engineering and scientific applications, covering areas from symbolic computation to digital filter design, control theory, fuzzy logic, and neural nets [20].

Simulink is built on top of the MATLAB. It is an interactive environment for modelling and simulating a wide variety of dynamic systems, including linear, non-linear, discrete-time, continuous-time, and hybrid systems. It combines the power and ease-of-use of an application package with the flexibility and extensibility of a language. It can be used to build block diagram models with click-and-drag operations, change model parameters on-the-fly, and display results "live" during a simulation. This tool is also a uniquely open system that allows choosing, adapting, and creating software and hardware components to suit each application

Together, Simulink and MATLAB provide an ideal integrated environment for developing models, performing dynamic system simulations, and designing and testing new ideas.

5.1.3 Power System Blockset

Power System Blockset is a design tool, developed by scientists and researchers at TEQSIM, Inc., and Hydro-Québec, for modelling and simulating electric power systems within the Simulink environment [21]. Power System Blockset block library contains Simulink blocks that represent common components and devices found in electrical power networks. Most of the blocks are based on well-known electrical components. These blocks use standard electrical symbols and therefore, creating graphical models of electrical power systems is easy [22].

Power System Blockset extends Simulink to provide a good environment for multi-domain modeling and controller design. By connecting the electrical parts of the simulation to blocks from Simulink's modeling library, it is possible to draw the circuit topology and simultaneously analyze the circuits [20].

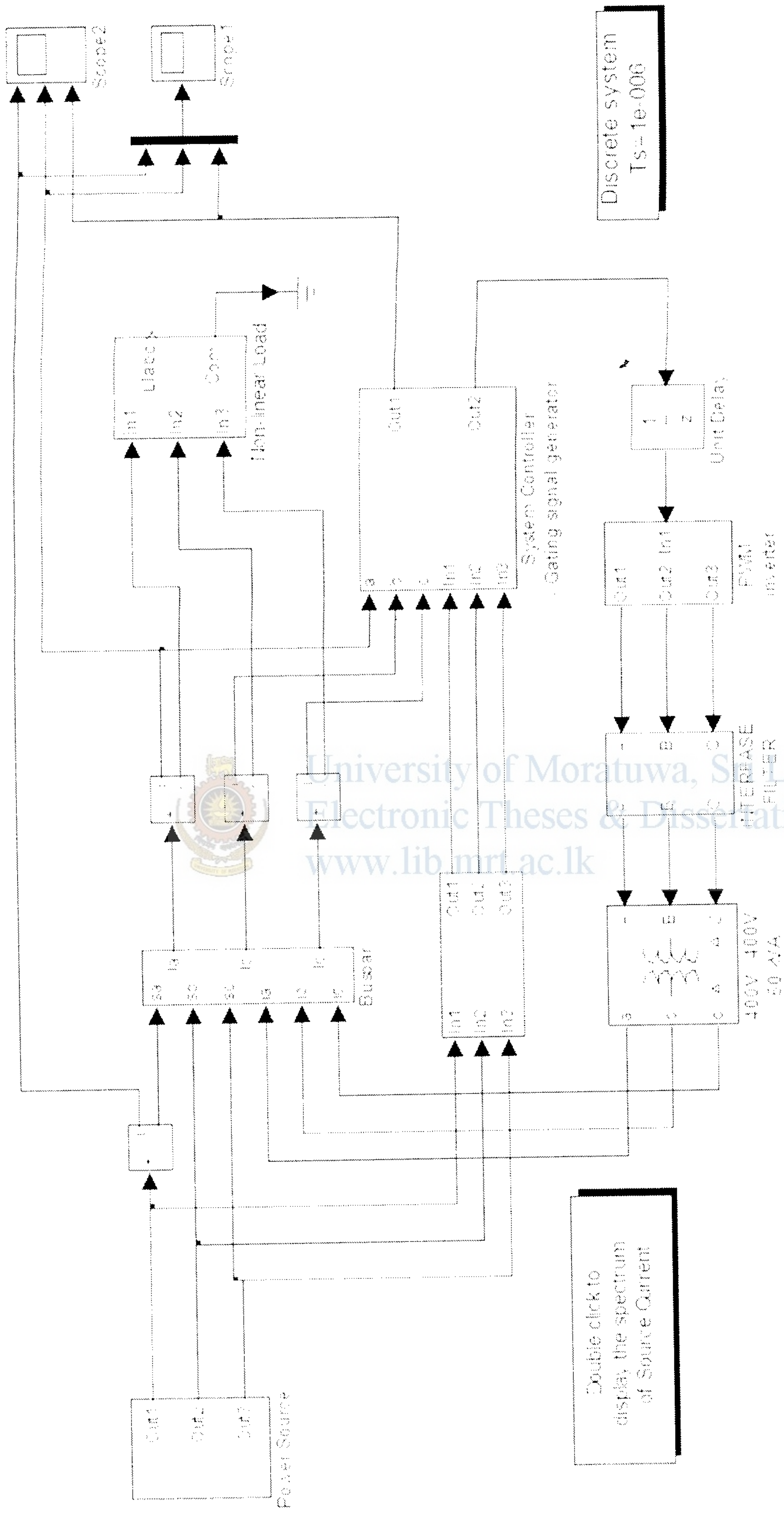

Figure 5.1 MATLAB / SIMULINK Model

5.2 Modeling the APF

In **Chapter 4,** a suitable configuration for APF was determined. So, a shunt APF with voltage-fed PWM linear control unit was selected for harmonic mitigation at UPC. The strategy used for harmonic determination is notch filtering method. And the power circuit selected is voltage-fed PWM inverter. The filter was modeled under the MATLAB / Simulink environment and the developed model is shown in **Figure 5.1.** It comprises set of several subcomponents of which a brief outline is given below.

5.2.1 Model of the power source

The three phase inductive source with neutral block available in three phase library of power system block set was selected as the power supply. Parameters of the power supply were set to suit 33kV, 50Hz and 10MVA source. The output of this source was connected to 33kV/400V, transformer to get a 400V three phase power supply, which is similar to the existence at UPC building. Selected transformer was the 3Φ two winding transformer block in the same block set. Other parameters were selected to give as far as possible an equivalent power supply that is available at UPC. The power source thus developed is given in **Figure 5.2.** This model of the power source grouped and included in the complete model as a subsystem named as "power source".

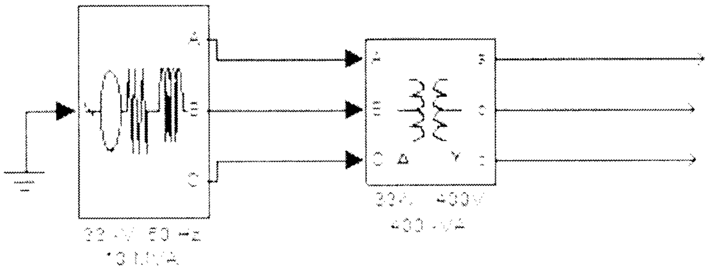

Figure 5.2 **MATLAB /Simulink model of the power source**

5.2.2 Model of the Nonlinear Load

To model an example non linear load, harmonic current measurements logged at UPC were used. **Figure 5.3** shows a spectrum of individual harmonics captured by Network analyzer at a worse case. The fundamental current is 40 A.

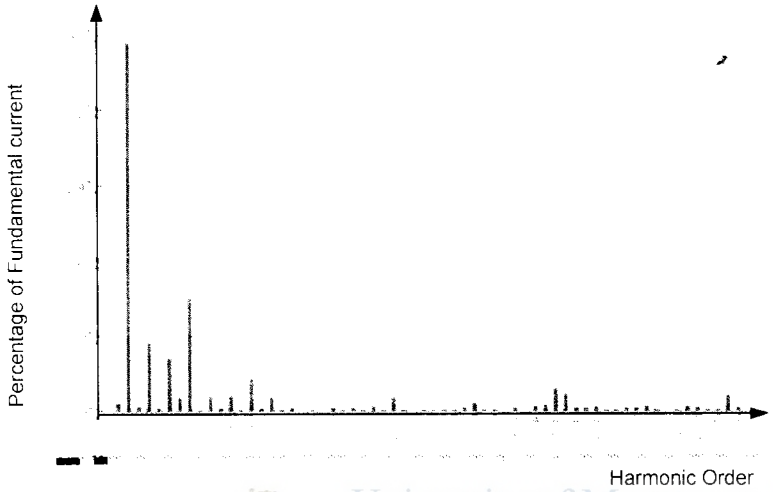

Figure 5.3 **Individual Harmonics of Load Current**

The non- linear load was formulated using an equivalent resistor and set of current sources with relevant percentage magnitudes to represent dominant harmonic components, as shown in **Figure 5.4**.

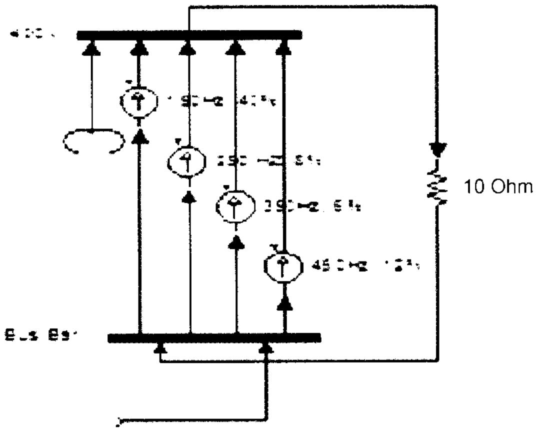

Figure 5.4 MATLAB /Simulink model of non-linear Load

The non linear load thus developed gives following response when simulating. **Figure 5.5** Shows that the dominant Harmonic components of the model are approximately equal to the spectrum given in **Figure 5.3**. This model of the load for three phases grouped and included in the complete model as a subsystem named as "Non-linear Load".

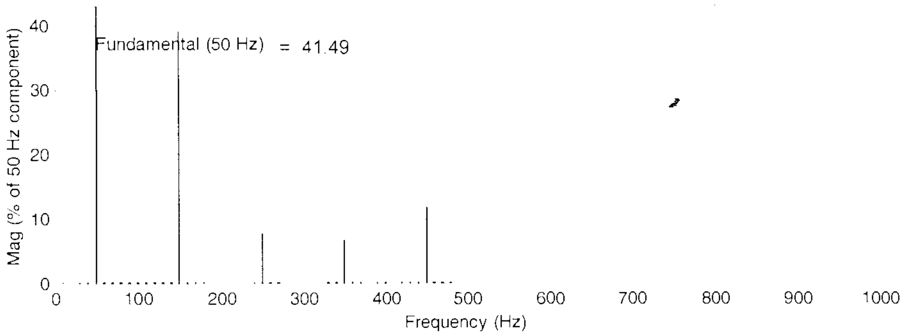

Figure 5.5 Frequency spectrum of load current

5.2.3 Model of system controller / gating signal generator

In this model harmonic components of load current are determined using a notch filter, and a voltage reference signal to PWM inverter is generated accordingly. A second order butterworth filter in the discrete control blocks of power system block set, with cut off frequency 50 Hz is used as a band stop filter to simulate the notch filter.

The developed controller unit is shown in **Figure 5.6**. The output signal of filter contains only the harmonic components of current and it is normalized by a gain controller with gain factor *k1*. The source voltage is normalized by a factor *k2*. Normalized voltage signal and harmonic components are then added to form the control signal to PWM inverter.

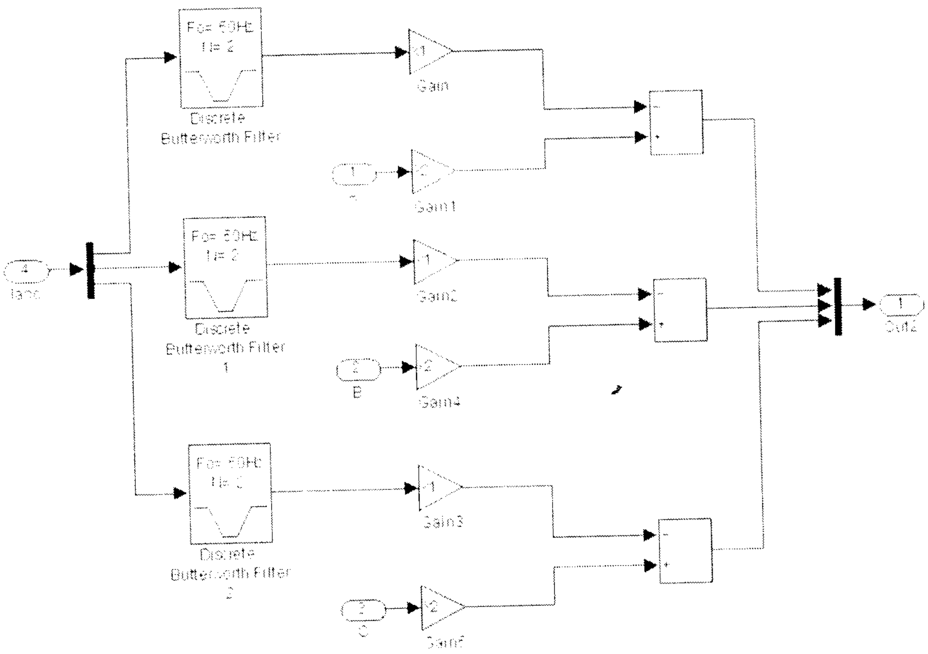

Figure 5.6 **MATLAB /Simulink model of Controller/ Gating signal generator**

5.2.4 Model of the PWM Inverter.

Universal bridge block having three arms available in the power electronics subset of power system blockset was used to model PWM inverter. The universal bridge block implements a three phase power converter that consists of six IGBT connected as a bridge [22]. A dc source block was used to give a dc supply to the inverter. To generate pulses to the IGBT inverter, PWM generator block available in power system blockset was used. The carrier frequency was set to 2000 Hz. This block generates pulses for the PWM inverter. The output of the inverter is controlled by the controlling signal coming from the gating signal generator **Figure 5.7** shows the MATLAB / Simulink model developed for inverter, and it is included in the complete model as a subsystem named as "PWM inverter".

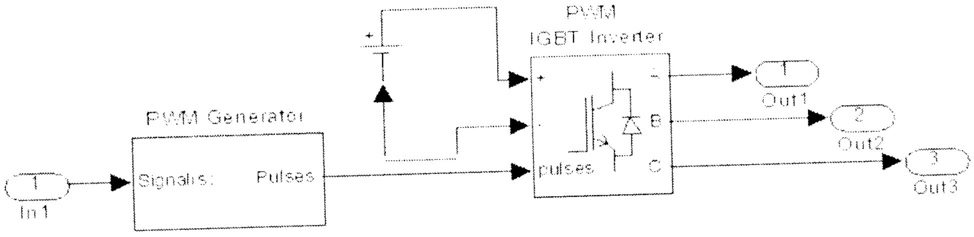

Figure 5.7 MATLAB /Simulink Model of PWM Inverter

5.3 Simulation results.

Figure 5.4 shows the load current of one of the phases, when the APF is not in action. The fundamental current is 80 A and relevant 3rd ,5th ,7th and 9th harmonics respectively are approximately 40%, 8%, 9% and 12%. It shows that the current wave form is highly distorted and the maximum harmonic component is high as 40 % of the fundamental.

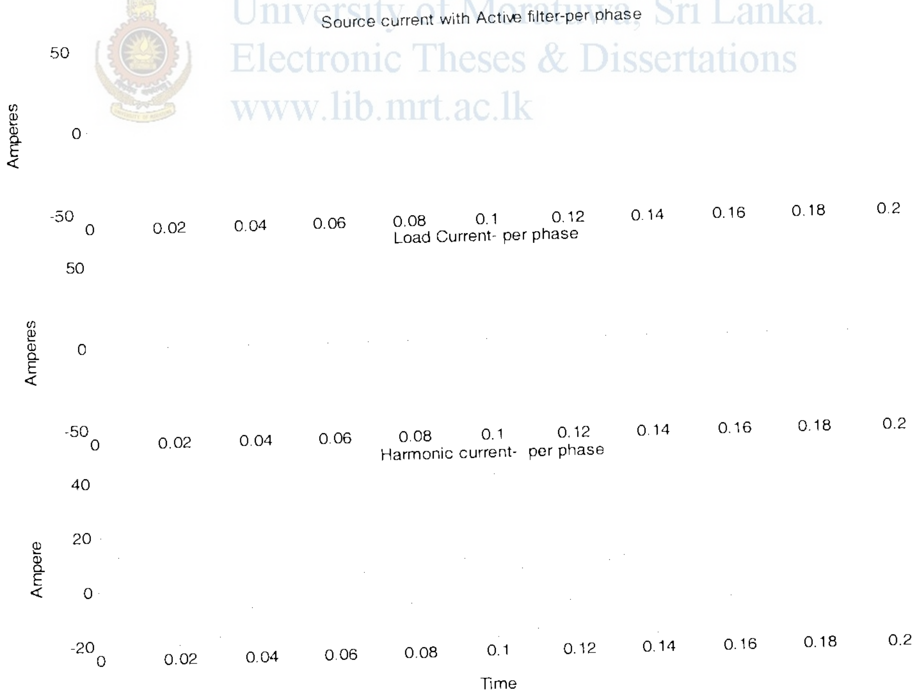

Figure 5.8 Per- phase Source current, Load current and Harmonic current with Shunt APF in action

Without the APF, source current has exactly the same waveform and spectrum as the load current.

With the APF in action, under the same load conditions, per phase Source current, Load current and Harmonic current extraction are shown in **Figure 5.8.** It indicates that though there is a highly distorted load current, when the APF is in action, source delivers a current with almost sinusoidal waveform. **Figure 5.9** shows the source current waveform together with the harmonic spectrum. The highest harmonic current in that case is 4 %. It denotes when the APF is on, third and fifth harmonics have become 4% and 2% respectively, whereas those were 40 % and 10% respectively without filtering.

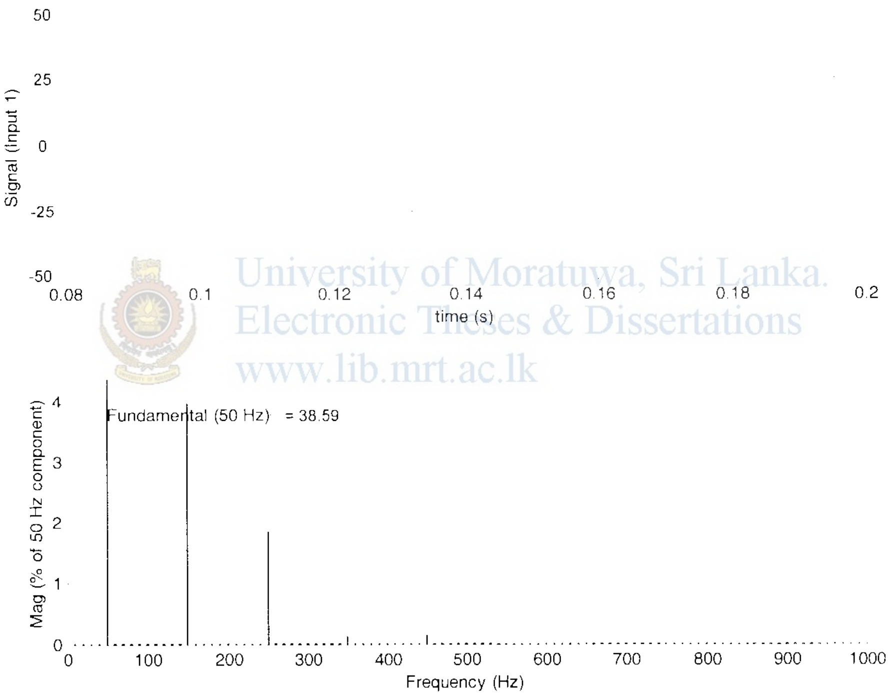

Figure 5.9 **Source Current waveform together with the Harmonic Spectrum**

For comparison, the harmonic spectrums with and without APF in action are given in **Figure 5.10.** Immense reduction in harmonics can be observed when APF is in action.

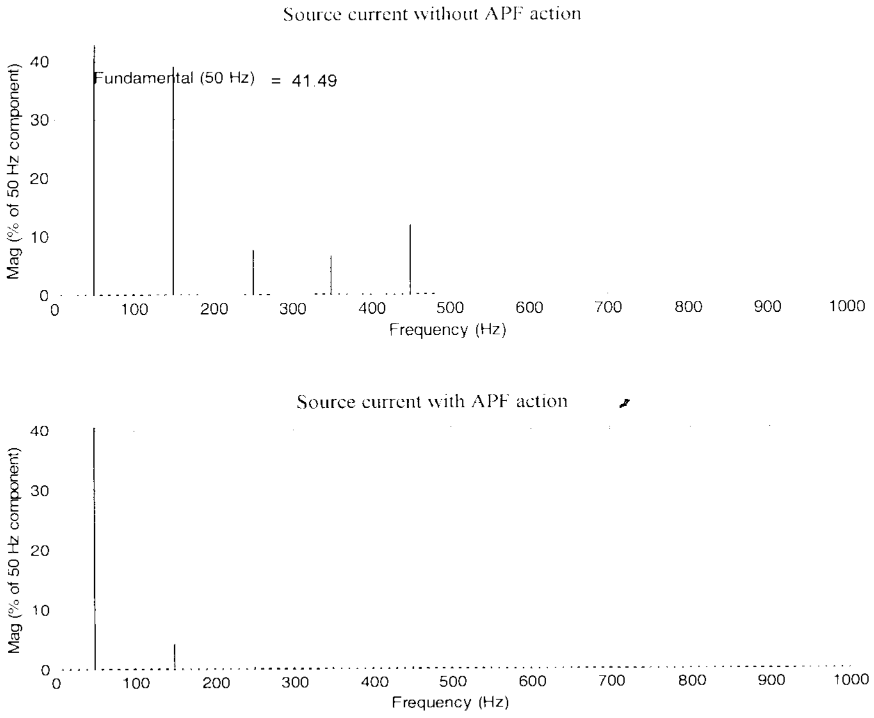

Figure 5.10 Harmonic spectrums with and without APF in action

Table 5.1 summarizes the source current harmonic effects with and without the action of APF. Simulation results obtained before and after the application of harmonic filters show APF can be employed to control harmonics in commercial buildings, effectively.

Property	Without APF	With APF
Percentage 3rd harmonics with respect to fundamental	40% (13.4 A)	4% (1.5 A)
Percentage 5th harmonics with respect to fundamental	8% (2.7 A)	2% (0.75 A)
Percentage 7th harmonics with respect to fundamental	9% (3.0 A)	negligible
Percentage 9th harmonics with respect to fundamental	12% (4.0A)	Negligible
Waveform	Highly Distorted	Almost Sinusoidal

Table 5.1 Comparison of source current with and without filtering action

Chapter 6

Conclusion

6.1 Conclusions

One of the objectives of this project was to investigate the quality of electric power supply of Uva Provincial Council. The logged data revealed that the Total Demand Distortion, as well as the individual Current Harmonic Distortion are beyond the limits prescribed by IEEE standard 519-1992. The main distortion consists of odd multiples of the fundamental component (50 Hz) and occurs in a frequency range up to 1 kHz. Moreover, it was observed that the Voltage Total Harmonic Distortion was within prescribed limits.

Presence of excessive harmonics could result equipment failure, mal-functioning and pre-aging. Additional losses due to the harmonics in the power system are less than one tenth of a percent of the total active power flow. But in long term the effect is significant.

Analysis of various harmonic mitigation techniques revealed that the shunt APF with voltage-fed PWM linear control unit is suitable for mitigating the harmonics at UPC building. The strategy suitable for harmonic determination is notch filtering and the power circuit appropriate is a voltage-fed PWM inverter.

Selected configuration was modeled, and an example simulation was done using MATLAB / Simulink environment. The results reveal that active power filters can be used successfully to mitigate the harmonics produced by non-linear loads. However, the location of harmonic reduction equipment within the building wiring is crucial for effectiveness. The greatest potential for loss reduction and harmonic mitigation can be achieved through filtering the harmonics near the harmonic generating loads, while installations near the service entrance may be of little value.

In this research, data were collected using limited resources within a limited period. There are several possible sources of error when analyzing the monitored data, not only the technical measurement, due to harmonic interaction in the system. However, proper monitoring the distortion is important to get real data of the harmonics amplitude and phase angle and of the variation over the time, i.e. the day, week or year.

6.2 Remarks and Discussion

The survey was conducted in a typical office building with many computers connected. The data obtained from case study indicates that it could be a problem commonly found in much similar office building in Sri Lanka. Problems of harmonics from non linear loads continue to grow with modern office buildings. This work may alert the electrical engineers interested in Power Quality issues, as well as those unaware of it by embracing a large number of aspects related with this subject. This analysis may provide useful information in the future dimensioning and project of the electrical installation in the facility buildings.

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Load Reading

Uva Provincial Council , Badulla

CEB Load readings, Year 2008/ 2009

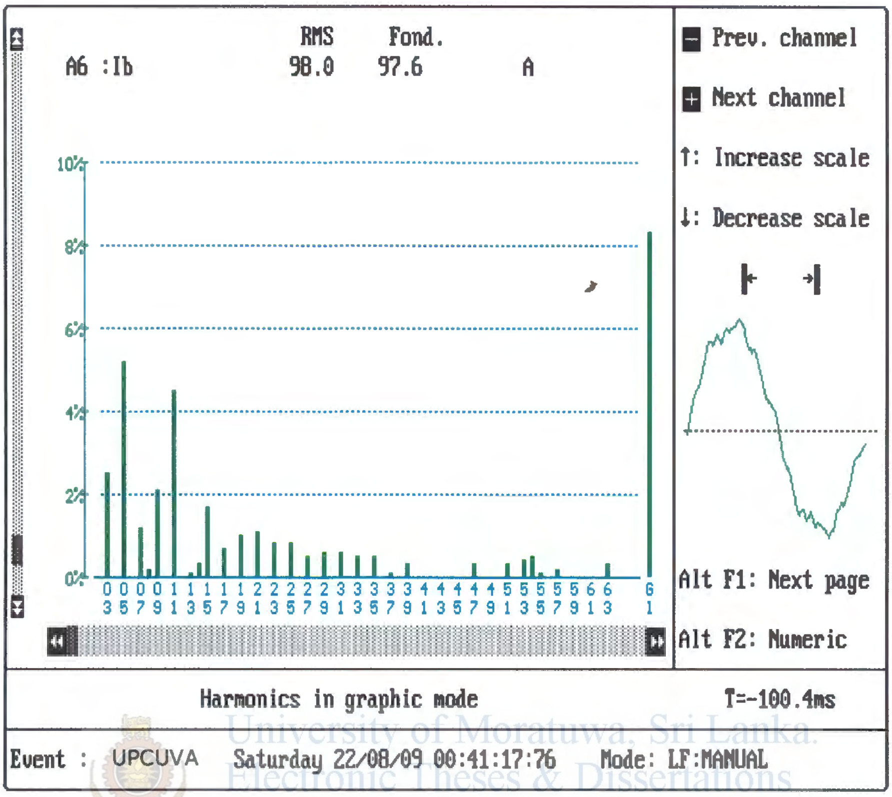
Account Number :3670101098

Month	**No. of Days**	**No. Of units Consumed**	
		kWH	**kVA**
September	29	17042	201
October	33	22500	207
November	30	19440	194
December	31	22474	188
January	33	21644	195
February	37	23552	213
March	25	16966	203
April	29	16376	199
May	34	24308	208
June	31	25256	208
July	26	16452	208
August	29	18978	165

Voltage harmonic measurements

Date	Time	THD VA	THD VB	THD VC	VA	VB	VC
Fri, 19-Jun-2009	2:06:00 PM	3.2	3.1	3	248	246.2	248
Fri, 19-Jun-2009	2:06:30 PM	3.3	3.1	3.1	248.2	246.4	248.2
Fri, 19-Jun-2009	2:07:00 PM	3.3	3.1	3.1	248.2	246.3	248.2
Fri, 19-Jun-2009	2:07:30 PM	3.3	3.2	3.1	248	246.1	248
Fri, 19-Jun-2009	2:08:00 PM	3.3	3.1	3.1	248	246.2	248
Fri, 19-Jun-2009	2:08:30 PM	3.3	3.1	3.1	248	246.1	248
Fri, 19-Jun-2009	2:09:00 PM	3.3	3.1	3.1	248	246.1	247.9
Fri, 19-Jun-2009	2:09:31 PM	3.3	3.1	3.1	248	246.1	247.8
Fri, 19-Jun-2009	2:10:01 PM	3.2	3.1	3	248	246.2	247.9
Fri, 19-Jun-2009	2:10:31 PM	3.2	3.1	3	248.2	246.3	248
Fri, 19-Jun-2009	2:11:01 PM	3.2	3.1	3.1	248.3	246.4	248.1
Fri, 19-Jun-2009	2:11:31 PM	3.2	3.1	3	248.2	246.2	248
Fri, 19-Jun-2009	2:12:01 PM	3.3	3.1	3	248	246.1	248
Fri, 19-Jun-2009	2:12:31 PM	3.2	3.1	3	248.4	246.4	248.3
Fri, 19-Jun-2009	2:13:01 PM	3.3	3.1	3.1	248.5	246.5	248.4
Fri, 19-Jun-2009	2:13:31 PM	3.4	3.1	3.1	248	246.1	248
Fri, 19-Jun-2009	2:14:01 PM	3.3	3.2	3.1	247.8	246	247.8
Fri, 19-Jun-2009	2:14:30 PM	3.3	3.2	3.2	248	246.1	248
Fri, 19-Jun-2009	2:15:00 PM	3.3	3.2	3.1	248.1	246.3	248.1
Fri, 19-Jun-2009	2:15:30 PM	3.3	3.2	3.1	248.2	246.3	248.1
Fri, 19-Jun-2009	2:16:00 PM	3.3	3.1	3.1	248.1	246.2	248
Fri, 19-Jun-2009	2:16:30 PM	3.3	3.2	3.1	248.2	246.3	248.1
Fri, 19-Jun-2009	2:17:00 PM	3.3	3.1	3.1	248.2	246.4	248.1
Fri, 19-Jun-2009	2:17:30 PM	3.4	3.2	3.1	248.2	246.3	248
Fri, 19-Jun-2009	2:18:00 PM	3.4	3.2	3.1	248	246.1	247.8
Fri, 19-Jun-2009	2:18:30 PM	3.4	3.2	3.1	248	246	247.6
Fri, 19-Jun-2009	2:19:00 PM	3.3	3.2	3.1	248.1	246.2	247.7
Fri, 19-Jun-2009	2:19:31 PM	3.3	3.2	3.1	248.2	246.3	247.8
Fri, 19-Jun-2009	2:20:01 PM	3.3	3.1	3	248.1	246.2	247.7
Fri, 19-Jun-2009	2:20:31 PM	3.4	3.2	3.1	248.1	246.2	247.7
Fri, 19-Jun-2009	2:21:01 PM	3.3	3.2	3.1	248	246.1	247.6
Fri, 19-Jun-2009	2:21:31 PM	3.3	3.2	3.1	248	246.1	247.6
Fri, 19-Jun-2009	2:22:01 PM	3.3	3.2	3.1	248.2	246.3	247.9
Fri, 19-Jun-2009	2:22:31 PM	3.3	3.1	3.1	248	246.1	247.7
Fri, 19-Jun-2009	2:23:01 PM	3.3	3.2	3.1	247.8	246	247.5
Fri, 19-Jun-2009	2:23:31 PM	3.3	3.2	3.1	247.8	246	247.5
Fri, 19-Jun-2009	2:24:01 PM	3.3	3.2	3.1	247.7	245.9	247.4
Fri, 19-Jun-2009	2:24:30 PM	3.3	3.2	3.1	247.7	245.9	247.4
Fri, 19-Jun-2009	2:25:00 PM	3.3	3.2	3.1	247.7	245.8	247.4
Fri, 19-Jun-2009	2:25:30 PM	3.3	3.2	3.1	247.8	245.9	247.4

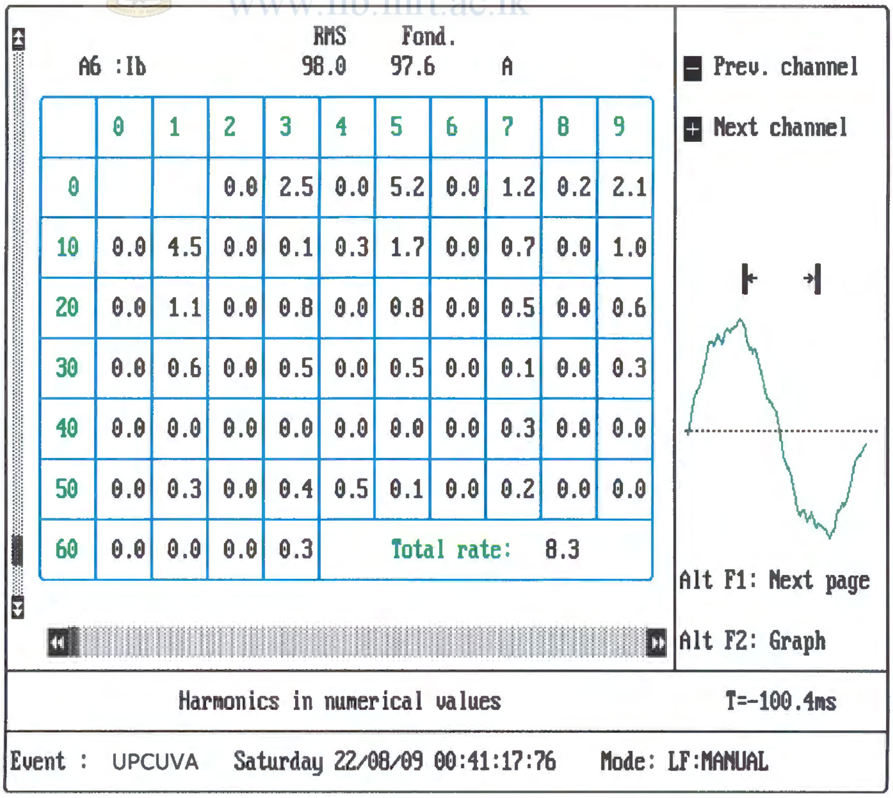
Current harmonics spectrum captured at UPC building



A6 :Ib RMS 98.0 Fond. 97.6 A

Harmonics in graphic mode T=-100.4ms

Event : UPCUVA Saturday 22/08/09 00:41:17:76 Mode: LF:MANUAL

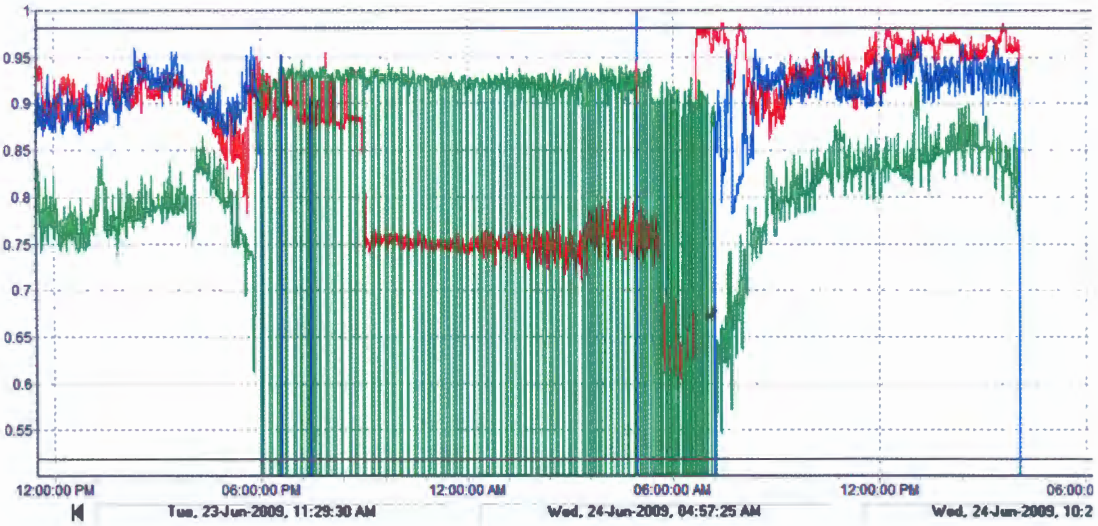


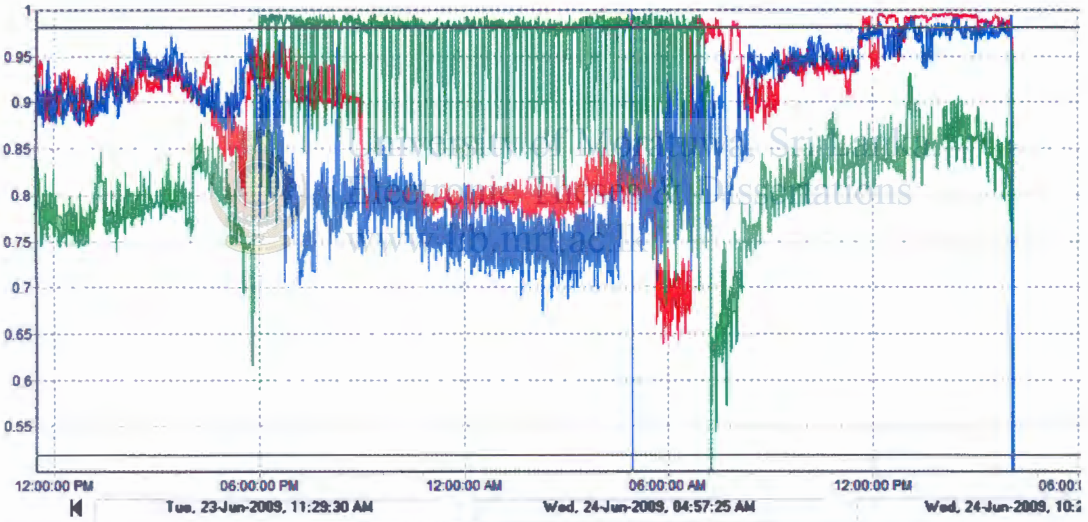
A6 :Ib RMS 98.0 Fond. 97.6 A

	0	1	2	3	4	5	6	7	8	9
0			0.0	2.5	0.0	5.2	0.0	1.2	0.2	2.1
10	0.0	4.5	0.0	0.1	0.3	1.7	0.0	0.7	0.0	1.0
20	0.0	1.1	0.0	0.8	0.0	0.8	0.0	0.5	0.0	0.6
30	0.0	0.6	0.0	0.5	0.0	0.5	0.0	0.1	0.0	0.3
40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0
50	0.0	0.3	0.0	0.4	0.5	0.1	0.0	0.2	0.0	0.0
60	0.0	0.0	0.0	0.3	Total rate: 8.3					

Harmonics in numerical values T=-100.4ms

Event : UPCUVA Saturday 22/08/09 00:41:17:76 Mode: LF:MANUAL


True power factor graph


Displacement power factor graph

Displacement and true power factor with calculated additional power (day time)

	Tue, 23-Jun-2009						DPF -TPF			Voltage / (V)			Current/ (A)			Additional power / (W)		
Time	TPF A	DPF A	TPF B	DPF B	TPF C	DPF C	A	B	C	VA	VB	VC	IA	IB	IC	PA	PB	PC
1:01:30 PM	0.88	0.89	0.76	0.76	0.91	0.92	0.01	0	0.01	246.6	244.4	246.8	130.6	203.2	170.2	322.06	0.00	420.05
1:02:00 PM	0.9	0.9	0.76	0.77	0.91	0.92	0	0.01	0.01	246.3	244.1	246.5	135.8	212.2	177.4	0.00	517.98	437.29
1:02:30 PM	0.88	0.89	0.76	0.77	0.91	0.91	0.01	0.01	0	246.2	243.9	246.3	129.4	207.6	169.8	318.58	506.34	0.00
1:03:00 PM	0.89	0.9	0.78	0.79	0.91	0.92	0.01	0.01	0.01	246	243.9	246.1	130.4	198.4	170	320.78	483.90	418.37
1:03:30 PM	0.88	0.88	0.79	0.79	0.9	0.91	0	0	0.01	246.3	244.2	246.4	130.6	196.4	171.4	0.00	0.00	422.33
1:04:00 PM	0.87	0.88	0.78	0.79	0.9	0.9	0.01	0.01	0	246.8	244.7	247	144.8	212.4	183.4	357.37	519.74	0.00
1:04:30 PM	0.89	0.89	0.77	0.77	0.9	0.91	0	0	0.01	247	244.8	247.5	146.4	224	157.4	0.00	0.00	389.57
1:05:00 PM	0.87	0.88	0.77	0.77	0.87	0.88	0.01	0	0.01	247	244.8	247.4	145.4	211.6	146.2	359.14	0.00	361.70
1:05:30 PM	0.88	0.88	0.77	0.77	0.87	0.88	0	0	0.01	246.6	244.6	247.1	147.4	199.8	145	0.00	0.00	358.30
1:06:00 PM	0.87	0.88	0.77	0.77	0.87	0.88	0.01	0	0.01	246.4	244.4	246.9	146.6	202.8	146.2	361.22	0.00	360.97
1:06:30 PM	0.89	0.89	0.77	0.77	0.88	0.89	0	0	0.01	246.3	244.3	246.8	145.4	200.2	143.6	0.00	0.00	354.40
1:07:00 PM	0.88	0.89	0.76	0.77	0.88	0.89	0.01	0.01	0.01	246.3	244.3	246.8	132	182.2	129.4	325.12	445.11	319.36
1:07:30 PM	0.9	0.9	0.76	0.77	0.88	0.89	0	0.01	0.01	246.3	244.3	246.5	131.2	181.8	154.6	0.00	444.14	381.09
1:08:00 PM	0.89	0.89	0.77	0.77	0.89	0.9	0	0	0.01	246.3	244.3	246.5	129.8	179.8	156.2	0.00	0.00	385.03
1:08:30 PM	0.89	0.89	0.76	0.76	0.88	0.89	0	0	0.01	246.4	244.5	246.6	131.2	179.2	154.6	0.00	0.00	381.24
1:09:00 PM	0.88	0.89	0.76	0.76	0.89	0.9	0.01	0	0.01	246.3	244.4	246.5	135	183.4	162.4	332.51	0.00	400.32
1:09:30 PM	0.87	0.88	0.76	0.77	0.88	0.89	0.01	0.01	0.01	246.3	244.4	246.5	131.6	180.4	159.4	324.13	440.90	392.92
1:10:00 PM	0.89	0.9	0.78	0.78	0.89	0.9	0.01	0	0.01	246.1	244.2	246.3	146.8	195.6	173.4	361.27	0.00	427.08
1:10:30 PM	0.88	0.88	0.77	0.77	0.88	0.89	0	0	0.01	246.2	244.2	246.4	148.4	196	173.6	0.00	0.00	427.75
1:11:00 PM	0.89	0.9	0.78	0.79	0.89	0.89	0.01	0.01	0	246.3	244.3	246.6	149	204.2	171	366.99	498.86	0.00
1:11:30 PM	0.88	0.89	0.78	0.78	0.88	0.89	0.01	0	0.01	246.3	244.3	246.6	147	208.2	169.2	362.06	0.00	417.25
1:12:00 PM	0.88	0.89	0.78	0.79	0.88	0.89	0.01	0.01	0.01	246.3	244.2	246.5	145.6	208	170.4	358.61	507.94	420.04
1:12:30 PM	0.91	0.91	0.81	0.81	0.91	0.92	0	0	0.01	246.3	244.2	246.5	153.2	220.2	177.2	0.00	0.00	436.80
1:13:00 PM	0.89	0.9	0.78	0.78	0.89	0.9	0.01	0	0.01	246.5	244.4	246.7	132.6	195.6	156.4	326.86	0.00	385.84
1:13:30 PM	0.9	0.91	0.81	0.81	0.9	0.91	0.01	0	0.01	246.6	244.5	246.7	138.2	199	163	340.80	0.00	402.12
1:14:00 PM	0.89	0.9	0.78	0.78	0.89	0.89	0.01	0	0	246.5	244.4	246.7	132.2	192	157.4	325.87	0.00	0.00
1:14:30 PM	0.89	0.9	0.78	0.78	0.89	0.9	0.01	0	0.01	246.6	244.5	246.8	130.8	192	155.4	322.55	0.00	383.53
1:15:00 PM	0.9	0.91	0.78	0.78	0.92	0.92	0.01	0	0	246.6	244.5	246.7	131.8	190.8	158.2	325.02	0.00	0.00
1:15:30 PM	0.88	0.89	0.78	0.78	0.88	0.89	0.01	0	0.01	246.5	244.4	246.7	140.4	200.4	168	346.09	0.00	414.46
1:16:00 PM	0.88	0.89	0.79	0.79	0.88	0.89	0.01	0	0.01	246.4	244.3	246.6	145.8	209.6	172	359.25	0.00	424.15
1:16:30 PM	0.89	0.89	0.78	0.79	0.88	0.89	0	0.01	0.01	246.3	244.2	246.5	149.2	208.8	172.8	0.00	509.89	425.95

Displacement and true power factor with calculated additional power (night time)

	Tue, 23-Jun-2009						DPF -TPF			Voltage / (V)			Current/ (A)			Additional power / (W)		
Time	TPF A	DPF A	TPF B	DPF B	TPF C	DPF C	A	B	C	VA	VB	VC	IA	IB	IC	PA	PB	PC
6:11:30 PM	0.89	0.93	0.93	0.99	0.77	0.89	0.04	0.06	0.12	247.5	246.3	248.3	38.2	10.4	4.2	378.18	153.69	125.14
6:12:00 PM	0.89	0.93	0.92	0.99	0.73	0.87	0.04	0.07	0.14	247.4	246.3	248.1	37.4	10.4	4.2	370.11	179.31	145.88
6:12:30 PM	0.93	0.96	0.93	0.99	0.76	0.89	0.03	0.06	0.13	247.7	246.5	248.4	38.6	11.6	6.6	286.84	171.56	213.13
6:13:00 PM	0.89	0.93	0.92	0.99	0.77	0.88	0.04	0.07	0.11	247.4	246.2	248.1	38	10.4	4.2	376.05	179.23	114.62
6:13:30 PM	0.89	0.93	0.92	0.98	0.77	0.92	0.04	0.06	0.15	247.2	246.1	248	37	10.4	4.2	365.86	153.57	156.24
6:14:00 PM	0.9	0.93	0	0.84	0.76	0.9	0.03	0.84	0.14	247.5	246.4	248.3	37.2	8.8	6.6	276.21	1821.39	229.43
6:14:30 PM	0.89	0.93	0	0.78	0.7	0.89	0.04	0.78	0.19	247.4	246.2	248.1	38.2	5.2	3.8	378.03	998.59	179.13
6:15:00 PM	0.89	0.93	0	0.82	0.76	0.92	0.04	0.82	0.16	247.1	245.9	247.8	37.4	7.4	6.8	369.60	1492.12	269.61
6:15:30 PM	0.91	0.94	0	0.86	0.73	0.92	0.03	0.86	0.19	247.5	246.3	248.2	39	5	3.8	289.57	1059.09	179.20
6:16:00 PM	0.89	0.93	0	0.85	0.72	0.9	0.04	0.85	0.18	247.2	246	247.9	38	5.2	3.8	375.74	1087.32	169.56
6:16:30 PM	0.93	0.95	0	0.83	0.79	0.91	0.02	0.83	0.12	247	245.8	247.7	38.6	5.2	4.2	190.69	1060.87	124.84
6:17:00 PM	0.89	0.93	0.91	0.99	0.72	0.9	0.04	0.08	0.18	246.9	245.7	247.6	37.4	11.2	6.8	369.30	220.15	303.06
6:17:30 PM	0.89	0.93	0.91	0.99	0.76	0.89	0.04	0.08	0.13	246.8	245.7	247.5	37	10.2	4.2	365.26	200.49	135.14
6:18:00 PM	0.89	0.93	0.92	0.99	0.78	0.81	0.04	0.07	0.03	246.7	245.5	247.4	38.4	10.4	5.6	378.93	178.72	41.56
6:18:30 PM	0.89	0.92	0.91	0.99	0.76	0.8	0.03	0.08	0.04	246.5	245.4	247.2	36.6	11.6	7.6	270.66	227.73	75.15
6:19:00 PM	0.89	0.93	0.92	0.99	0.73	0.8	0.04	0.07	0.07	246.7	245.5	247.3	36.6	10.4	5.6	361.17	178.72	96.94
6:19:30 PM	0.89	0.93	0.92	0.99	0.76	0.83	0.04	0.07	0.07	246.6	245.4	247.3	35.4	11.8	7.6	349.19	202.70	131.56
6:20:00 PM	0.88	0.92	0.92	0.99	0.78	0.84	0.04	0.07	0.06	246.4	245.3	247.1	36.8	11.8	7.6	362.70	202.62	112.68
6:20:30 PM	0.89	0.93	0.92	0.99	0.74	0.8	0.04	0.07	0.06	246.3	245.1	246.9	35.4	10.4	5.6	348.76	178.43	82.96
6:21:00 PM	0.89	0.93	0.92	0.99	0.71	0.84	0.04	0.07	0.13	246.4	245.3	247	38	11.8	7.8	374.53	202.62	250.46
6:21:30 PM	0.89	0.93	0.92	0.99	0.8	0.85	0.04	0.07	0.05	246.6	245.4	247.2	36.4	11.8	7.4	359.05	202.70	91.46
6:22:00 PM	0.89	0.93	0.92	1	0.77	0.87	0.04	0.08	0.1	246.4	245.3	247	37.4	10.8	5.6	368.01	211.94	138.32
6:22:30 PM	0.89	0.93	0.93	0.99	0.76	0.84	0.04	0.06	0.08	246.3	245.1	246.9	36	10.8	5.6	354.07	158.82	110.61
6:23:00 PM	0.89	0.93	0.92	0.99	0.8	0.84	0.04	0.07	0.04	246.3	245.2	246.9	38.4	10.8	5.6	378.32	185.37	55.31
6:23:30 PM	0.89	0.93	0.93	0.99	0.78	0.82	0.04	0.06	0.04	245.9	244.7	246.5	36.6	12	7.6	360.00	176.18	74.94
6:24:00 PM	0.9	0.94	0.92	0.99	0.81	0.86	0.04	0.07	0.05	247	245.8	247.6	38.8	12	7.6	383.54	206.47	94.09
6:24:31 PM	0.89	0.92	0.92	0.99	0.76	0.89	0.03	0.07	0.07	246.4	245.1	246.9	36.6	10.8	5.6	270.55	185.30	96.78
6:25:01 PM	0.93	0.95	0.92	0.99	0.77	0.9	0.02	0.07	0.13	246.3	245.1	246.9	39.2	12	7	193.10	205.88	224.68
6:25:31 PM	0.89	0.93	0.92	0.99	0	0.9	0.04	0.07	0.9	246.1	245	246.8	39.8	10.8	4.2	391.79	185.22	932.90
6:26:01 PM	0.89	0.93	0.92	0.99	0	0.91	0.04	0.07	0.91	246.1	244.9	246.7	35.8	10.8	4.2	352.42	185.14	942.89
6:26:31 PM	0.89	0.93	0.92	0.99	0	0.91	0.04	0.07	0.91	246	244.7	246.6	36.2	11.8	6.6	356.21	202.12	1481.08