UNIVERSITY OF MINES AND TECHNOLOGY, TARKWA

FACULTY OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

MSc THESIS REPORT ENTITLED

TECHNO-ECONOMIC ANALYSIS OF HARMONIC DISTURBANCES IN A UNIVERSITY ENVIRONMENT: A CASE STUDY AT THE UNIVERSITY OF CAPE COAST

BY

BENEDICT ADDO-YEBOA

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

THESIS SUPERVISOR

……

DR JOSEPH C. ATTACHIE

TARKWA, GHANA

JULY, 2020

DECLARATION

I declare that this thesis is my own work. It is being submitted for the Degree of Master of Science in Electrical and Electronic Engineering in the University of Mines and Technology (UMaT), Tarkwa. It has not been submitted for any degree or examination in any other University.

.....

(Signature of candidate)

…… day of October, 2020.

ABSTRACT

Nonlinear electrical loads connected to the power grid have increased within the past decade and estimated to reach 95% of all connected electrical loads in the coming decade. However, these loads are major sources of harmonics. Direct linkage could be established between the adverse effects of harmonics and avoidable costs as utilities and consumers alike are recording rather huge loss of revenues globally as a result of harmonic disturbances. In Ghana and at the University of Cape Coast, the proliferation of these nonlinear loads, owing to nonexistent standards to curb the influx, has led to high harmonic distortions on the distribution network and the attendant disturbances is evident. Problems of harmonics in the University are presented in the form of frequent fusing of CFLs, LEDs, botching of all capacitor types, including PF correction capacitors. This has necessitated rampant replacements of the aforementioned and other susceptible loads at huge economic expense to the University. This research investigates the adverse impact of harmonic disturbances present in the electrical installations and distribution network of the University of Cape Coast in economic terms. Modelling and simulation of the electrical distribution system was carried out using Electrical Transient and Analysis Program (ETAP) software, which was able to extract harmonic waveforms and spectrums. Power quality analyser, using the "very-short time" monitoring duration and referenced against the IEEE 519-2014 harmonics standard, was also employed to obtain both the Voltage Total Harmonic Distortion (THD_V) and Current Total Harmonic Distortion (THD_I). The average total harmonic distortions measured at the University is 16.43% with dominant harmonics of the 3rd, 5th, 7th, 11th and 13th orders culminating in a reduced true power factor of 0.944. Analysis on the network showed a reduction of the THD_I level from 16.43% to 8%. Significant improvement of the true power factor with considerable cost savings of about Gh¢1,161,493.71 per annum was realised. The installation of tuned paralleled passive filters to mitigate harmonics gave a net present value of Gh¢2,736,028.00 at a discount rate of 8% with a payback period of 6.23 years.

ACKNOWLEDGEMENTS

My deepest gratitude goes to God Almighty, the infinite source of energy from whom I tapped all the strength, wisdom and knowledge I required to complete this thesis.

My sincerest appreciation also goes to Dr J. C. Attachie for his insightful guidance and unwavering patience throughout the course of this thesis and for all the experiences shared.

To my boss at work, Ing J. W. Ansah whose understanding and encouragement helped maintained my focus when things were tough.

Finally, to my entire family whose prayers and support continue to do the trick.

DEDICATION

This thesis is dedicated to the memory of my beloved father Patrick Alfred Yeboa.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
AC	Alternating Current
AHF	Active Harmonic Filter
ASD	Adjustable Speed Drive
BCR	Benefit Cost Ratio
BEDAS	Bogazici Electricity Distribution Incorporated
CA	Chauvin Arnoux
CCTV	Closed-Circuit Television
CFL	Compact Fluorescent Lamp
DC	Direct Current
DPBP	Discounted Payback Period
DPDEM	Directorate of Physical Development and Estate Management
DPF	Displacement Power Factor
DVR	Digital Video Recorder
EAF	Electric Arc Furnace
ECG	Electricity Company of Ghana
ETAP	Electrical Transients Analysis Program
EU	European Union
FHL	Harmonic Loss Factor
HHF	Hybrid Harmonic Filter
HT	High Tension
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor

IHD	Individual Harmonic Distortion
KF	K Factor
LED	Light Emitting Diode
LPQI	Leonardo Power Quality Initiative
LV	Low Voltage
MEB	Maintenance of Existing Building
MV	Medium Voltage
NPV	Net Present Value
PANDA	equiPment hArmoNic DAtabase
PC	Personal Computer
PCC	Point of Common Coupling
PCRF	Parallel-Connected, Series LC-Resonant Circuit
PDC	Power Distribution Centre
PF	Power Factor
PHF	Passive Harmonic Filter
PLT	Long Term Flicker
PPE	Personal Protective Equipment
PQ	Power Quality
PQA	Power Quality Analyser
PST	Short Term Flicker
PV	Present Value
PVC	Polyvinyl Chloride
PWM	Pulse Width Modulation
RMS	Root Mean Square
SCR	Short Circuit Ratio
SCRF	Series-Connected, Parallel LC-Resonant Circuit
SF_6	Sulphur Hexafluoride

SLT	Special Load Tariff
SMPS	Switch Mode Power Supply
STD	Standard
SVC	Static Var Compensator
SVD	Singular Value Decomposition
SWA	Steel Wire Armoured
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
THD_I	Current Total Harmonic Distortion
THD_V	Voltage Total Harmonic Distortion
TPF	True Power Factor
TUS	Time Use Survey
UCC	University of Cape Coast
UPS	Uninterrupted Power supply
VFD	Variable Frequency Drive
V_{RMS}	Root Mean Square Voltage
VSD	Variable Speed Drive
XLPE	Cross-Linked Polyethylene
δPF	Distortion Power Factor

LIST OF SYMBOLS

f_h	Harmonic Frequency
Gh¢	Ghana Cedis
h	Harmonics
$I_{Harmonic}$	Harmonic Current
I_L	Load Current
I_m	Maximum Current
I_{rms}	Root Mean Square Current
I_{SC}	Short circuit Current
LC	Inductance Capacitance
n	Harmonic Order
p	Pulses
PF_{True}	True Power Factor
US$	US Dollars
V_{L-L}	Line to Line Transformer Voltage
V_m	Maximum Voltage
V_{rms}	Root Mean Square Voltage
$Z_{p.u}$	Per Unit Impedance
Z_{System}	System Impedance

INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

Quantity	**Unit**	**Symbol**
Apparent Power	Volt Amperes	VA
Cross Sectional Area	Squared Metre	m^2
Electric Capacitance	Farad	F
Electric Current	Ampere	A
Frequency	Hertz	Hz
Length	Metre	m
Power	Watts	W
Reactive Power	Volt Ampere Reactive	VAr
Time	second	s
Time	hour	h
Voltage	volts	V

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background to the Research

Many electrical engineering professionals are becoming increasingly aware of the adverse impacts of harmonic currents and its associated voltage distortions on electrical installations and equipment. Electrical systems are extensively subjected to harmonic distortions in an unmitigated environment owing to the proliferation of non-linear loads that incorporate solid-state electronic components in their functionality and the increasing need for energy conservation. Arikan *et al.* (2015) suggests that the extensive usage of nonlinear loads is due to energy efficiency and improved functionality. Consequently, cost of increased power losses and high utility bills are visible where the effects of harmonics are ignored. Other concession to the problem is noncompliance of equipment with harmonic standards, which further aggravates the pollution of the electrical network.

Harmonic problems are exhibited in several ways with its severity hinging on the level of pollutions in the system. Evidently, installations and systems less affected by the seemingly tolerable levels of harmonic pollutions suffer the consequences in economic terms in the long term (Abid *et al.*, 2016).

In Ghana, it is safe to suggest that issues of power quality have not fully been addressed and harmonics in particular, with its attendant consequences, has been totally ignored (Akpakloh *et al*., 2014; Eduful and Atanga, 2016). Power system monitoring carried out by Electricity Company of Ghana (ECG) in 2012 showed that an estimated Gh¢2,400,000.00 per annum is lost as heat in the distribution network as a result of harmonics from analysed results (Akpakloh *et al*., 2014). This is expected as there is not a harmonic standard in place to establish checks and to regulate the influx of non-compliant imported electronic-based equipment. The practical side of this unintentional negligence is the entailed costs such as increased leakage, transformer overload and derating, conductor overload, joules effect losses in lines and machinery, higher electrical consumption, etc. that are not always easy to detect and evaluate (Beleiu *et al.*, 2018; Pejovski *et al.*, 2017). Therefore it is important to take necessary steps to curb the increasing impacts of harmonics and realise some savings when quantified in absolute terms.

1.2 Problem Definition

The electrical distribution network of the University of Cape Coast (UCC) accommodates over 80% nonlinear loads out of the total connected electrical loads. These harmonic producing loads create various disturbances on the electrical system. Meanwhile, newer installations with improved functionality and efficiency at the UCC do not conform to any harmonic standards.

Overheating of electrical wirings in existing buildings is an outstanding issue at UCC owing to the high usage of electronics-based equipment. The existing building wirings, which were designed for relatively light office loads in the 1960s and 1970s, may be overloaded by the present day trend of harmonic-producing loads (Elphick *et al*., 2015; Jiang *et al*., 2012).

Ballasts (magnetic or electronic) and capacitor banks, including capacitors utilised in electrical equipment, are prone to damages at the UCC. According to maintenance and procurement records, capacitors for motor starting and in air conditioners are indiscriminately botched. These capacitors and the auxiliary winding possibly create a series resonance that can be an ideal path for low-order harmonics, which are already residing in the system thereby acting as harmonic sinks. Typical interaction of the capacitor motors with the system has no effect on power quality; however, damage to the capacitor motor due to excessive harmonic currents for which the motor generates a resonance condition may be of concern (Das, 2017).

Compact Fluorescent Lamps (CFLs), T5 fluorescent tubes and sodium vapour discharge lamps including power packs of Personal Computers (PCs) and Uninterrupted Power Supplies (UPS) are evidently affected by the power quality disturbances as they fuse out prematurely. According to maintenance records obtained at the Electricity Section of the University, 55% of all lighting fluorescent tubes, except for Light Emitting Diode (LED) lighting fixture procured fuse out before a year elapse. Meanwhile, up to 35% of power packs become defective within the first three years according to the data obtained from the Information and Communications (ICT) Directorate of the University.

60% of the alternators in standby generators located at various facilities within the University have been rewound at least once even though the operator defined limits for these generators in many cases were not exceeded.

Transformers situated at UCC hum quite nosily, suggesting serious overloading and saturation. Conversely, various tests and measurements show a rather less loading with most units having around 65%, although, increases in temperatures of hot spots and top oil was observed. This situation is akin to harmonic polluted power system according to Salles *et al*. (2012) and Zobaa *et al.* (2018).

Underground cables do not produce harmonics but the harmonic pollution at UCC is suspected to be exacerbated by the presence of underground cables, which make up about 90% of the entire electrical distribution network, according to the electrical distribution layout for the University. Cables may amplify any existing harmonic disturbances and can lower the frequency at which system resonance occurs due to the capacitance distributed along the cable length causing damage to capacitor banks (Gandhare and Patil, 2013).

The Electrical Installation Guide (2018), according to International Electrotechnical Commission (IEC) Standard, suggests that life span of equipment is significantly reduced when operated in harmonic environment exceeding 10% Total Harmonic Distortion (THD). The estimated reductions are purportedly 32.5%, 18% and 5% for single phase loads, three-phase loads and transformers, respectively. This effectively means that to retain the service lives equivalent to a rated load, equipment must be oversized whereas existing equipment face the threat of hastened ageing and early deterioration, as is the case for UCC.

In terms of cost, the University spent an estimated total of Gh¢193 018.00, Gh¢166 795.00 and Gh¢183 455.80 on frequent replacement of harmonic loads effected in the year 2017, 2018 and 2019 respectively as depicted in Table 1.1.

Table 1.1 Estimated Cost of Replacement of Harmonic Loads at UCC

Harmonic Loads	Year of Replacement								
	2017			2018			2019		
	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)
CFLs	11.00	243	2673.00	12.50	176	2200.00	13.20	210	2772.00
100 W LED Lights	655.00	54	35370.00	699.00	54	37746.00	720	42	30240.00
28 W Electronic Ballasts	25.00	874	21850.00	26.50	652	17278.00	29.50	785	23157.50
250 W Choke	70.53	268	18902.00	77.25	200	15450.00	80.34	165	13256.10
2.5 µF Fan Capacitor	10.50	284	2982.00	12.10	165	1996.50	15.40	183	2818.20
45 µF A/C Capacitors	42.00	68	2856.00	48.00	71	3408.00	56.00	64	3584.00
PC PSUs	230.00	87	20010.00	246.00	52	12792.00	288.00	56	16128.00
800 VA UPS	505.00	175	189375.00	103.00	308	216524.00	287.00	150	91500.00
Total			**193 018.00**			**166 795.00**			**183 455.80**

1.3 Purpose of the Research

This research investigates, in economic terms, the adverse impact of harmonic disturbances present in the electrical installation and distribution network at the University of Cape Coast and attempts to draw a contrast of the situation with mitigated or tolerable levels of harmonic distortions. The research also proposes some mitigation techniques in addressing the disturbances at the various facilities.

1.4 Research Questions and Hypothesis

This research is guided by the following questions:

i. What percentage of harmonic-producing loads forms part of the total loads in UCC?

ii. Are the upgraded equipment and installations at the University compliant with IEEE 519-2014 harmonic standards?

iii. Does the negative impact of harmonic disturbances have economic consequences on the overall cost of running the University?

iv. Can the economic loss if any, be curbed by employing some mitigation techniques?

Therefore, the research hypothesis is stated as: Reduction in harmonics and power factor related issues in consumer electrical systems could be achieved by employing harmonic compliant equipment and suitable mitigation methods.

1.5 Objectives of the Research

The principal objective of this research is to establish a definite economic loss owing to the uncontrolled harmonic disturbances in the electrical system at the University of Cape coast.

The specific objectives are to:

i. Ascertain the veracity of the harmonic distortions in the electrical system by taking measurements at various points of supply intake on the University campus;

ii. Model, simulate and propose suitable harmonic mitigating measures; and

iii. Evaluate and present the economic implications of the impact of harmonic disturbances.

1.6 Scope of the Research

This research is conducted within the framework of investigating the negative impact of harmonic disturbances in relation to economic loss at the University of Cape Coast. This

includes taking actual measurements, modelling and simulating the distribution network and proposing suitable mitigation methods.

1.7 Research Methods Used

The following methods were used to achieve the objectives:

i. Extensive literature review on various harmonic-producing loads resident on the University electrical distribution network;

ii. Data collection using Chauvin Arnoux CA 8335 Qualistar+ Power Analyser;

iii. Data analyses of field measurements obtained using DataView analyses software;

iv. Modelling and simulation of the electrical distribution system using Electrical Transient and Analysis Program (ETAP) 16.0.0 software;

v. Economic Analysis; and

vi. Curbing economic loss through mitigation techniques.

1.8 Facilities Used for the Research

The facilities used in this research work include the following:

i. Chauvin Arnoux CA 8335 Qualistar Plus Power Analyser;

ii. Internet, Laboratory and Library Facilities at UCC and UMaT;

iii. The entire electrical distribution network at the UCC;

iv. The electrical installations at UCC including all types of electrical loads therein; and

v. Laptop computer with Etap software and DataView Analysis software.

1.9 Limitations of the Research

Even though every critical electrical load connected to the distribution network of the University were considered in the research, it was impracticable to determine the individual harmonic contributions of some of these loads owing to the large diversity of appliance and the configuration of distribution system.

The IEEE 519-2014 Harmonics Standard was used as the research benchmark against which references were made. This research work equally shares in the limitations of this standard.

1.10 Definition of Terms and Key Concepts

In conducting harmonic analysis, it is crucial to understand the following terms as newly introduced and redefined by the IEEE STD 519-2014:

Nonlinear load: A load is said to be nonlinear when the current it draws does not have the same waveform as the supply voltage.

Harmonic component: A component of order greater than one of the Fourier series of a periodic quantity. For example, in a 50 Hz system, the harmonic order 5, also known as the "fifth harmonic," is 250 Hz sinusoidal voltage or current wave.

Harmonic current: It is the kind of current that is drawn by nonlinear loads.

Harmonic voltage: It is the distortion of the supply voltage as a result of harmonic currents through the system impedance.

Total Harmonic Distortion (THD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental. Harmonic components of order greater than 50 may be included when necessary.

Maximum demand load current: This current value is established at the point of common coupling and considered as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12.

Harmonic standards: Harmonic emissions are subjected to various standards and regulations. In view of rapidly attenuating the effect of harmonics, a system of standards and regulations; such as IEEE–519 and IEC–61000 are in place.

Harmonic pollution: It is the attendant power quality problem by the proliferation of non-linear loads on the power network. The harmonic pollution constitutes both current and voltage harmonics.

Harmonic disturbances: It is the adverse effects of harmonic pollution experienced by the connected loads

Point of common coupling: It is a point in the electrical system where multiple customers or multiple electrical loads are connected. According to IEEE-519, this should be a point which is accessible to both the utility and the customer for direct measurement.

Short-Circuit Ratio: At a particular location, refers to the ratio of the available short-circuit current, in amperes, to the load current, in amperes.

Voltage Notch: A switching (or other) disturbance in the normal power voltage waveform, lasting less than 0.5 cycles, which is initially of opposite polarity than the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to 0.5 cycles.

1.11 Organisation of Thesis

This rest of the thesis is organised as follows. Chapter 2 delves into extensive review of literature from diverse and reliable sources on theories and concepts of harmonics, sources of harmonics, effects of harmonics on equipment, and mitigation techniques. Related works on the economic impact of harmonic disturbances has been discussed.

Chapter 3 explains the approach adopted in conducting harmonic measurements. Here, the case study site including measurement setup, measurement points and monitoring durations is presented.

Chapter 4 is dedicated to the results and discussions of economic impact of harmonic disturbances at the University of Cape Coast. Field study and simulation results obtained from harmonic measurement and analysis using power quality analyser and ETAP software are presented. The summary of findings is also given in this chapter.

Chapter 5 presents the conclusions and recommendations to the research. It also gives direction for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter opens up discussions on harmonic phenomena, harmonic-generating load types otherwise known as non-linear loads, the effects on various dynamics of the electrical system and equipment including their mitigation. The chapter sheds light on various attempts by researchers to justify the financial consequences and economic impact of unmitigated harmonic disturbances to architects, engineers, designers, equipment manufacturers, and network operators. Harmonic disturbances are increasingly becoming the centre of discourse amongst personnel in the electrical and electronic engineering field owing to the increasing awareness and acceptance of the problem. More so, there is an increasing trend of the production of electronic-based gadgets with an equally consequent consumer demand for these electronic based products. To put simply, issues regarding the disturbances of harmonics are here to stay (Gil-de-Castro *et al*., 2014).

2.2 Review of Theories and Concepts

Harmonics are the integral multiples of the fundamental supply current or voltage waveform. They normally present as high frequency distortions that influence the dynamics of electrical system (De La Rosa, 2017). Harmonics result from the non-linear V-I characteristics exhibited by loads that incorporate more solid-state electronic components in their operational functions. Examples are Variable Frequency Drives (VFDs) for AC/DC motors, Switch Mode Power Supply (SMPS) for personal computers, digital video recorders, television sets etc. Domestic electronic appliances such as microwave ovens, compact fluorescent fittings and electronic ballasts, industrial equipment such as welding machines, arc furnaces, battery chargers and inverters are typically harmonic-producing loads.

The term harmonics originally emanated from the field of acoustics, where it was related to the vibration of a string or an air column at a frequency that is a multiple of the base frequency. It is a steady state phenomenon with the tendency of repeating itself every 50 Hz or 60 Hz cycle. In spite of the characteristic repetitions at some definite frequency, it must

not be confused with other forms of power transients such as impulses or oscillation or even other power quality issues like dips, spikes etc. (Attachie and Amuzuvi, 2014).

Harmonic frequency f_h can mathematically be expressed as

$$f_h = h \times f \tag{2.1}$$

where, f = fundamental frequency in Hz

h = integer to be multiplied or harmonic order (h = 1, 2, 3, 4….n)

A third harmonic would yield a harmonic component of $f_h = 3 \times 50 = 150$ Hz and $f_h = 3 \times 60 = 180$ Hz in 50 and 60 Hz systems respectively. Likewise, a fifth harmonic would yield a harmonic component of $f_h = 5 \times 50 = 250$ Hz and $f_h = 5 \times 60 = 300$ Hz in 50 and 60 Hz systems respectively.

2.2.1 Harmonic Order

The terms Even and Odd harmonics refer to the components, whose order numbers are either even or odd. Even harmonics are 2f, 4f, 6f, 8f…and odd harmonics are 3f, 5f, 7f, 9f...
Owing to the symmetrical nature of even harmonics, they usually cancel each other out in a power system and tend to be harmless because they can only occur and become noticeable from waveforms that are unsymmetrical to the time axis (Soni and Soni, 2014). The odd harmonics on the other hand pose many problems to the power system, they are the characteristic harmonic components of the present day electrical and electronic infrastructure, and are frequently encountered largely due to the three-phase symmetry where almost all signals are symmetrical by configuration even in the presence of distortions (Kamenka, 2014). These odd harmonics should therefore be eliminated by some filtering techniques and other compensation methods. Fig. 2.1 shows current waveforms of fundamental, second, third and fourth harmonic orders (Anon., 2019).

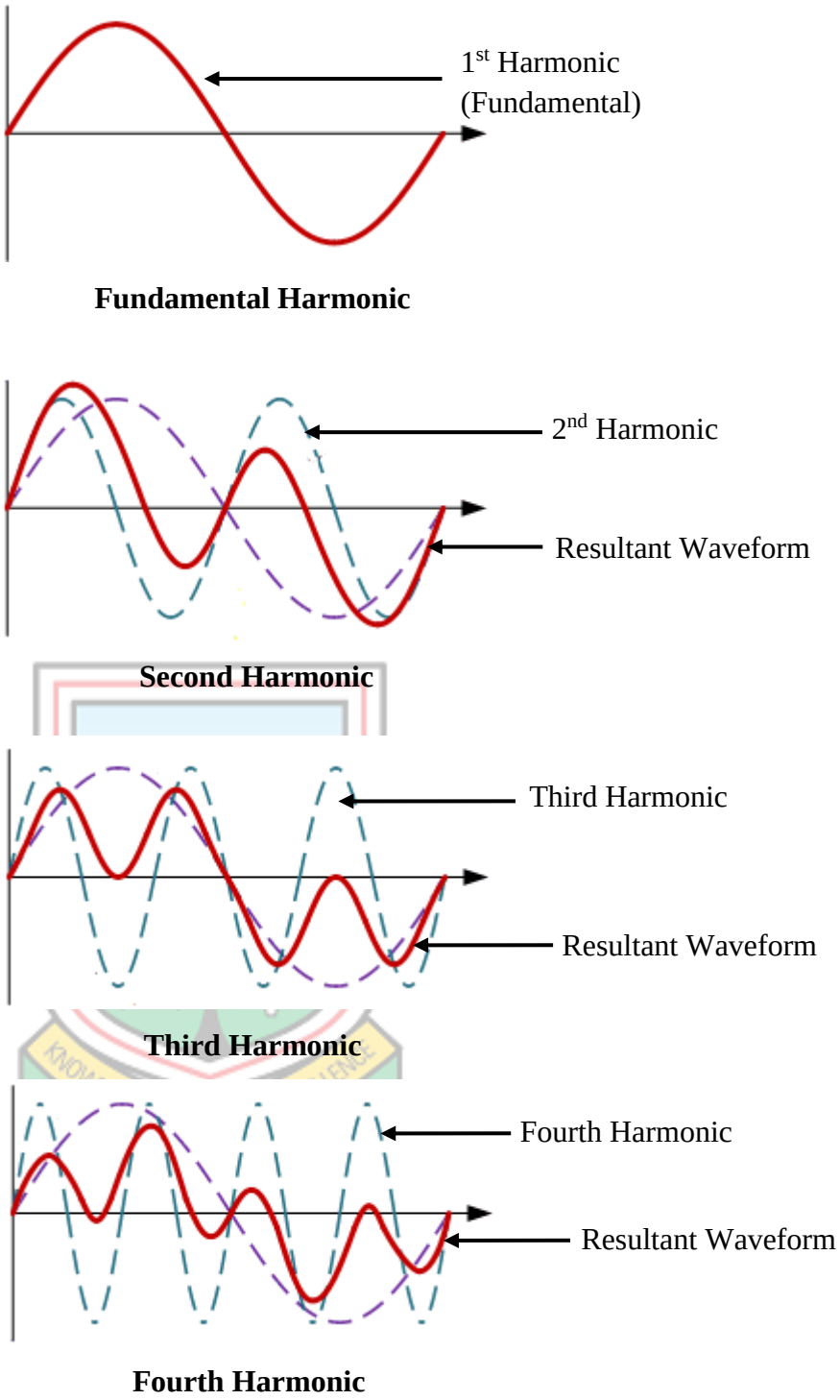

Fig. 2.1 Current Waveforms Showing the Fundamental, Second, Third and Fourth Harmonics

2.2.2 Positive, Negative and Zero Sequence Harmonics

In a balanced three-phase system, harmonics depict quite a simple relation between the harmonic order and the corresponding phase sequence. It can follow similar categorisation as in the case of the fundamental harmonics as positive sequence, negative sequence and

zero sequence harmonics. Table 2.1 shows the relationship between harmonic orders and the symmetrical components.

Table 2.1 Relationship between Harmonic Orders and Symmetrical Components

Symmetrical Components	**Harmonic Order**
Positive Sequence	1st, 4th, 7th, 10th $\ldots 3k + 1$
Negative Sequence	2nd , 5th , 8th , 11th $\ldots 3k + 2$
Zero Sequence	3rd , 6th , 9th , 12th $\ldots 3k + 3$

where $k = 0, 1, 2, 3\ldots$

The positive sequence harmonics such as 4th, 7th, 10th, 13th, 19th etc. produce magnetic fields and current in the same direction and have the same phase rotation as the fundamental components where they circulate between phases.

The negative sequence harmonics such as 2nd, 5th, 8th, 11th, 17th, 23rd, and the like, produce magnetic fields and currents that rotate in the opposite direction with respect to the fundamental harmonics. The currents and harmonics for this negative sequence are very problematic in particular for motors and generators.

The zero sequence are integer multiples of 3 such as the 3rd, 6th, 9th, 15th, 21st and so on. These zero sequence harmonics are also known as triplen harmonics. They do not rotate in either direction and they remain in phase with each other. Whereas the positive and negative sequence sum up and cancels out each other, the zero sequence adds up in the neutral line of the power system and requires to be adequately sized to carry the additional current.

2.2.3 Interharmonics

Interharmonics can be thought of as harmonic components with frequencies between two consecutive harmonics or those components whose frequencies are not integer multiples of the fundamental power frequency. Like its precursor, power harmonics, it is becoming worrisome to the major players in the electrical and electronic industry as its effects and disturbances are increasingly having a toll on electrical equipment due to significant increase in interharmonics inducing loads (Das, 2017; Marz, 2017). Two major standards play central role in imposing limits on this issue and they define interharmonics differently.

The International Electrotechnical Commission (IEC) defines interharmonics as: “Between the harmonics of the power frequency voltage and current, further frequencies can be

observed that are not integers of the fundamental. They can appear as discrete frequencies or as a wide-band spectrum".

The Institute of Electrical and Electronic Engineers (IEEE) defines interharmonics as "A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating (e.g., 50 Hz or 60 Hz)".

Interharmonics can consequently be perceived as the "inter-modulation" of the fundamental and harmonic components of the system with any other frequency components and is made evident in an increasing number of loads (Fuchs and Masoum, 2015). These are mostly loads that do not pulsate synchronously with the fundamental power system frequency, which notably include static frequency converters, cycloconverters, sub-synchronous converter cascades, induction motors and arc furnaces (Das, 2017).

2.2.4 Sub-Harmonics

Sub-harmonics is a term commonly used to describe harmonics with a frequency which is a non-integer multiple and is less than the frequency of the fundamental. It is well known that nonlinear loads will produce harmonics by drawing nonsinusoidal currents. Essentially, inductive loads create harmonics that are multiple integers of the fundamental. Such as 100 Hz, 150 Hz, 200 Hz etc. Similarly, a circuit having resistor, inductor and capacitor connected in series will create voltages and currents with frequencies which are below the fundamental frequency such as 20 Hz, 25 Hz 30 Hz, etc. (Das, 2017).

Both harmonics and interharmonics can be defined in a quasi-steady state in terms of their spectral components over a range of frequencies that is:

Harmonics: $f = h \times f_1$ where h is an integer > 0

Interharmonics: f is not equal to $h \times f_1$, where h is an integer >0

Sub-harmonics: $0 > f < f1$, where f_1 is the fundamental frequency

As expected, because sub-harmonics are a specific type of interharmonics, sub-harmonics are caused by many of the same sources as the interharmonics with a frequency greater than the fundamental frequency. These sources include cycloconverters, arc furnaces, and automated spot welders. Kerestes (2014) cautioned that this subset of interharmonics is

only a class of interharmonics and similarly affects power quality and be noted as a class of their own for further analysis; additionally, formulas which are valid with interharmonics also hold true for sub harmonics.

2.2.5 Supraharmonics

In power quality, the power system frequency (50 or 60 Hz) is used as the fundamental frequency and the integer multiples (up to the 40th) of the fundamental frequency are defined as harmonics. Supraharmonics refers to the distortions of currents and voltages in the frequency range between 2 kHz and 150 kHz (Waniek *et al*., 2017).

The phenomenon is relatively new and is rapidly gaining attention because Supraharmonics currents tend to remain in installations and propagate to high extent towards neighbouring connected loads that offer low impedance (Moreno-Munoz *et al.*, 2015).

Unlike the low frequency harmonics, they are not propagated as a result of distortion of the fundamental frequency waveform but are due to very fast switching of inverter output circuits. The presence of very fast switching inverters is also known to increase the levels of Supraharmonics thus acting as sinks and source (Moreno-Munoz *et al.*, 2015).

2.2.6 Triplen Harmonics

Triplen harmonics refers to odd integer multiples of the third harmonics, including the 3rd, 9th, 15th, 21st and so on. Triplen harmonics can lead to overheating in transformers and increased current in the neutral conductor resulting in overloading among other power quality disturbance. Triplen harmonics also lead to nuisance tripping of protective devices, brown-outs and could cause random equipment failure etc. which is why it is of major concern to engineers and designers because they do more than distort the waveforms. Excessive neutral current can cause overheating of the neutral conductor, which in turn can result in possible fire hazards. Triplen harmonics are not normally present in three-phase, delta-connected loads with no neutral. Triplen harmonics add up arithmetically in neutral conductors resulting in neutral currents being well in excess of phase currents (Kamenka, 2014). This behaviour can easily be depicted mathematically.

The neutral current is given by Equation (2.2) as,

$$i_n = i_A + i_B + i_C \tag{2.2}$$

For currents of the fundamental frequency ω_1, the frequency neutral current i_{N1} is given as:

$$i_{N1} = i_{A1}\cos(\omega_1 t) + i_{B1}\cos(\omega_1 t + 120°) + i_{C1}\cos(\omega_1 t - 120°) \quad (2.3)$$

where i_{A1}, i_{B1}, and i_{C1} are the peak values of the respective Phase A, Phase B and Phase C fundamental currents. These values are equivalent in balanced systems, $(i_A = i_B = i_C = i_1)$ and the neutral fundamental current is always zero.

$$i_{N1} = i_1\left[\cos(\omega_1 t) + i_{B1}\cos(\omega_1 t + 120°) + i_{C1}\cos(\omega_1 t - 120°)\right] = 0 \quad (2.4)$$

To include harmonics of nth order, Equation (2.4) can be generalized as:

$$i_{Nn} = i_n\left[\cos(n\omega_1 t) + i_{B1}\cos(n\omega_1 t + n120°) + i_{C1}\cos(n\omega_1 t - n120°)\right] = 0 \quad (2.5)$$

For 2nd order harmonics (n=2) and all other even order non-zero sequence harmonics, Equation (2.5) becomes zero:

$$i_{N2} = i_2\left[\cos(2\omega_1 t) + \cos(2\omega_1 t + 240°) + \cos(2\omega_1 t - 240°)\right]$$

$$= I_2\left[\cos(\omega_2 t) + \cos(\omega_2 t - 120°) + \cos(\omega_2 t + 120°)\right] = 0$$

Similarly, for 5th order harmonic (n = 5) and all other even order non-zero sequence harmonics, Equation (2.6) becomes zero:

$$i_{N5} = i_5\left[\cos(5\omega_1 t) + \cos(5\omega_1 t + 600°) + \cos(5\omega_1 t - 600°)\right]$$

$$= I_5\left[\cos(\omega_5 t) + \cos(\omega_5 t - 120°) + \cos(\omega_5 t + 120°)\right] = 0$$

On the other hand, for 3rd order harmonics (n=3) and all other zero sequence harmonics, the individual currents are in phase and add arithmetically in the neutral:

$$i_{N3} = i_3\left[\cos(3\omega_1 t) + \cos(3\omega_1 t + 360°) + \cos(3\omega_1 t - 360°)\right]$$

$$= I_3\left[\cos(\omega_3 t) + \cos(\omega_3 t) + \cos(\omega_3 t)\right] = 3I_3\cos(\omega_3 t)$$

Fig. 2.2 further illustrates a fundamental current waveform superimposed by 3rd, 9th, 15th, and 21st triplen harmonics (Shamala and Lakshminarayana, 2015).

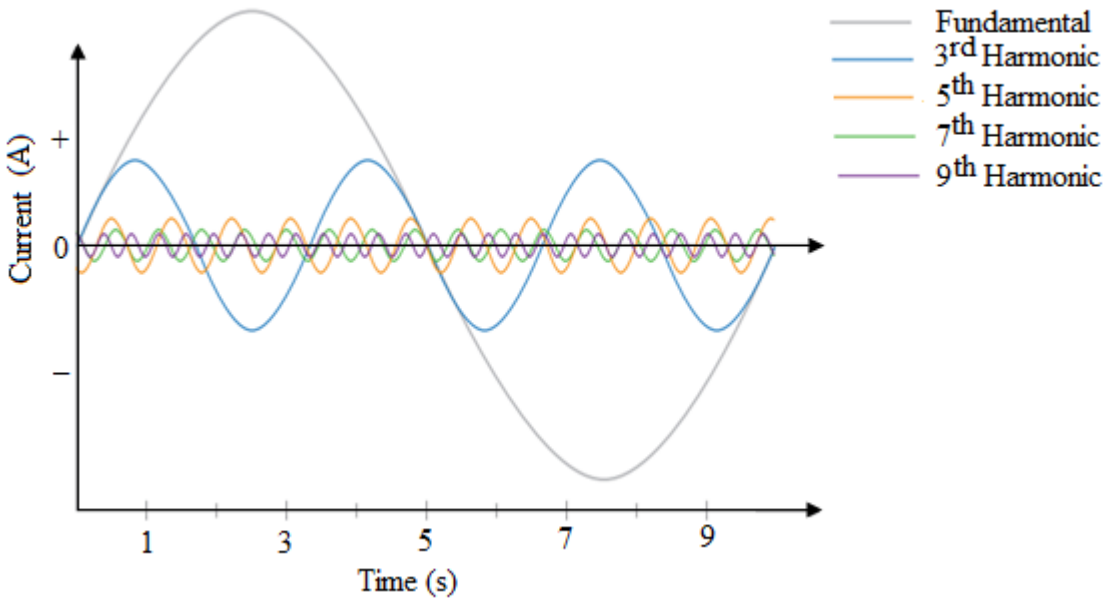

Fig. 2.2 Waveforms of Triplen Harmonics

2.2.7 Harmonic Resonance

Resonance refers to an undesirable condition in power system where the capacitive reactance of a system coincides narrowly with or offsets its inductive reactance such that they cancel out. This leaves the small resistive elements in the network as the sole means of limiting the resonant currents. Resonant currents can reach high levels which adversely affects transformers and other electrical machines by increasing their heating rate. Malfunctioning of electronic equipment which depends on voltage zero crossing detection is common including interference with telephone circuits, operation failure of protective relays, incorrect readings on meters, etc. The prospect of such ill effects arising is significantly amplified if a resonant condition occurs (Das, 2017; De La Rosa, 2017; Fuchs and Masoum, 2015).

Two forms of resonance can occur; parallel resonance and series resonance. One major issue in a power system that can result in their occurrence is the use of capacitors without recourse to proper placement and adequate sizing. Capacitor banks are normally specified for power factor correction and reactive–power compensation purposes and usually act as harmonic

current sinks in harmonic-polluted systems since their reactance decrease with frequency (Das, 2017). The result is a shortened lifespan owing to increased heating and high voltage and dielectric stresses as high frequency harmonic or resonant currents pass through it.

Parallel resonance

Parallel resonance phenomenon occurs when the installed capacitance interacts with the existing power system to create high impedance at some resonant frequency greater than the 50 or 60 Hz system frequency. As a result, harmonic currents near the resonant frequency are amplified, in turn producing harmonic voltage levels higher than would normally be expected. Fig. 2.3 shows a configuration of a parallel-connected resonance circuit where a capacitor is connected in parallel with an inductive load.

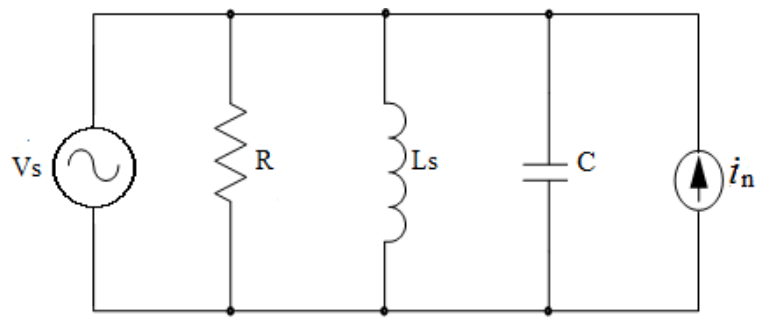

Fig. 2.3 Equivalent Diagram of Parallel Resonant Circuit

The impedance for the equivalent diagram of Fig. 2.4 is calculated by:

$$Z = \frac{jL_s\omega}{1-L_sC\omega^2} \tag{2.6}$$

where, L = supply inductance (upstream network + transformer + line)

C = capacitance of the power factor correction capacitors

R = resistance of the linear loads

I_h = harmonic current

Resonance occurs when the denominator $(1 - L_sC\omega^2)$ approaches zero. The resultant frequency is called the resonance frequency of the circuit. At that frequency, impedance is at its maximum and high amounts of harmonic voltages appear thereby resulting in major distortion of the voltage. The voltage distortion is accompanied in the $(L_s + C)$ circuit, by the flow of harmonic currents greater than those drawn by the loads. This can lead to

substantial amplification of the harmonic current that flows between the capacitors and the system inductance and cause capacitor fuse blowing or failure or transformer overheating.

Series resonance

In a series resonance circuit, the inductive impedance of the system and the capacitive reactance of a capacitor bank are in series to a source of harmonic current as depicted in Fig. 2.4 (Das, 2017). Series resonance usually occurs when capacitors are located toward the end of a feeder branch (De La Rosa, 2017). From the harmonic source perspective, the line impedance appears in series with the capacitor. At, or close to, the resonant frequency of this series combination, its impedance will be very low. If any harmonic source generates currents near this resonant frequency, they will flow through the low impedance path.

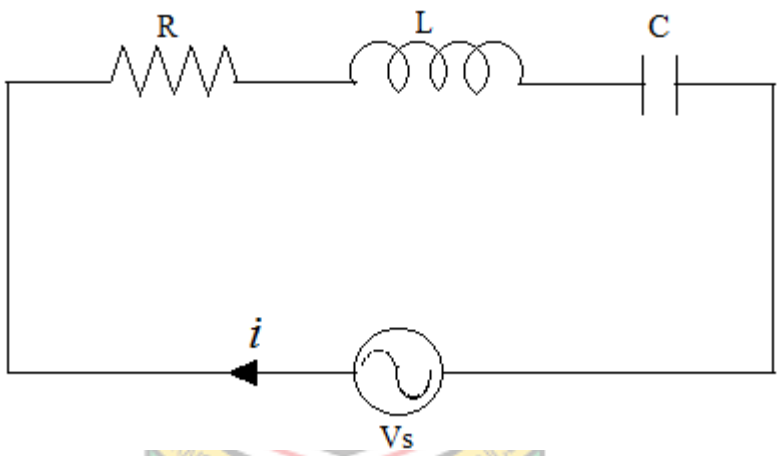

Fig. 2.4 Equivalent Diagram of Series Resonant Circuit

2.2.8 Harmonic-Generating Sources

Ahmed *et al.* (2013) suggests that the main sources of harmonics in any power system are loads that exhibit some non-linearity in the voltages and currents drawn. They also exhibit nonlinear magnetization characteristics as in the case of transformers or electronic power converters supplied from the ac system in which the switching of devices is synchronised to zero-crossings of the voltage or its fundamental component etc.

Again, when a voltage with sinusoidal waveforms is applied to certain types of loads, the currents drawn by this loads are proportional to the voltage and impedance and takes after the envelope of the voltage waveform (Al-Duaij, 2015). This essentially means that the power drawn by the load follows a sinusoidal pattern without any distortion to its pure sine

wave. This type of Loads is referred to as linear loads as shown in Fig. 2.5 (McKenzie, 2017).

In contrast, some loads cause the current drawn and voltage applied to vary disproportionately during every half cycle as illustrated in Fig. 2.6. These types of loads are known as non-linear loads. They are essentially classified so because the voltage and current have waveforms that are not sinusoidal and do contain distortions whereby the 50 or 60 Hz waveforms has a number of additional waveforms superimposed upon it. Multiple frequencies are created within the 50/60 Hz sine wave and are known as harmonics of the fundamental frequency.

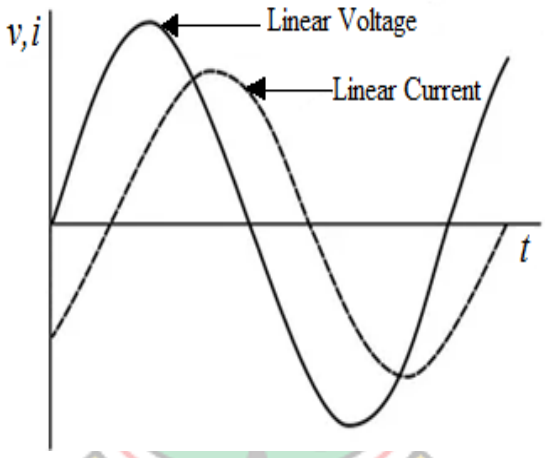

Fig. 2.5 Voltage and Current of a Linear Load

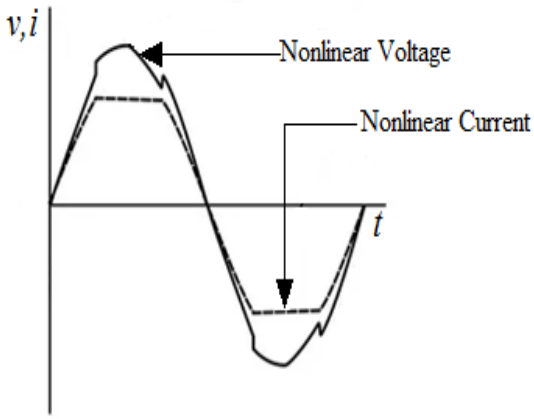

Fig. 2.6 Voltage and Current of a Nonlinear Load

According to Zobaa *et al*. (2018), harmonic–generating sources can be characterised mainly into:

i. Magnetic core-based equipment such as power transformers, electric motors, and generators.
ii. Arcing Equipment such as electric arc furnace, induction furnace, arc welders, discharge lamps and magnetic ballasts etc.
iii. Power electronic-based equipment such as computers, television sets, CFLs and LEDs, VSDs, UPS etc. and other equipment utilising Switch Mode Power Supply (SMPS).

Magnetic core-based equipment source

The magnetic core-based type of loads displays fairly constant steady state impedance that results in a sinusoidal current upon the application of voltage under normal operating conditions (Zobaa *et al*., 2018). This means that the production of harmonics only initiates when operating condition are outside actual conditions.

Transformers: Harmonics in transformers are created due to saturation, switching and high magnetic flux densities according to Das (2017) and Zobaa *et al.* (2018). Harmonics could also result from winding connections as in the case where triplen harmonics created in the neutral conductor of a star-connected transformer or in instances where triplen harmonics occur due to magnetizing currents but are trapped within the delta connected coils. In view of these, transformers are usually operated in the Knee Saturation region but when the amplitude of the voltage is large enough to enter the nonlinear region of the B-H Curve, the magnetizing current required at that point will be distorted and create harmonics (Das, 2017; De La Rosa, 2017). The transformer magnetizing current curve is shown in Fig. 2.8 (Csanyi, 2016).

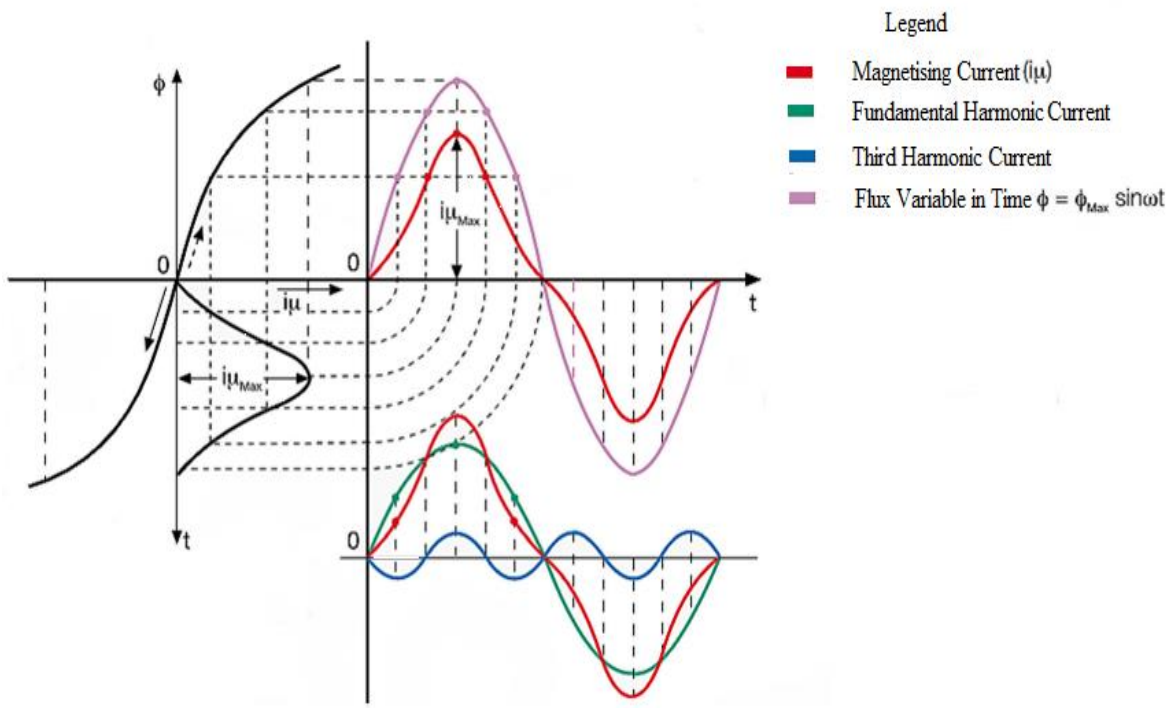

Fig. 2.7 Transformer Magnetizing Current Curve

In their work on "an overview of harmonic sources in power systems", Ahmed *et al.* (2013) stated emphatically that transformers are liable to produce harmonics when operating above two notable conditions. Firstly, when operating above rated power; and secondly, when operating above rated voltage. The first situation can arise during peak demand periods, and the second case can occur during light load conditions, especially if utility capacitor banks are not disconnected accordingly and the feeder voltage rises above nominal values.

Rotating machines: The causes of harmonics in a power system with a rotating machine being considered as the source are due to a number of factors. The slots of a rotating machine are not perfectly distributed to house the embedded windings. This alternates with the teeth which cause the reluctance of the magnetic flux to vary in a similar fashion thereby creating a condition that promotes the generation of harmonics. Rotor saliency in this case accounts for both the variation in reluctance of magnetic path and reactance in electric path (Ahmed *et al*., 2013; Al-Duaij, 2015).

Studies by Akhani (2014), and Al-Duaij (2015) also mentions that the non-linearity of the core material and the non-uniformity of the flux distribution in the air gap of the rotating machines are also a major factor in the creation of harmonics.

According to Akhani (2014), design parameters like distribution factor and pitch factor are influencing factors particularly in synchronous machines. Rotor misalignment mass unbalance crawling, fractal error, cogging and unsymmetrical faults all have some compelling stake in generating harmonics out of a rotating machine.

Arc devices source

This class comprises arc furnaces, arc welders, and discharge-type lighting (fluorescent, sodium vapour, mercury vapour) with magnetic ballasts. Fig. 2.8 gives a simplified diagram representing an arcing device. The arc is essentially a voltage "clamp" formed in series with a reactance that reduces current to a practical limit. Electric arcs exhibit certain nonlinearity with its voltage-current characteristics. A decrease in voltage with a consequent increase in current immediately occurs following an arc ignition. The impedance of the power system limits this increase in current. This gives the arc the appearance of having a negative resistance for a section of its operating cycle reminiscent of fluorescent lighting applications.

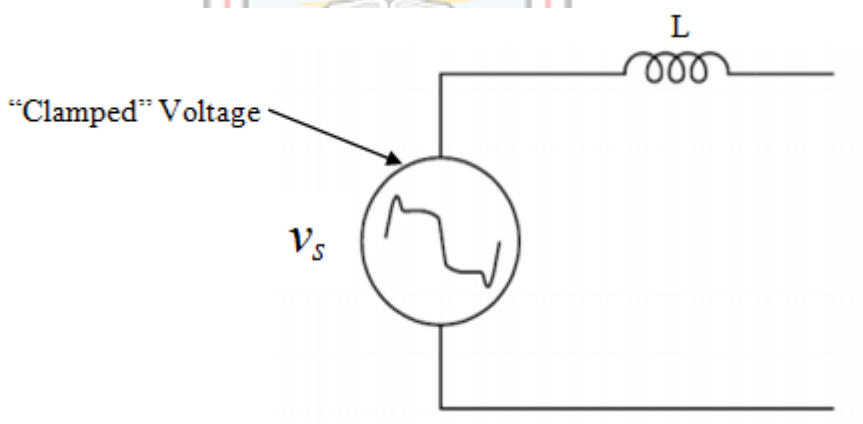

Fig. 2.8 Equivalent Circuit of an Arcing Device

The electric arc itself is actually best represented as a source of voltage harmonics. If a probe were to be placed directly across the arc, one would observe a somewhat trapezoidal waveform. Its magnitude is mainly a function of the arc's length. However, the impedance of ballasts or furnace leads acts as a buffer so that the supply voltage is only reasonably distorted (Cano-Plata *et al.*, 2015). The arcing load thus seems to be a somewhat stable harmonic current source, making it suitable for purposes of analysis.

Electric arc furnaces (EAFs): These are considered among the notorious harmonic sources because of their huge capacity that is concentrated in one place (Mon *et al.*, 2015). The

current chopping and igniting process during each half-cycle causes significant harmonic distortion. Their harmonic distortions with its attendant detrimental effect on power system equipment and other consumers connected to the Point of Common Coupling (PCC) can be significant.

The arc of EAF has inherent high frequency voltage instability. However, if the arc is characterized by its average behaviour, the instantaneous arc voltage can be considered as practically independent of the arc current and fixed in value by its physical mean length from electrode tip to bath (Das, 2017). The instantaneous arc voltage of the EAF fixed in value by its fixed physical length measuring from the electrode tip to the furnace bath is practically independent of the arc current making EAFs different from other harmonic sources in that EAFs generate harmonic voltages instead of harmonic currents (Cano-Plata *et al.*, 2015).

In this sense, the arc furnace load actually looks like a harmonic voltage source behind series impedance consisting of the secondary cables to the electrodes. Fig. 2.9 depicts a typical setup for electric arc furnace (Cano-Plata *et al.*, 2015).

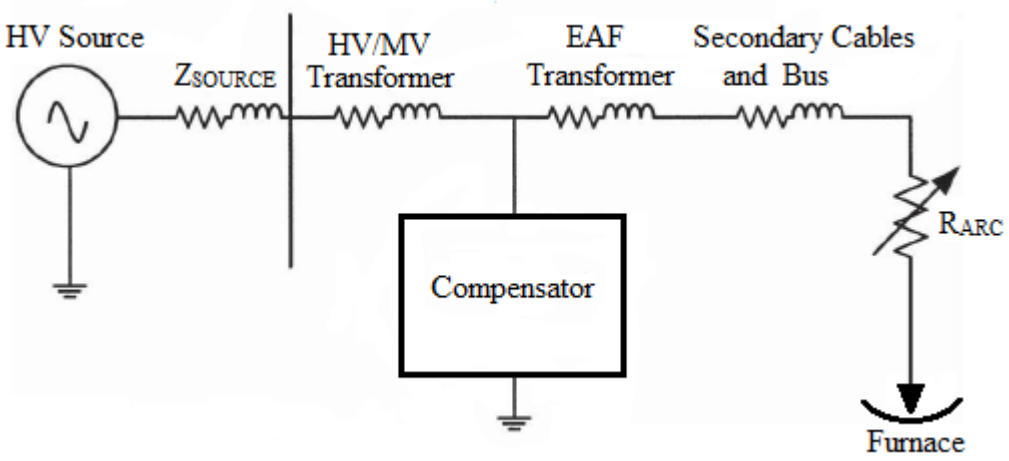

Fig. 2.9 A Typical Setup for Electric Arc Furnace

The impedance of the connection between the secondary bus of the furnace transformer and the electrodes of the arc furnace is known as the lead impedance with a large voltage drop across it hence making it highly critical for any power considerations. Owing to the operating principles of EAFs, they have very low power factor and usually require some reactive power compensations to augment the power system in addition to the installation

of filters to mitigate the harmonics generated (Junior *et al.*, 2015). Fig. 2.10 shows a waveform of a typical electric arc furnace (Khan and Junaid, 2009).

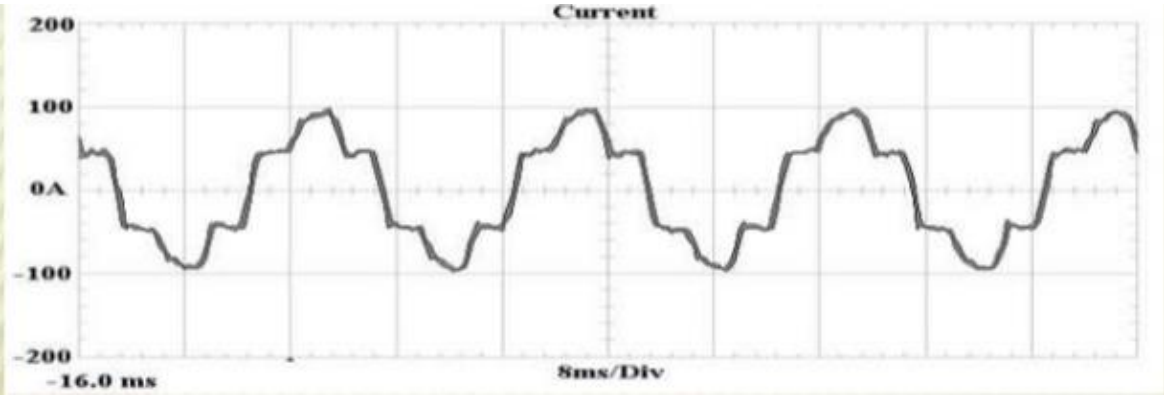

Fig. 2.10 Waveform of a Typical Electric Arc Furnace

In electric arc furnace applications, the limiting impedance is principally the furnace cable and leads. This happens after arc ignition when the voltage drops abruptly. The power system and furnace transformer are also noted to offer some significant impedance. Currents in excess of 60,000 amperes are commonly available with these applications (Cano-Plata *et al.*, 2015; Das, 2017).

Discharge lamps: The lighting types in this category include fluorescent; high and low pressure sodium or mercury vapour lamps, metal halide lamps etc. and require a ballast to deliver a high initial voltage to establish the discharge for the flow of electric current between two electrodes in the discharge lamp tube. As soon as the discharge is initiated, the voltage decreases and the arc current correspondingly rises. It is essentially a short circuit between the electrodes at both ends of the tube and the ballast must limit the current to within the capability of the fluorescent tube and stabilise the arc. In a three-phase four-wire system, the 3rd, 5th, and 7th are the dominant current harmonics of fluorescent lighting if they employ a magnetic ballast, whiles the 5th harmonic is the most significant disturbance with an electronic ballast as depicted by Fig. 2.11. Triplen harmonics add up in the neutral, the third being the most prevailing for magnetic ballast but multiple harmonics if an electronic ballast is used (De La Rosa, 2017).

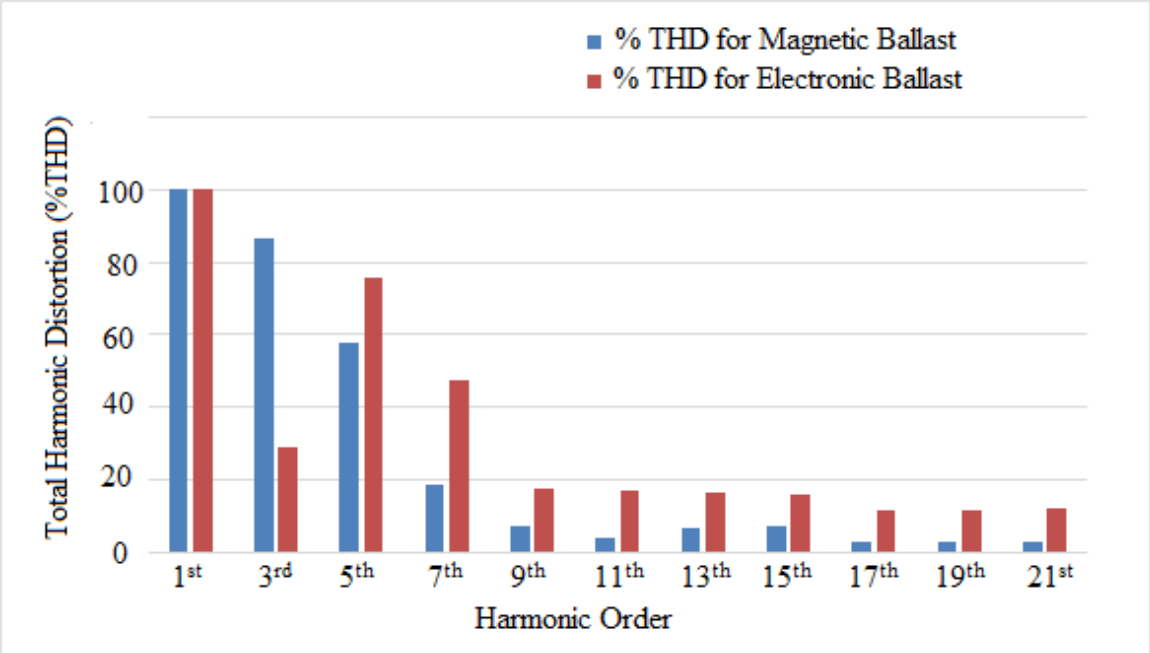

Fig. 2.11 Harmonic Spectra of Fluorescent Lamps Utilizing Magnetic and Electronic Ballasts

Arc welding plants: Welding transformers are the main culprits in producing harmonics. A welding transformer typically converts the high voltage and low current supply from the mains into low voltage usually 15 to 45 V to high currents with typical values range of 200 to 600 A. Research investigations revealed that 3rd harmonics are generally produced when the welding machine are in idle or standby mode (Kumar and Singh, 2015).

During actual welding however, large current and voltage harmonics occurs. Welding plants are as much a harmonic source as they have a pitiable power factor. To reduce harmonics and to improve power factor they are incorporated with a suitable capacitor of an adequate kVAr rating. The incorporation of a capacitor is observed to have improved and reduced the power factor and harmonics alike.

Power electronic-based equipment source

Sources of harmonics under this category could be subdivided in to three groups. These are SMPSs, power converters and Adjustable Speed Drives (ASDs).

Switched-mode power supplies: These are electronic devices that are employed to regulate the voltage and current from mains supply to power single phase or three phase loads. Owing to their relatively smaller and lighter frame; including better efficiency, there has been a

drift towards using SMPSs instead of the traditional linear power supplies of the same power rating over the last decade. Fig. 2.12 illustrates a simplified circuit diagram of an SMPS.

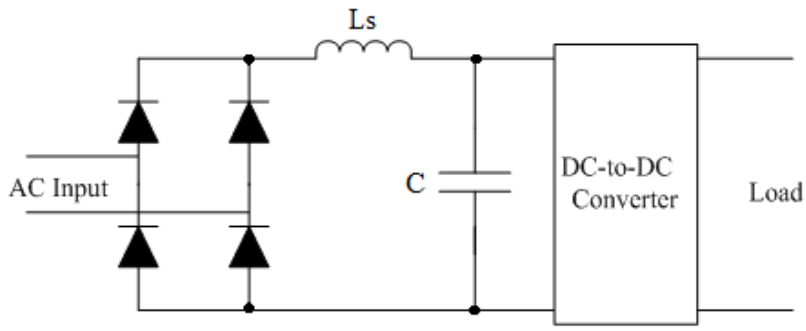

Fig. 2.12 Simplified Circuit Diagram of a SMPS

The rectifier stage in simple SMPSs comprises a simple full-wave rectifier with a capacitor to convert the mains ac input voltage to dc voltage. The DC voltage is switched on and off at very high frequencies (typically between 50 kHz and 1 MHz). Voltage regulation is accomplished by varying the duration of the 'on' time and the 'off' time. The high-frequency voltage passes through a high-frequency transformer or inductor.

These SMPSs draw current from the supply in short pulses or busts to recharge the capacitor. As a result, the input current to the SMPS has a high harmonic content. Single phase SMPSs find their applications in electronic equipment such as photocopiers, printers, computers, flat-screened television sets, chargers for laptops and mobile phones, Digital Video Recorders (DVRs) for Closed Circuit Televisions (CCTVs), etc. and are characteristically contributors of high third harmonics (De La Rosa, 2017).

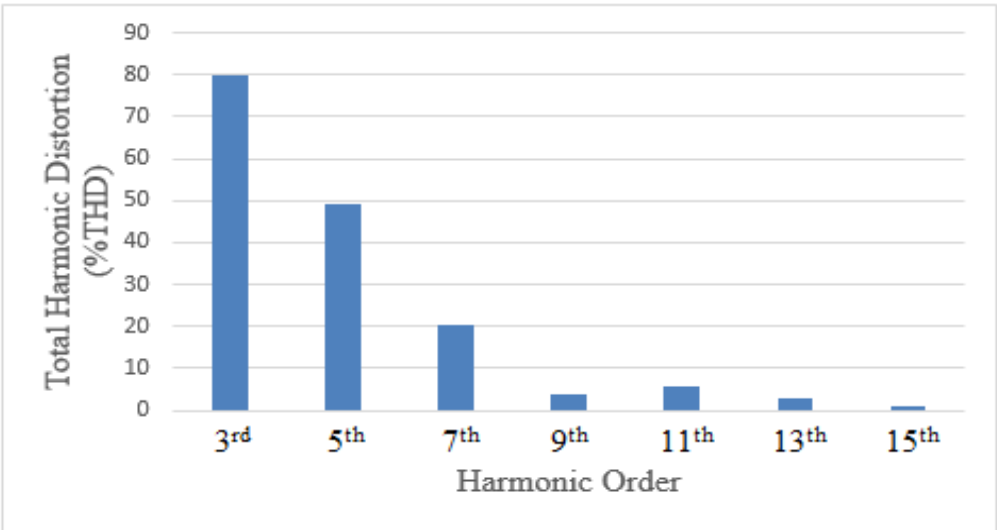

Fig. 2.13 Harmonic Current Spectrum for Television

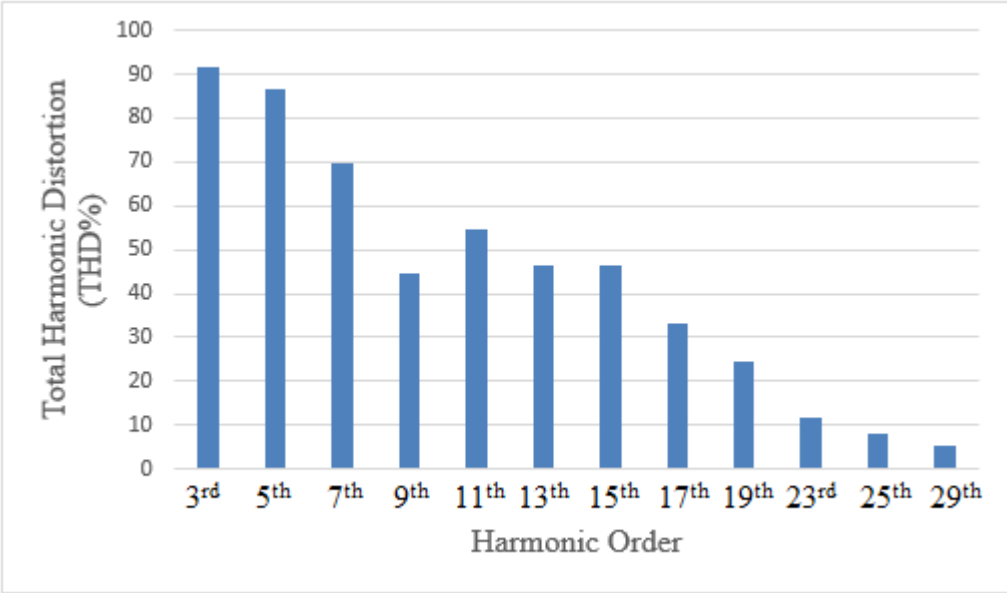

Fig. 2.14 Harmonic Current Spectra for Personal Computer

Power converters and adjustable speed drives: Three-phase power converters have different harmonic characteristics than single phase converters and are not characteristically third harmonic dominant. Pulse-Width Modulation (PWM) scheme is commonly employed in order to control the power in three-phase converters, which are essentially a three-phase version of the control scheme used in single phase SMPS. Power supplied to the load is controlled by the 'on' and 'off' periods of switching. The most prevailing harmonics h depend on the number of pulses p used in the converter and can be calculated using Equation (2.7).

$$h = p \cdot n \pm 1 \tag{2.7}$$

where $n = 1, 2, 3, 4$ ....

For example, in a 6-pulse converter (p = 6) the dominant harmonics are 5th, 7th, 11th, 13th etc. and for a 12-pulse converter (p = 12) the dominant harmonics are 11th, 13th, 23rd, 25th and so on.

Balanced voltages and equally spaced firing pulses in the converter bridges including equal commutating reactance under perfect circumstances would have the magnitude of the harmonics decrease with increasing harmonic order h by a factor of $1/h$.

Distribution system for a building may be well designed yet it is practically difficult to obtain a perfectly balanced system. Minor imbalance, such as 458:460:462 V are allowable

by most utilities up to 3% (Soni and Soni, 2014). It is therefore difficult to determine accurately the harmonic current characteristic of domestic appliances with ASDs due to the large diversity of appliances (clothes dryers and washers, air conditioners, photovoltaic inverters, uninterrupted power supplies, elevators etc.).

Even for appliances of a given category, the harmonic current characteristics can vary considerably. IEEE 519 (2014) suggests that the current THD for equipment with ASDs can vary between 16% and 123%.

2.2.9 Harmonic Effects on Equipment

The harmonic current generated by any nonlinear load flows from the load in to the power system. Descriptions of the general undesirable effect of harmonic distortion on the power system equipment and connected loads are as follows:

Harmonic effect on lighting

One noticeable effect on lighting is the phenomenon of "flicker" (i.e. repeated fluctuations in light intensity). Lighting is highly sensitive to rms voltage changes; even a slight deviation (of the order of 0.25%) is perceptible to the human eye in some types of lamps. Superimposed interharmonic voltages on the supply voltage are a significant cause of light flicker in both incandescent and fluorescent lamps (Das, 2017; Fuchs and Masoum, 2015).

Harmonic effect on transformers

Transformers are operated sometimes in very harsh environments and conditions that are polluted with harmonic distortions. These transformers are subjected to many unwanted detrimental effects such as excessive heating and its corresponding transformer losses that tend to accelerate the aging of the unit.

Most distribution transformers in-service today were not designed to be operated or handle nonlinear loads and usually the negative effects of harmonics on these transformers commonly go unnoticed and completely disregarded until disaster hit in terms of operational failure. It has become well known that loads employing SMPS, VFDs, electronic ballasts

and the likes constitute mostly the loads in modern times and these loads nonetheless aggravate the quality of power that is already gaining critical attention from all stakeholders.

The effect of disturbances, however which form it takes or its source on power quality is becoming more and more noticeable and a transformer being among the most expensive assets of a power system that cannot be in operation up until its stipulated life expectancy would definitely be considered an economic loss.

Harmonic current loadings affect the I^2R losses, eddy current losses and stray losses of a transformer, which ultimately leads to increased transformer losses and a decreased thermal capacity. Fig 2.15 shows the effect of harmonic on transformer windings (Vos, 2019).

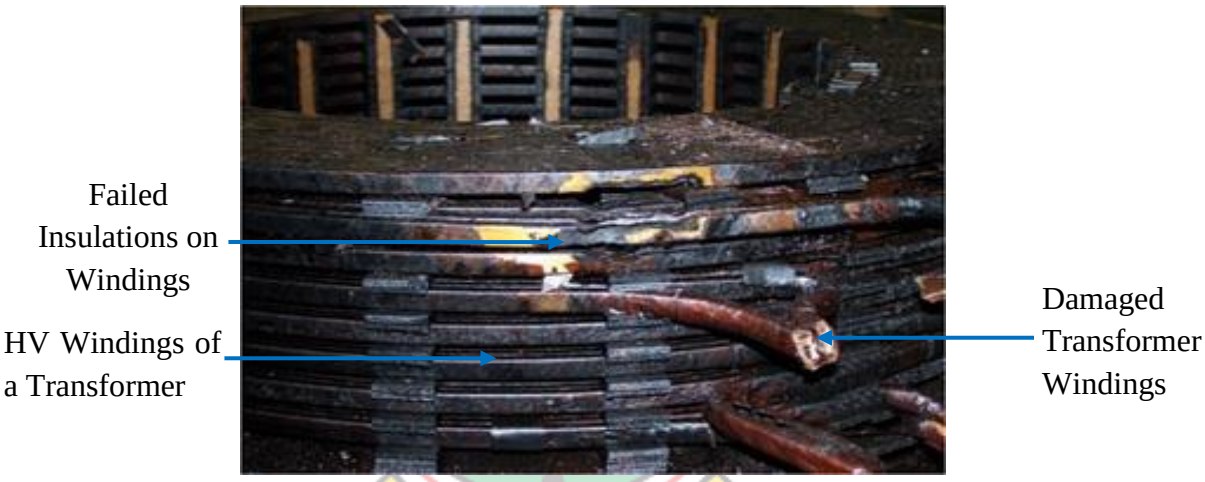

Fig. 2.15 A Pictorial View of Harmonics Effects on Transformer Windings

In addition, harmonic currents are expected to be frequently accompanied by a dc component in the load current. This dc component will cause an increase in the transformer core loss slightly due to an increase in the magnetizing currents thereby leading to an increase in audible sound levels considerably. However, a relatively small dc component is expected to have no effect on the transformer load handling and thermal capabilities (Pejovski *et al.*, 2017).

Harmonic current effect on ohmic losses of a transformer: The ohmic (I^2R) losses are the losses attributable to primary and secondary distorted currents flowing through the copper windings. If the root mean square value of the load current is increased due to a harmonic component, the I^2R loss will be increased accordingly (De La Rosa, 2015).

Harmonic current effect on eddy current losses of a transformer: The eddy-current loss of a transformer core in the power frequency spectrum is proportional to the square of the load current and the square of frequency. This characteristic according to Pejovski *et al.* (2017) will create excessive core losses thereby producing abnormal temperature rise in transformers when supplying non-sinusoidal load currents.

Harmonic current effect on other stray losses of a transformer: Other stray losses in the core, clamps, and structural parts will also increase at a rate proportional to the square of the load current, but these losses will not increase at a rate proportional to the square of the frequency, as transformer core eddy-current losses.

Studies by manufacturers and other researchers have shown that the eddy-current losses in bus bars, connections and structural parts increase due to the harmonic exponent factor of approximately 0.8 or less. For dry-type transformers, temperature rise in these regions are less critical than in the windings but it has to be properly accounted for in transformers that are liquid filled according to Pinyol (2015).

Harmonic current effect on rise of top oil temperature of a transformer: This will increase as the total load losses increase with harmonic loading for liquid-filled transformers. Any increase in other stray losses will consequently affect the top oil rise which will affect the windings insulation (Singh *et al.*, 2017).

Harmonic effect on capacitor bank

Capacitors are extensively used and indispensable in power systems for controlling voltage profile, power-factor correction, filtering, and reactive power compensation of power systems. However, as frequency increases, due to other higher frequencies superimposed on the fundamental, the impedance consequently decreases. Since capacitive reactance is inversely proportional to frequency, harmonic currents in the power system find their way into capacitor banks. These banks act like a sink, attracting harmonic currents, thereby becoming overloaded (Das, 2017).

A more serious condition, with potential for substantial damage, occurs as a result of harmonic resonance. Resonant conditions are created when the inductive reactance offset the capacitive reactance leaving only a small resistance as the sole impedance in the circuit resulting in flow of high harmonic currents. Essentially, the presence of the capacitor bank

might increase the harmonic currents due to the presence of harmonic voltages by reducing the equivalent impedance as stated earlier.

Problems with harmonics often show up at capacitor banks first in every power (Arikan *et al*., 2015; Fuchs and Masoum, 2015), often resulting in fuse blowing and/or failure of capacitor. The main reason is that series resonance produces voltage amplification and parallel resonance causes current multiplication within an electrical system. In a harmonic rich environment, both types of resonance could exist.

During resonant conditions, if the amplitude of the offending frequency is large enough, the consequences would be a significant destruction to the capacitor banks. Moreover, there is a high probability that other electrical equipment on the system would also be dangerously affected. This attributes make capacitor banks prone to damage and vulnerable to failure especially when they are not properly located and appropriately sized.

The optimal location and sizing are carried out per some design and specification of the capacitor bank and evidently will have an impact on the cost. Fig. 2.16 shows the effect of harmonics on capacitor banks (Anon., 2017).

Fig. 2.16 Effect of Harmonics on Capacitor Bank

Harmonic effect on neutral conductor

High neutral currents in buildings usually result from two situations. The first, and most common, is where there are simply heavily unbalanced loads. The second situation involves

current harmonic distortion with the unbalanced currents influencing the severity levels (De La Rosa, 2017).

Firstly, on a three phase system where the loads are predominantly single phase loads, the neutral carries the unbalanced currents of all the other phases. Admittedly, the loads may have been balanced at one time but in sizing and distributing loads within a panel, only the full load currents are taken into consideration and not how often the loads are switched on or off. This effectively means that at any given instance there may be a significant unbalance within the three phase, four wire system rendering it practically impossible to have a perfectly balanced three phase system.

Neutral currents resulting from unbalance conditions are usually high whether it is caused by load shifts or change or due to diversity of loads being on or off at some point in time, these neutral currents are seldom excessive. Problems do occur though and they manifest in the form of high rise in temperature of the neutral conductors owing to the flow of unbalance currents and consequently leading to burnt neutral with its attendant return currents that always cause damage to connected single phase loads at the time of the neutral break.

Secondly, many electronic loads, such as Personal Computers (PCs) and Compact Fluorescent Lamps (CFLs) create harmonic distortions of different orders and chiefly amongst the harmonics produced are the third harmonics (De La Rosa, 2015). Settings such as large residential buildings, commercial buildings and similar facilities found at educational and recreational environments, are particularly predisposed to excessive third harmonic distortion due to a large concentration third-harmonic generating loads lumped on the network.

The neutral conductor in a three phase, four wire distribution systems particularly warrants extra attention and consideration because harmonic currents results in extra heating regardless of the type of conductor (Arikan *et al*., 2015). This is because zero-sequence harmonics add up cumulatively in the neutral conductor resulting in overloading and hampering of the overall power system capacity for the neutral line. For instance, many PCs produce 3rd harmonic currents greater than 80% of the fundamental current. For a balanced three-phase load consisting entirely of PCs, the neutral conductor will carry 240% (3 × 80%) 3rd harmonic current (Csanyi, 2016). Measurements performed in commercial buildings in

which a large fraction of the load is 3rd-harmonic producing show neutral currents that are between 1.5 and 2.1 times larger than the phase currents (Csanyi, 2016).

Harmonic effect on network cabling system

Modern commercial and industrial buildings typically comprise different electrical systems. These systems can include power distribution, telephone, energy management controls, audio, time-clock synchronization and computer networks. Ideally, these systems operate independently of one another, with no unplanned interaction, but the laws of electromagnetism, combined with Murphy`s law, may dictate otherwise (Arrillaga and Watson, 2004). Typically, where power cables and telephone signal cables are run parallel to each other, voltages are possibly induced in the unshielded pairs of telephone cables. The frequency ranges are characteristically 540 Hz to 1200 Hz (9th harmonic to 20th harmonic at 60 Hz fundamental).

Harmonic loads carried by cables tend to set up electromagnetic interference (EMI) in adjacent signal or control cables by way of conducted and radiated emissions. This "EMI noise" has a destructive effect on telephones, televisions, radios, computers, control systems and other types of equipment (Pinyol, 2015). Any attempt to reduce the effect of EMI means that additional effort with regards to correct earthing procedures in external wiring systems and proper segregation within enclosures must be utilised.

Harmonic effect on rotating machinery

Harmonics increases both copper and core losses thereby resulting in overheating and reduction of efficiency of machines. Fuchs and Masoum (2015) noted that increases in losses are evident in the stator windings, rotor circuit, and stator and rotor lamination. It is also worth noting that owing to the presence of eddy current and skin effect, the associated harmonic losses in AC rotating machines are quite high compared to the DC counterparts. At frequencies above 300 Hz, the losses are observed to be compounded by skin effect.

According to De La Rosa (2015), each harmonic component adds to the magnetic force and has a telling effect on speed/torque characteristics. However, the harmonic current present in the stator of an AC machine gives rise to induction motoring action that produce torques in the same direction as the harmonic field velocities in such a way that all positive sequence harmonic will develop shaft torques aiding shaft rotation. However, negative sequence

harmonics will have the opposite effect where it will act against the direction of rotation resulting in torque pulsations.

The zero sequence components are stationary and do not rotate, thus, the attendant energy is dissipated as heat. The magnitude of torque pulsations created owing to these harmonic sequence components can be significant and could bring about problems in shaft torsional vibration in motors (Shah, 2013).

The harmonic current also creates leakage magnetic fields in the stator and rotor end windings creating further stray frequency eddy current dependent losses. Substantial iron losses can also be produced in induction motors with skewed rotors due to high-frequency-induced currents and rapid flux changes in the stator and rotor. Excessive heating can deteriorate the bearing lubrication and end in bearing breakdown. Harmonic currents also can result in undesirable currents flow in bearings; however, this could be avoided by employing insulated bearing, this is commonly seen in motors with VFDs (Fuchs and Masoum, 2015).

Harmonic effect on generators

Generators are rotational machines and share in the enumerated effects of harmonics in rotational machines. However, owing to generators having more source impedance (typically, three to four times that of distribution transformers), the effects of harmonic voltages and currents are expressively more pronounced (De La Rosa, 2017). This is especially so when stand-alone generators used as back-up or those on the ships or used in marine applications. The chief effect of voltage and current harmonics is to increase the machine heating owing to increased iron losses, and copper losses, since both are dependent on frequency and increase with increased harmonics. To minimize this effect of harmonic heating, the generators supplying nonlinear loads must have a derated capacity (Shah, 2013).

Harmonic effect on armoured cables

Losses in cables increase when carrying harmonic currents due to elevated I^2 R losses. This is as a result of the cable resistance, R, determined by its DC value in addition to skin and proximity effects. Thus, the resistance of a conductor is dependent on the frequency of the

current being carried. Skin effect is a phenomenon whereby current tends to flow near the surface of a conductor where the impedance is least.

A related phenomenon, proximity effect, is due to the mutual inductance of conductors arranged closely parallel to one another. Both of these effects are dependent upon conductor size, frequency, resistivity and the permeability of the conductor material. At fundamental frequencies, the skin effect and proximity effects are usually negligible, at least for conductors with smaller cross-sectional area (Das, 2017). The associated losses due to changes in resistance, however, can increase significantly with frequency, adding to the overall I^2 R losses.

Harmonic effect on protective devices

The bulk of low voltage circuit breakers are thermal-type that utilises bi-metallic trip mechanisms. These thermal or magnetic strips respond to the heating effect of the rms current. In the presence of nonlinear loads, the rms value of current will be higher than for linear loads of same power (De La Rosa, 2015; Wagner *et al.*, 1993). Consequently, the breaker may trip unnecessarily and prematurely while carrying nonlinear currents except the current trip level is adjusted accordingly.

Circuit breakers are designed to interrupt the current at a zero crossover. On highly distorted supplies that contain line notching and/or ringing, spurious "zero crossovers" may cause premature interruption of circuit breakers before operating correctly in the event of an overload or fault (Soni and Soni, 2014). However, in the case of a short circuit current, the magnitude of the harmonic current will be very minor in comparison to the fault current.

Fuse rupturing under over-current or short-circuit conditions is based on the heating effect of the rms current according to the individual I^2 t characteristics. The higher the rms current, the faster the fuse will operate. On nonlinear loads, the rms current will be higher than for similarly rated linear loads, therefore fuse derating may be necessary to prevent premature operation. Additionally, fuses at harmonic frequencies, tend to be affected by skin effect and more significantly, proximity effect, resulting in non-uniform current distribution across the fuse elements, thereby imposing further thermal stress on the mechanism (Soni and Soni, 2014).

In the presence of nonlinear loads, protection devices or other equipment, as well as any other telemetry devices that rely on conventional measurement techniques or the heating effect of current will tend not to function properly (Arikan *et al.*, 2015).

Harmonic effect on metering devices

Harmonics can upset the performance of metering apparatus and in so doing affect the billing charges of consumers. In order to estimate the billing charges for consumers and to decide on additional penalties for low power factor surcharges, reading of energy, reactive power, and volt-ampere meters are essentially required. Hence, the consumers' billing is based on the definitions of three basic electrical quantities: the apparent power, active and reactive power, S, P and Q, respectively (Masri *et al*., 2017).

When the real-world concerns of measuring the defined quantities and indices began to be deliberated and examined, it was soon understood that the conventional instruments (mainly active and reactive energy meters) applied under sinusoidal conditions to measure the utilization of energy, both from a quantitative and qualitative perspectives were stark inadequate (Arikan *et al.*, 2015). They are however, increasingly being operated in the environments that are polluted with harmonic disturbances. Under these circumstances, the measuring method implemented in the revenue meter is vital. Field data indicates that the difference in kVA demand meter readings can be as large as 28% for distorted waveforms (Al-Duaij, 2015).

The differences are mainly due to the different definitions of apparent power implemented in revenue meters. The open and widely discussed question in the metering community is how active power and especially reactive power should be defined and measured when distortion is present. For example, distortion of the current waveforms can result in significantly different demand and power factor charges depending on the type of meters used. As a result, a meter change can sometimes trigger a power factor penalty where previously there had been none.

2.2.10 Economic Consequences of Harmonics

The circulation of harmonic currents within any system or installations presents a hidden liability. The economic implications of harmonic disturbances are difficult to evaluate and

not easily noticeable. However, certain obvious effects exist in assessing the economic impact of harmonics.

The costs of harmonics are estimated in terms of equipment derating, premature aging of electrical equipment, misoperation of electrical systems and reduced power factor.

Equipment derating

In a harmonic polluted environment, power sources such as transformers, generators and UPS systems are oversized. Neutral conductors are also oversized since circulating triplen harmonics in the system tend to add up in the neutral. The phase conductors owing to the excessive losses due to joule effect are also oversized. The cost associated with derating and overdesign can be weighty.

Premature ageing of electrical equipment

Studies reveal that service life of equipment operated in harmonic environment exceeding 10% THD_I are set to reduce (Ajenikoko and Ojerinde, 2015; McBee, 2017). The reduction, according to Electrical Installation Guide 2018 published by IEC International Standards has been estimated at 32.5% for single phase loads and 18% and 5% for three phase loads and transformers respectively thereby increasing their rate of replacement. Table 2.2 shows the minimum service life expectancy for some selected harmonic loads.

Table 2. 2 Minimum Service Life Expectancy for some Selected Harmonic Loads

Harmonic Load	**Expected Average Service life**
23 W CFLs	10 000 Lighting Hours
100 W LED Floodlights	50 000 Lighting Hours
28 W Electronic Ballasts	30 000 Lighting Hours
250 W HPS Magnetic Ballasts	65 000 Lighting Hours
2.5 µF Fan Capacitors (Class B)	10 000 Hours Run
45 µF A/C Capacitors (Class B)	50 000 Hours Run
PCs Power Pack	80 000 'ON' Hours
800 VA UPS Circuit Board	12 years

(Source: Anon., 2018a)

Frequent equipment replacement occasioned by harmonics can escalate capital expenses by 15% approximately and increase the costs of operation by virtually 10% (Carnovale, 2003).

Misoperation of electrical systems

The operating characteristics of frequency-dependent components within devices are affected high harmonic frequencies which leads to misoperation of certain electronic component and the sporadic operation of circuit breakers which in turn results in nuisance tripping. This ultimately results in processes shutdown and operational downtimes. These downtimes can translate to huge financial losses.

Reduced power factor

The presence of harmonics increases the total apparent power demand in the network. Increase in the apparent power demand can plunge the contracted demand subscription into a higher tariff bracket. Also, depending on the tariff method employed by the utility, the reduction in the total Power Factor (PF) can result in power factor surcharges.

Typically, the PF are indicated on the utility bills as does ECG for bills submitted to customers. However, the indicated PF is the Displacement Power Factor (DPF) and not the actual or true power factor. Owing to harmonics, Distortion Power Factor (δPF) plays a crucial part in determining the True Power Factor (TPF) with significant savings potential (Anon., 2018a; Fuchs and Masoum, 2015; Grady and Gilleskie, 1993).

Invariably, the presence of harmonics signifies a reduced true power factor where improvement unlike displacement power factor, is only possible by harmonics mitigation. When the THD_I is mitigated to 8% THD_I or lower, Grady and Gilleskie (1993) proves that the distortion power factor can be considerably improved thereby consequently improving the net true power factor.

2.2.11 Harmonic Mitigation

Diverse techniques exist for minimising harmonic currents since they do not produce useful work and create losses in the power system. For example, it is a known fact that harmonic currents that flow toward the 50 Hz power supply encounter the impedance inherent in the system and produce distorted voltages. However, to limit the propagation of harmonics in

the distribution network, different solutions are available and should be taken into account especially when taking on a new project.

The complexity of harmonics mitigation lies in designing the most cost-effective remedy that will facilitate the system compliance with the limits imposed by the accepted harmonic standards – IEC 61000-3-2 and the IEEE 519-2014. These standards provide specific limits for current and voltage distortion at the point of common coupling, which is the point of interconnection between customers of a utility company.

Some basic strategies for harmonics mitigation are available. These include (Anon., 2018a):

i. Positioning the harmonic-producing loads as far upstream in the system as practicable.

ii. Grouping the harmonic-producing loads, so that sensitive equipment and nonlinear devices are supplied by different sets of busbars.

iii. Supplying nonlinear loads via a separate transformer. The only caveat here is increased cost.

iv. Employing transformers with special winding connections. Different winding connections can eliminate specific harmonic orders. For example, A Dyd winding suppresses 5th and 7th harmonics. Whilst a Dy and a Dz5 winding suppresses 3rd and 5th harmonics respectively.

v. Installing harmonic suppression reactors on capacitor banks. This increases the impedance of the reactor/capacitor combination for high-order harmonics and this minimizes the occurrence of resonance thus protecting the capacitors. Also, when ASD-fed loads are predominant in a system, it is always possible to smoothen the current by installing a line reactor to increase the impedance of the system so that the effect of harmonic currents is well accommodated.

vi. Over-sizing the neutral conductor. It is practically impossible to achieve perfectly balanced 3-phase 4 wire system that supplies single phase loads. However, owing to the vast proliferation of nonlinear loads, 3rd harmonics and other triplen harmonics abound in the electrical systems. These triplen harmonics tend to add up in the neutral. Therefore, in a building with a large

number of PCs installed, the neutral wire can carry much higher currents than it was designed for.

In fact, the harmonic current alone in the neutral wire can, in theory, be up to 200% larger than the full rated current of the phase conductor. Over sizing the neutral conductor allows the addition of triplen harmonic currents to be safely accommodated.

Several harmonic filtering devices are widely employed especially when it pertains to existing installations or systems. These filters, positioned near the nonlinear loads, mainly are to bypass harmonic currents and/or block them from entering the power system. Some filtering techniques involves locally supplying harmonic currents to compensate for the system harmonics. Harmonic filters are generally categorized into passive, active, and hybrid types.

Passive harmonic filters

Passive Harmonic Filters (PHF) entail the series or parallel connection of a tuned LC and high-pass filter circuit to form a low-impedance path for a precise harmonic frequency. The filter is connected in parallel or series with the nonlinear load to divert the tuned frequency harmonic current away from the power supply as shown in Fig. 2.17. Passive harmonic filters tuned to particular harmonic orders and paralleled with other tuned passive filters within a filter bank provide maximum elimination of the harmonics order to be damped which results in significant reduction of the total harmonic distortion at the connected bus (Motta and Faundes, 2016). Passive filters are custom designed with specific system impedance in mind with a quality factor of a high or low type. Typically, the high Q factors lies between 30 and 60 and are tuned to one of the lower harmonic frequencies whereas the low Q factor type normally are between 0.5 and 5.5.

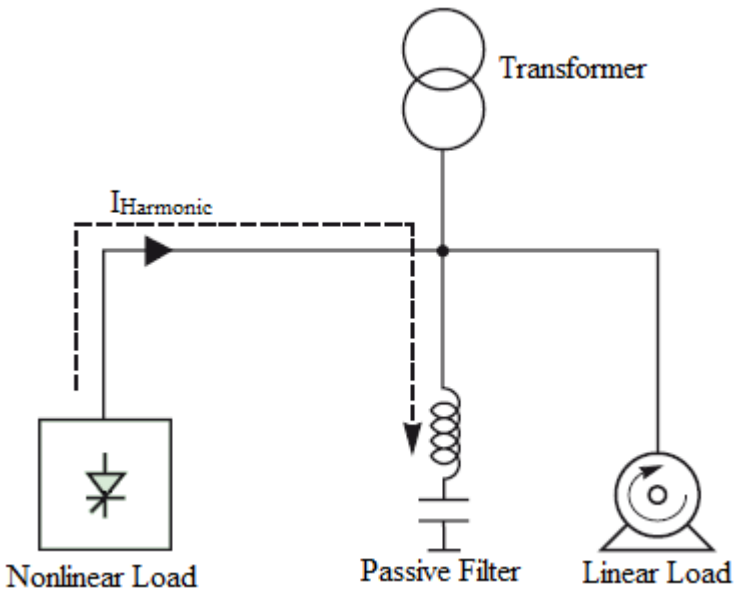

Fig. 2.17 Operating Principle of a Passive Harmonic Filter

Harmonic filters do not eliminate all harmonic frequencies like series line reactors do but attenuate a single harmonic frequency from the supply current waveform. They are comparatively inexpensive compared with other means of harmonics mitigation, but also disadvantaged by certain inherent limitations, including creating a parallel resonance which worsens the situation being corrected and often resulting in equipment breakdown (Fuchs and Masoum, 2015).

Active harmonic filters

Active Harmonic Filters (AHFs) employ fast-switching Insulated Gate Bipolar Transistors (IGBTs) to create an output current of the wanted shape such that when injected into the AC lines, it negates the initially generated harmonics thereby attenuating the distortion. Effectively, active harmonic reduction techniques work by injecting equal-but-opposite current or voltage distortion into the network thus improving the power quality.

AHF is designed with two types of control scheme. These control strategies play essential roles in ensuring improvement of the performance and stability of the filter (Markose *et al.*, 2016).

i. The first performs fast Fourier transforms to calculate the amplitude and phase angle of each harmonic order. The power devices are directed to produce a

current of equal amplitude but opposite phase angle for specific harmonic orders.

ii. The second technique of control is often referred to as full spectrum cancellation in which the full current waveform is used by the controller of the filter, which eliminates the fundamental frequency component and controls the filter to inject the inverse of the remaining waveform.

The AHF filters are typically sized based on how much harmonic current the filter can generate. The proper amperage can be selected after the amount of harmonic cancellation current is ascertained (Motta and Faundes, 2016).

Active harmonic filter essentially comprises a VSD with a special electronic controller, which affects the cancellation by injecting a 180º out of phase harmonic current into the system. For instance, if the VSD created 60 A of 5th harmonic current, and the AHF produced 50 A of 5th harmonic current, the amount of 5th harmonic current carried onto the power network would be 10 A. The AHF may be classified as single phase or three phase filters and as parallel or series AHF depending on the circuit configuration. Fig. 2.18 shows the action of a shunt connected active filter injecting a compensation current I_{AHF} opposite in phase and equal to the generated harmonic current $I_{Harmonic}$ by the nonlinear load (i.e. $I_{Harmonic} = - I_{AHF}$). This action of the active filter neutralises the injected harmonics of the system.

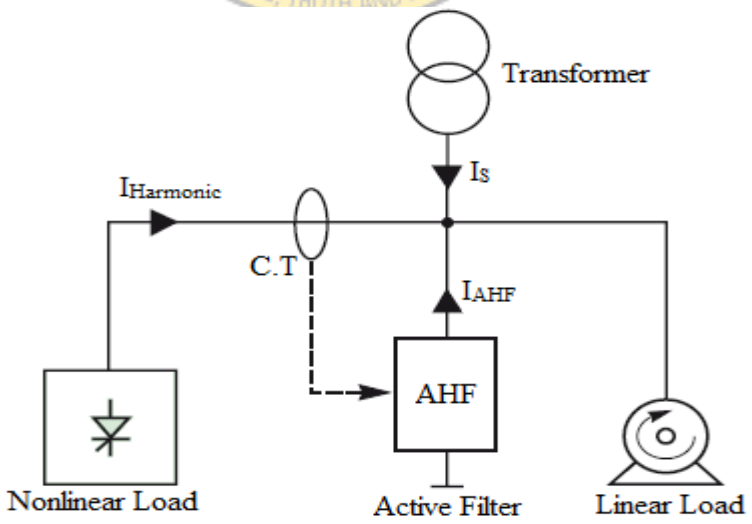

Fig. 2.18 Operating Principle of an Active Harmonic Filter

Hybrid harmonic filters

Hybrid Harmonic Filter (HHF) is essentially a hybrid connection of AHF and PHF used to decrease harmonics distortion levels in the system.

The PHF with constant compensation characteristics is ineffective to eliminate the current harmonics. AHF overcomes the downside of the PHF by employing the switching-mode power converter to achieve the harmonic current elimination. However, the cost of AHF construction is expensive and power rating of AHF power converter is very large. These limit the applications of AHF in the power system. Therefore, using low cost PHF in the HHF, the power rating of active converter is reduced compared with that of AHF. HHF retains the benefits of AHF and does not have the disadvantages of PHF and AHF. Fig. 2.19 illustrates the operating principle of a hybrid harmonic filter.

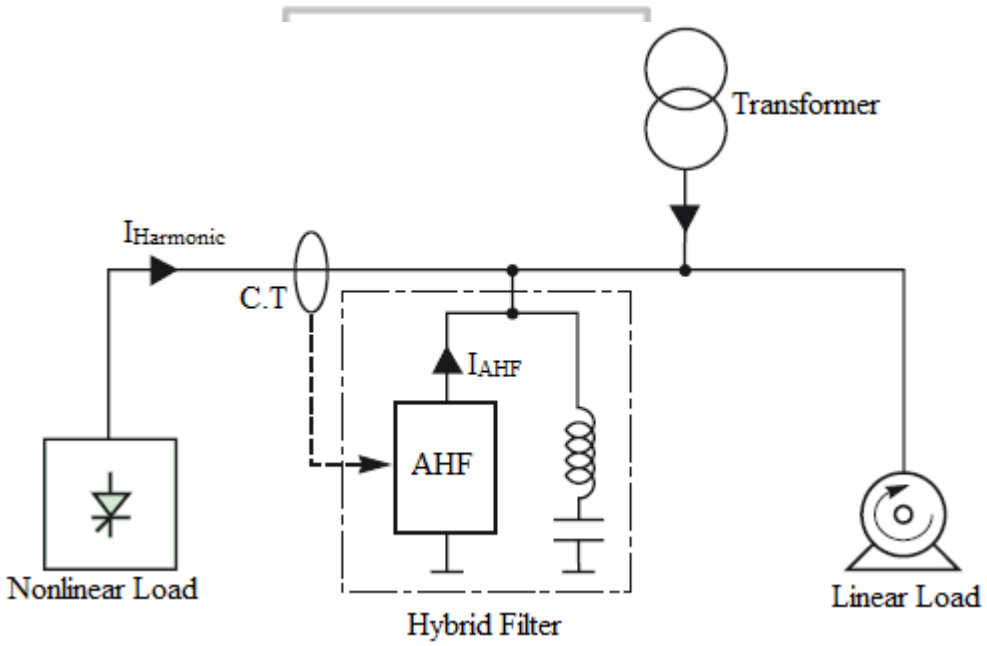

Fig. 2.19 Operating Principle of a Hybrid Harmonic Filter

2.2.12 Choice of Placement of Harmonic Elimination Scheme

While it is established that harmonic elimination at the identified source(s) provides the most effective mitigation, no single mitigation method best suits any harmonic application (De La Rosa, 2017; Fuchs and Masoum, 2015). Therefore, several considerations and trade-offs are weighed regarding the cost and choice of mitigation equipment and their practical placement within the installations in achieving maximum potential savings from the harmonic elimination.

Fig. 2.20 shows possible placement positions “A” through “D” where harmonic elimination could be effected.

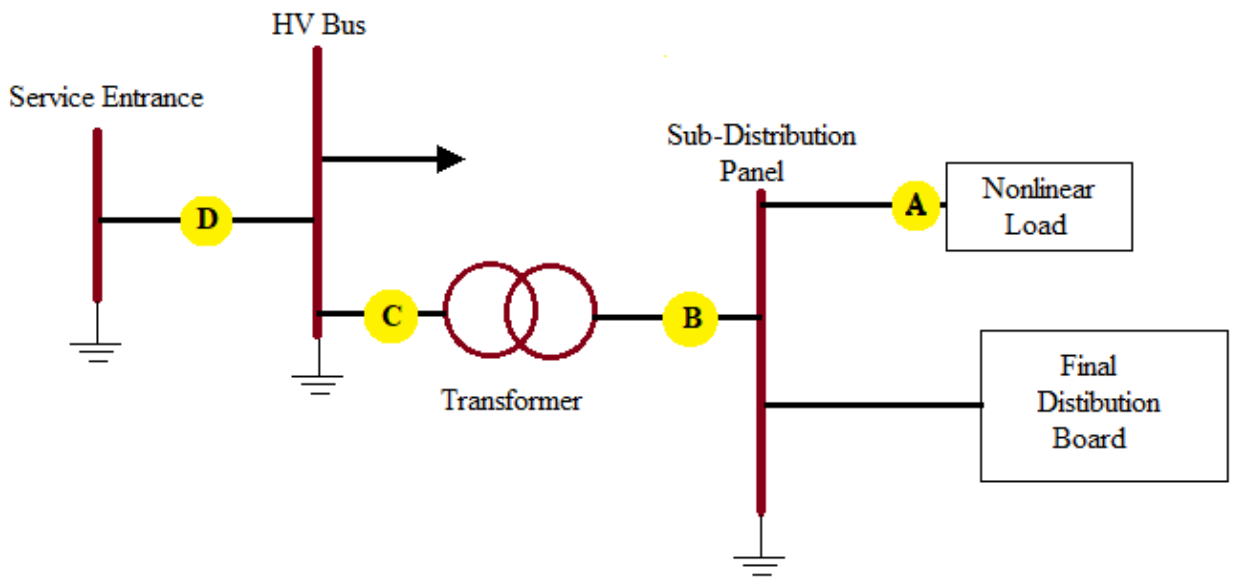

Fig. 2.20 Possible Locations of Harmonic Mitigating Equipment

According to Singh (2018), elimination at source of harmonics i.e. position ‘A’ provides the most effective mitigation. However, it requires installations of several filtering units to cater for each harmonic loads. This approach tends not to be economical.

Position ‘B” when evaluated in terms of practicality, ease of installation and relative cost, is deemed appropriate and most cost effective since it requires installing one large mitigating unit at the sub distribution panel to cater for all outgoing loads.

Built-in harmonic compensation

Many research outcomes reveal that harmonic elimination at the source is the most effective option from both system and economic point of view (Singh, 2018). And manufacturers continue to device more effective means of annihilating harmonics right within the equipment itself. Methods employed by several manufacturers include employing:

i. A series inductor at the input circuit;

ii. An active boost converter current shaping;

iii. A Parallel-Connected, Series Lc-Resonant (PCRF); and

iv. A Series-Connected, Parallel Lc-Resonant (SCRF).

The adoption of built-in compensation methods relies on several considerations including high cost, bulkiness of the completed product with filtering circuit and reliability of the additional filtering components.

2.3 Harmonics Standards and Essential Harmonic Indicators

Only two internationally recognised harmonic standards are available: IEEE STD 519 series and IEC 61000 series are the preferred regulatory standards for America and Europe respectively. In Ghana, both harmonic standards are adopted (Eduful *et al*., 2014).

2.3.1 IEC 61000 Series

The IEC 61000-3-2:2005+A1:2008+A2:2009 is an international standard that limits mains voltage distortion by defining the upper limits value for harmonic currents from the second harmonic up to and including the 40th harmonic current. Meanwhile, the 3rd edition of IEC61000-3-2 has been superseded by the 4th edition: IEC61000-3-2:2014. The 4th edition is already withdrawn, and now the 5th edition IEC 61000-3-2:2018 is the most recent standard (Anon., 2018a).

The IEC 61000-3-2 standard aims to set limits for the general requirements of harmonic current emissions and voltage fluctuations of electrical equipment as applied to equipment using voltage not less than 220 V line currents lower than 16 A per phase. It is actually a compromise between cost and the performance of additional front-end circuits. For the purposes of limiting harmonic current, the equipment is divided into 5 groups: One group with excluded equipment that needs no testing, and 4 groups A, B, C and D with different IEC standard requirements (Anon., 2018a).

i. Class A: refers to balanced three-phase equipment, household appliances, excluding equipment identified by Class D, tools (excluding portable tools), dimmers for incandescent lamps, audio equipment and everything else that is not identified as B, C or D;

ii. Class B: refers to portable tools and arc welding equipment that is not professional equipment;

iii. Class C: refers to lighting equipment; and

iv. Class D: refers to personal computers and personal computer monitors and television receivers having a rated input power of 75 W up to and not exceeding 600 W.

2.3.2 IEEE 519 Series

IEEE-519 is a system directive for setting restrictions on voltage and current distortions. This standard details the recommended practices and requirements on the subject of harmonic control in electrical power systems. IEEE STD 519 was first introduced in 1981 to offer clear course on managing harmonics introduced by electronic based equipment and other nonlinear loads with the intention that problems of power quality will subside.

Consulting engineers, practitioners and utilities are applying and enforcing these standards in recent years owing to growing trend in the use of ASDs and other nonlinear loads (Pinyol, 2015). Full details on the recommended practices and harmonic limits could be obtained from Anon. (2014a).

According to Eduful *et al*. (2014), two difficult aspects of applying the IEEE STD 519 hinges on:

i. Determining an appropriate PCC and

ii. Establishing a demand current at the design stage.

This is because the standard fails to outline a concise definition of the PCC and the recommended definition of demand current is a value that can only be established by measurements taken after installation. Like its European counterpart, the IEEE 519 Standard on harmonics has undergone various reviews right from its inception till date.

The first edition was the IEEE 519-1981: An IEEE guide for harmonic control and reactive compensation of static power converters. The IEEE 519-1992 followed and the most recent the IEEE 519-2014 dubbed “IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems”.

It is noteworthy; however, that IEEE 519 is bounded within limits to being a collection of recommended practices that act as a guide to both suppliers and consumers of electrical energy. It is therefore incumbent upon suppliers and consumers to resolve the issues within

a mutually acceptable structure where there are issues caused by introduction of excessive harmonic current or excessive voltage distortion.

For purposes of recommending limits, the IEEE 519 doles out harmonic distortion recommendations according to two distinct criteria (Anon., 2014a), namely:

i. There is a limitation on the amount of harmonic current that a consumer can inject into a utility network; and

ii. A limitation is placed on the level of harmonic voltage that a utility can supply to a consumer.

This IEEE 519-2014 standard sets out goals for the design of electrical systems that comprise both linear and nonlinear loads. The interface between sources and loads is described as the point of common coupling. The limits in this standard represent a collective responsibility for harmonic control between utilities and consumers.

2.3.3 Total Harmonic Distortion

THD is an essential harmonic index used to indicate power quality issues in transmission and distribution systems. It is particularly used to indicate the harmonic content of a distorted waveform by a single number by considering the contribution of every individual harmonic component on the signal. As a measure of effective value of harmonic components of a distorted waveform, it is defined as the rms of the harmonics expressed as percentage of the fundamental current or voltage component.

THD is defined for current and voltage signals, respectively, as follows:

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{2.8}$$

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \tag{2.9}$$

where, I_h = harmonic current

I_1 = fundamental current component

V_h = harmonic voltage

V_I = fundamental voltage component

This means that the ratio between rms values of signals including harmonics and signals considering only the fundamental frequency define the total harmonic distortion.

The main advantages of THD are:

i. It is commonly used for a quick measure of distortion; and

ii. It can be easily calculated.

The demerits are:

i. It does not provide amplitude information; and

ii. The detailed information of the spectrum is lost.

The current total harmonic distortion THD_I indicates the distortion of the current wave. To identify the load causing the disturbance, the THD_I must be measured on both the incomer and the outgoing feeder circuits. The measured THD_I can provide information on harmonic occurrences detected in the installation.

A THD_I value of less than 10% is considered normal and there is practically no risk of equipment malfunctions. A THD_I value between 10% and 50% indicates high harmonic distortion. Temperature rise may occur, which means cables and sources must be oversized. A THD_I value higher than 50% indicates high harmonic distortion where equipment malfunctions are probable.

The voltage total harmonic distortion THD_V indicates the distortion of the voltage wave. The measured THD_V can provide information on phenomena observed in the installation. A THD_V value of less than 5% is considered normal and there is virtually no risk of equipment malfunctions. A THD_V value between 5% and 8% indicates significant harmonic distortion. Some equipment malfunctions may occur. A THD_V value higher than 8% indicates high harmonic distortion and equipment malfunctions are probable (Santiago *et al*., 2016).

2.3.4 Total Demand Distortion

Total Demand Distortion (TDD) according to IEEE 519 is defined as the total root square of harmonic current distortion, in percentage of the maximum demand load current. It is expressed as:

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \tag{2.10}$$

where, I_L = maximum load demand current at the PCC

This current value is the mean of the maximum currents which are demanded by the load through twelve months prior of measurement. TDD index is especially emphasised in IEEE Standard 519. The TDD is the same as the total harmonic distortion except that the distortion is expressed as a percent of some rated load current rather than as a percentage of the fundamental current magnitude at the instant of measurement.

2.3.5 Harmonic Spectrum

The spectrum is a practical graphical means of representing the harmonics contained in a periodic signal. The graph indicates the amplitude of each harmonic order.

2.3.6 Displacement Power Factor, Distortion Power Factor and True Power Factor

There arises a complication when the power factor is computed for a signal in a harmonic environment since the attendant frequencies of the harmonics superimposed on the fundamental signal is taken into consideration. Thus, the conventional definition of power factor as the cosine of the angle between fundamental frequency voltage and current has proceeded to consider the rms values of signals, which make up the contribution of components of different frequencies.

Displacement Power Factor (DPF) characterises the power frequency factor, while Distortion Power Factors (δPF) emerges as the index that pursues rms signal disparities.

The true power factor PF_{True} is defined as the product of the displacement power factor and distortion power factor and is given by Equation (2.11).

$$PF_{True} = DPF \times \delta PF = \cos\theta \times \frac{1}{\sqrt{1+THD^2}} \quad (2.11)$$

In essence, DPF pertains to fundamental quantities only and PF_{True} pertains to both fundamental and harmonic quantities. Where harmonics are not present, the two factors are indistinguishable. However, where harmonics are present, PF_{True} is always smaller than the DPF. In view of the fact that true power factor is always less than unity, it also holds that:

$$PF_{True} \leq DPF \quad (2.12)$$

2.3.7 Crest Factor

The crest factor is the ratio between the value of the peak current (I_m) or peak voltage (V_m) and the corresponding rms value. This is given by Equation (2.13)

$$k = \frac{I_m}{I_{rms}} \quad \text{or} \quad k = \frac{V_m}{V_{rms}} \quad (2.13)$$

For a sinusoidal signal, the crest factor is therefore equal to 2. For non-sinusoidal signals, the crest factor can be greater than or less than 2. This factor is particularly useful in drawing attention to exceptional peak values with respect to the rms value. A very high crest factor indicates that high over currents occur from time to time. These over currents, detected by the protection devices, may cause nuisance tripping.

2.4 Financial Savings from Power factor Improvement

Financial savings are attainable through overall power factor improvement either by way of improving the DPF or by mitigating the harmonics in the system to cause a reduction in the δPF. This is generally achievable by reduction in power consumption kWh losses and the removal of penalties on electricity bill in the form of power factor surcharges. Other benefits accrued from power factor improvement is the reduction in supply capacity charges that consequently result in a reduction in maximum demand and other demand based charges.

Fig. 2.21 illustrates a maximum demand **OC** of kVA (kW of cos $\phi 1$) at a True Power Factor (TPF) of cos ϕ_1 and a corresponding reactive power component kVAr **CE** of kW at tan ϕ_1.

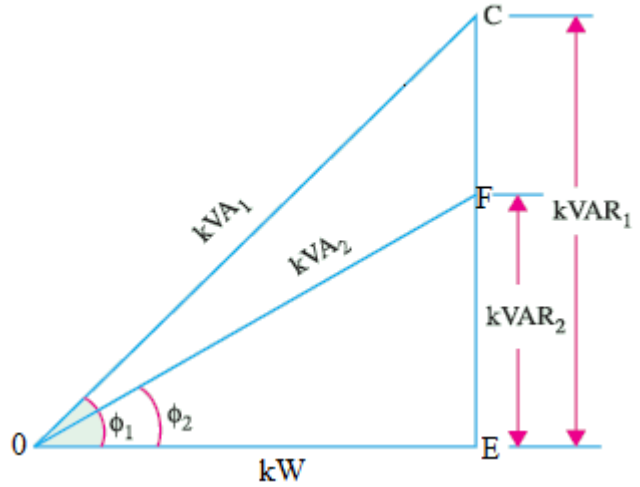

Fig. 2.21 Illustration of Power Factor Improvement

With the application of a power factor improvement measure, the initial TPF (ϕ_1) is improved to a new TPF (ϕ_2). This new TPF reflects a reduction in the kVA demand OF as kVA_2 (i.e. kW of cos ϕ_2) and a $kVAr_2$ **EF** by kW tan ϕ_2. The savings ($kVA_1 - kVA_2$) are accrued from the reduction in the contracted demand at a fixed cost per kVA (Anon., 2018b; Theraja and Theraja, 2005).

Some savings are also realized from the compensated reactive component ($kVAr_1 - kVAr_2$) and is essential in computing savings in the midst of proposals to eliminate the maximum demand charge as a policy direction targeted to ensure affordability in the special load tariff group (Anon., 2018b).

2.5 Important Indicators for Testing Project Viability

2.5.1 Benefit Cost Ratio

Benefit Cost Ratio (BCR) is the ratio of gross return and total cost. The BCR is used in cost benefit analysis to ascertain the overall relationship between the relative costs and benefits of a proposed project. Sapkota and Sapkota (2019) expresses BCR as a ratio of benefit to cost, thus a division of the proposed total cash benefits of a project by the proposed total cash outlays of the project. If the proposed project has a BCR that is greater than 1.0, the project is expected to deliver a positive net present value and will generate an internal rate of return above the discount rate used in the discounted cash flow calculations and should therefore be accepted.

A BCR of exactly 1.0 indicates a break-even point where benefits of the proposed project equate the cost. If the BCR is less than 1.0, it means the project's costs outweigh the benefits and should not be considered (Greer and Ksaibati, 2019).

2.5.2 Net Present Value

The Net Present Value (NPV) is one of two approaches engaged in deciding courses of action in capital budgeting when discounted cash flows are to be considered (Seal *et al.*, 2018). The method comprise the computation of the difference between the present values of a project's cash inflows and the present values of the expected cash outflows (Noreen *et al*, 2017).

The NPV while simpler to use also makes some reasonable assumptions and these make it more credible than the Internal Rate of Return. The NPV uses the cost of capital as the discounting rate and screening tool. Projects with positive NPVs are deemed worthy of the required investment and provide insight into the economic efficiency and validity of the investment even though the criterion may not capture some practical considerations (Heydt, 2018). Projects with negative NPVs are rejected unless other factors dictate its acceptance (Noreen *et al.*, 2017).

2.5 Review of Related works on Techno-Economic Impact of Harmonic Disturbances

Elphick *et al.* (2015) investigated several power quality disturbances and proposed methods of quantifying the effects and costs. They stated that economic impacts of harmonics could be analysed as direct, indirect and social impacts. Furthermore, associated costs due to additional losses and equipment maloperation were explored. Finally, it was explained that owing to the complex nature of equipment performance with regard to power quality, there was a need for extensive research leading to the development of a generalised approach to equipment life cycle and cost evaluation.

Bhattacharyya *et al.* (2011) compared their research on the consequences of poor Power Quality (PQ) with the Leonardo Power Quality Initiative (LPQI) survey of 2004 in the EU-25 countries. Their findings revealed that electronic equipment, electrical motors, variable speed drives and static converters were the most affected equipment in the industries. The other affected devices were cables, capacitors, lighting equipment and relay contactors. It

was further explained that estimating the financial losses of consumers was complicated as they included some direct and indirect costs. The paper lamented on the inadequacy of standards to clearly specify the responsibility of consumers regarding various PQ parameters at the point of connection to the network. Finally, factors leading to responsibility sharing of PQ problems were proposed.

Shwehdi and Al-Ismail (2012) conducted a research on PCs effect on line currents harmonics at King Fahd University. The SMPS used in the PCs caused nonlinear currents to be drawn. The cluster of SMPS resulted in over loading of the neutral conductor and the overheating of the distribution transformers. The authors modelled a mathematical representation of the odd harmonics generated and 29% THD was found in one of the PC Labs. Finally, the installation of passive harmonic filter was proposed alongside the UPS. The obvious disadvantage of the approach being increased capital cost, wiring installation cost and downtime.

Han *et al*. (2013) researched on the performance of energy meters amidst the proliferation of nonlinear loads. The study revealed that the induction meter performed accurately when measuring pure sinusoidal waveform since it was designed in a very narrow band near the power frequency range. They explained further that the grid voltage and current produce distorted waveforms due to the influence of non-linear loads and the measurement errors increased with increase in higher harmonics and resulted in high economic impacts on the users and the power sector. Through the analysis described in the study, they concluded that; nonlinear loads of switch-mode power supply type adversely impacted measurements of the electric meter. To eliminate the influence of distorted waveforms, a simple low-pass filter circuit was designed based on the consideration of actual use of cost. It resulted in a better reading and was recommended for the improvement of energy meters.

Jegadeesan and Venkatesh (2014) published a research in estimation and mitigation of current and voltage harmonics in distribution system using distributed generation. Their work intimated that power quality problems occur due to “non-standard” current, voltage or frequency, which result in malfunctioning of consumer equipment. They conducted harmonic analyses to study the behaviour of equipment connected to the non-sinusoidal environment and to help design, place and size the distributed generation. IEEE 13-Bus test system was employed for the analyses and a balanced distribution model was simulated using MATLAB/SIMULINK software with static and nonlinear loads. The simulation

results showed that best performance of the distributed generation placement was achieved at/near the non-linear load buses.

Arikan *et al*. (2015) centred their harmonic investigations on Medium Voltage (MV) distribution system of Bogazici Electricity Distribution Inc. (BEDAS) at Istanbul, Turkey with the aim of finding the influence of harmonics on their system. A ring network consisting of residential loads was taken into account for the study. Real system parameters and measurement results were used for simulations. Furthermore, probable working conditions of the system were analysed for 50%, 75%, and 100% loading of transformers with similar harmonic contents using four different scenarios to analyse the impact of harmonics and loading rate on $\%THD_V$, PF and technical losses of the MV distribution system. Cyme Power Engineering Software was used for simulations and obtained results showed that $\%THD_V$ values of the buses were increasing according to the rising of the loading rate and $\%THD_V$ values of the buses were decreasing when the bus was away from the nonlinear loads. Again, it was found that the harmonic components and increase of loading rate reduced the PF while the transformer losses and total system losses also increased due to the loading rate and harmonic content.

Mazin *et al.* (2012) presented a measurement technique to estimate the harmonic contributions of residential loads. It was largely a study to determine the harmonic sources and impedances of residential houses and other facilities at the utility metering point. The results were then applied to establish contributions of harmonic voltage and current to the residential premises. Four residential houses were investigated by using the proposed method. The characteristics of the load-side harmonic impedances and sources were studied, and their harmonic contributions were determined. The results showed that voltage distortion was affected mainly by background harmonic sources that existed within the supply system and concluded that residential loads and the supply system affect the current harmonics.

Santiago *et al.* (2016) researched on appliances in the residential sector in relation to economic impact of harmonic losses. The research confirmed that contemporary residential appliances produced harmonic emissions which increased losses in the building wirings as well as a higher apparent power demand. They analysed the active power consumption of audiovisual equipment in the residential sector using data obtained from Time Use Survey (TUS). Additionally, harmonic measurements from different types of household appliances

from equiPment hArmoNic DAtabase (PANDA) including active, non-active annual power demand were analysed and determined. The study revealed an insignificant contribution by a single appliance but a substantial effect when they are aggregated over the course of a year. 19000 GWh was recorded. The research depicted a significant reduction of energy losses up to the tune of one billion Euros in annual energy savings when a reduction of THD_I from 20% to 5% in the distribution system was achieved. The results highlighted that a 1% variation in active energy demand of the residential sector translated to an annual cost of 23 million Euros.

Adamu *et al.* (2014) published a study that focuses on evaluating the extent of THD on medical facilities and various ways of mitigation, using radiology unit of an existing hospital as a means of making a case of economic impact. They conducted measurements with a power analyser at the point of common coupling. Results obtained from the measurement revealed that the level of harmonic distortions for connected equipment exceeded recommended limits by IEEE 519-1992. The researchers employed active filters with suitable control algorithms as a means of mitigating the harmonic distortions. A shunt active filter with synchronous detection algorithm was developed to extract the fundamental component of the source currents using a Fuzzy logic controller modelled in MATLAB/SIMULINK to control the filter. The simulation of the THD with the modelled filter showed that the harmonics were within the recommended limits.

Timens *et al.* (2011) conducted a study on limitations of existing harmonic standards and the harmonic current generation of modern electronic devices by showing an increase in harmonic distortion in new building due to a multitude of non-linear equipment connected. They highlighted that actual standards for power delivery and consumption fails to factor the effect of connecting a multitude of modern equipment to the mains supply even when they complied with standard individually. The study observed limitations in the conventional approach to use the displacement power factor and simultaneity to determine the power supply since the distortion factor will determine the total apparent power. They cited that ‘energy-saving’ lights do reduce the real power consumed, but will still cause a high apparent power consumption. The study finally recommended that the concepts of power factor, displacement factor, distortion factor in the determination of actual power should be revised including those standards that excluded low-energy consumers.

Farraq *et al.* (2017) described in their research on analysis and mitigation of harmonics caused by air conditioners in a distribution system that a distribution system with high penetration of air conditioners, had high levels of harmonic pollution. Their study simulated a model of the harmonics distortion of air conditioners using ETAP software for the simulation of a low voltage network in Pakistan as an example of a warm territory. The simulation results indicated individual harmonic distortions of currents and voltages at the PCC were found to be outside the recommended IEEE 519 harmonic limits. The study observed further distortion rate as length of transmission line increases from the transformer including an increase during off-peak periods compared to peak load periods. A power conditioner was introduced as a mitigating device and successfully yielded a substantial reduction of harmonic pollution levels in the distribution system.

Shama *et al.* (2018) reviewed economic aspects of power quality; impact, assessment and mitigation. The work stated that the consumers and network operators suffer heavy economic loss due to poor power. For each phenomenon, the behaviour of electrical devices varies making the quantification of losses due to poor power quality a complex subject. Diverse case studies showing the effect of power quality problems in various regions of the world were conducted amidst different reliability indices and economic assessment methodologies proposed by past researchers to quantify power quality phenomenon. Sensitivity curves of various equipment were analysed using a hypothetical set of data to validate some of the proposed methodologies. Drawbacks in the proposed methodologies were discussed by the researchers. It was revealed that the estimation of economic loss due to poor power quality required much information about the loads and power supply. Sometimes the available information was insufficient to accurately calculate the economic loss because no single method is individually sufficient to calculate the economic loss due to poor power quality. The study finally recommended the combination of proposed methodologies as a better solution to estimating economic loss.

Senra *et al.* (2017) assessed how harmonic currents generated by single phase loads depended on the distortion parameters of the voltage supply. The study explained that in dealing with the representation of a nonlinear load through admittances, the magnitude and angle depend on the harmonic content of the supply voltage which makes tensor-based procedures accurate when the load admittance loci yield to a circle. The study introduced collection of admittance matrices to account for the admittance variation due to the

dependency on the supply voltage angle. The proposed method based on the iterative calculation using updated Norton admittance, took into account the magnitude and angle voltage dependency behaviour of the nonlinear load. The study compared measurements and numerical analysis obtained from time-domain simulations with the proposed methodology for validation purposes. The research finally recommended the method provided as a deterministic way of assessing the line current produced by a single or group of nonlinear loads.

Papadopoulos *et al.* (2012) conducted harmonic analysis at the low voltage bus of two higher education buildings. The harmonic spectrum of the obtained measurements were analysed against time. Their investigations were subdivided to periods of working hours and non-working hours, each day with ON and OFF indexes respectively. Box plots were adopted for the statistical processes of the recorded data groups. Furthermore, minimum and maximum samples, the lower, median and upper quartiles in addition to outliers were presented. Analyses of the voltage harmonic distortions showed 5th harmonic as most significant in both installations but concluded that the voltage limits established by Harmonic Standards were not violated. Analyses of current harmonic spectrum and the harmonic profiles of both installations were compared. The 3rd harmonic components followed by the 5th in both installations were highest, with values not exceeding 20% and 15%, respectively. It was observed that the $THD_{I(rms)}$ and the current harmonic profiles follow the 24 hour cyclicity. The authors consequently recommended the use of the proposed method of analyses to further identify solution to suppress harmonic contents.

Ajami and Bangheri (2012) presented an improved technique for determining the contribution of harmonic distortion created by utility and consumer at the PCC in a polluted power system. They estimated the magnitude and phase of voltage and current at the PCC in each frequency using adaptive Kalman filter. Then the parameters of Thevenin equivalent circuits of load and utility sides were estimated using the recursive least squares technique based on Singular Value Decomposition (SVD). Finally, the contribution of utility and customer in harmonic distortion of the 3-phase voltage waveforms were calculated by three approaches. A case study was conducted to validate the accuracy of the proposed method and also tested using IEEE 13-bus test system. Simulation results showed that the proposed method can accurately determine the harmonic contributions of utility and customer for measurements made at the PCC.

2.6 Summary of Chapter

In this chapter, the cumulative effects of harmonic disturbances have been reviewed. The disturbances, which are gaining more attention, are occasioned by the proliferation of nonlinear loads predicted in many literatures to be the nature of future electrical loads. Different methods of quantifying the associated costs of harmonic disturbances were expounded.

Several harmonic investigation approaches and measurement techniques were proposed by researchers including analysis and mitigation methodologies. Economic indices, which indicate the viability of embarking upon a particular mitigation method, were also discussed.

Furthermore, harmonic investigations and economic analysis were presented on selected nonlinear loads individually and not on the collective effect of aggregated loads for residential, commercial and industrial settings. Therefore, this research work focuses on the economic impact of harmonic disturbances catalysed by aggregated nonlinear loads in a University environment.

CHAPTER 3

METHODS USED

3.1 Introduction

This chapter describes the various approach employed in obtaining the required data for the techno-economic evaluation of harmonic disturbances at UCC being the case study area. The total load of the University is estimated in terms of kVA demand including dominant harmonic loads. Actual field measurements, data collection at every significant facility is carried out and subsequently, financial analysis is conducted to ascertain the veracity of harmonic disturbances in economic terms.

3.2 The Case Study Area

The University of Cape Coast is a prestigious public collegiate research University located five kilometres west of Cape Coast, Ghana. The University, which, is on a hill overlooking the Atlantic Ocean, covers a total land area of 12 square kilometres and operates on two campuses: Southern Campus (Old Site) and Northern Campus (New Site).

Established in 1962, it continues to train graduate teachers for teacher training colleges and technical institutions. The University has since added to its functions the training of medical doctors and health care professionals, as well as education planners, administrators, and agriculturalists and legal practitioners. Fig. 3.1 depicts a pictorial view of the west gate entrance of the University.

Fig. 3.1 A Pictorial View of the West Gate Entrance of the University of Cape Coast

3.2.1 The Power Distribution Network

The University is a Special Load Tariff (SLT) consumer and takes 11 kV bulk supply from the Electricity Company of Ghana (ECG) power network to its Power Distribution Centre (PDC) located at the control station of the University. The 11 kV PDC equipped with a sulphur hexafluoride gas (SF_6) circuit breakers are fed from two 11 kV incoming feeders. Fig. 3.2 illustrates a hindered front view of the power distribution centre at UCC.

There are 17 distribution transformer substations situated on campus with a total installed capacity of 11.14 MW. Each substation is fitted with kVAr compensation equipment (capacitor bank) of appropriate capacity for power factor correction purposes. Table 3.1 shows the transformer substations and their respective nominal parameters. Underground cables of 3×185 mm^2 XLPE/PVC/SWA copper/aluminium are typically employed for the interconnection between the substations whereas armoured cables of 500 mm^2 single core XLPE/PVC/SWA copper are used for hooking the LV sides to the feeder pillars as depicted by Fig. A1 in Appendix A. In addition, these underground cables accounts for more than 80% of the High-Tension (HT) distribution network. The HT distribution network on the campus has circuitry kilometres of 26.3 km.

Fig. 3.2 A Hindered Front View of the Power Distribution Center at UCC

Table 3.1 Transformer Substations Situated at the University of Cape Coast

Name of Substation	Transformer Capacity (kVA)	Impedance (%)	Full Load Amps (A)	Secondary Line Voltage (V_{L-L})	Vector Group	Fitted Capacitor Bank (kVAr)
Control Station	1000	5.61	1440	400	Dyn 5	200.0
Southern	500	4.00	720	433	Dy 11	122.5
Hill Top	630	4.54	840	433	Dy 11	125.5
Atlantic	1000	4.55	1342	430	Dyn 5	245.0
Casford	750	4.50	1000	433	Dy 11	125.5
Science	1000	4.36	1332	433	Dy 11	245.0
Auditorium	1000	4.54	1342	430	Dyn 11	245.0
Library	1000	4.56	1342	430	Dy 11	245.0
Valco-Trust	500	5.00	667	433	Dyn 11	95.5
CODE	1000	4.47	1334	430	Dy 11	200.0
Northern	750	4.55	1008	433	Dyn 11	122.5
Ghana Hostels	500	4.41	667	433	Dyn 11	95.5
Tech Village	100	4.28	135	430	Dy 11	46.0
Superannuation	500	4.05	696	415	Dyn 11	122.5
SRC/Medical	1000	4.56	1333	433	Dyn 11	245.0
Filling Station	50	5.65	69	433	Dyn 11	Nil

3.2.2 Physical Infrastructure

According to the 2018 Property Register obtained from the Directorate of Physical Development and Estate Management (DPDEM) of the University, there are 63 prominent academic facilities and 13 halls of residence for students strategically located over the entire campuses of the University. Other less-imposing structures, such as residential bungalows, satellite offices, fuel stations, police station, fire service, snack bars, etc. number up to 227 building units of various dimensions on the University campus. Out of the physical

infrastructure on the University campus, the academic and administrative facilities house up to 3000 refrigeration and air conditioning equipment of mixed capacities and operational modes. Over 11 000 T5 fluorescent lighting fittings, and 7 367 office equipment, etc. Appendix B gives the estimated total power of electrical loads for the essential physical infrastructure in the University.

Dominant loads

Nonlinear loads make up 82% of the total electric loads on the University distribution network. Lighting, provided by T5 fluorescent fittings, dominate the entire loading on the network by 45%. However, nonlinear loads of the SMPS type account for 67% of the total harmonic-producing loads. These are illustrated in Fig. 3.3 and Fig. 3.4.

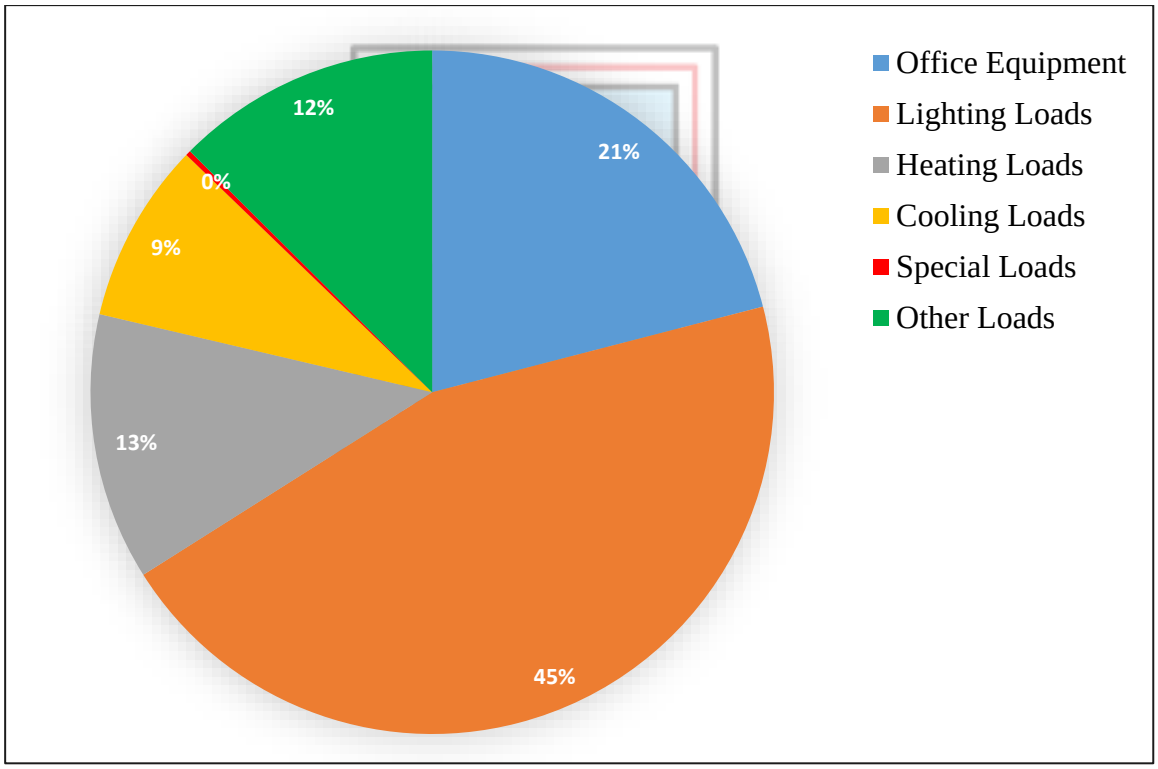

Fig. 3.3 Pie Chart of Load Types on the UCC Network

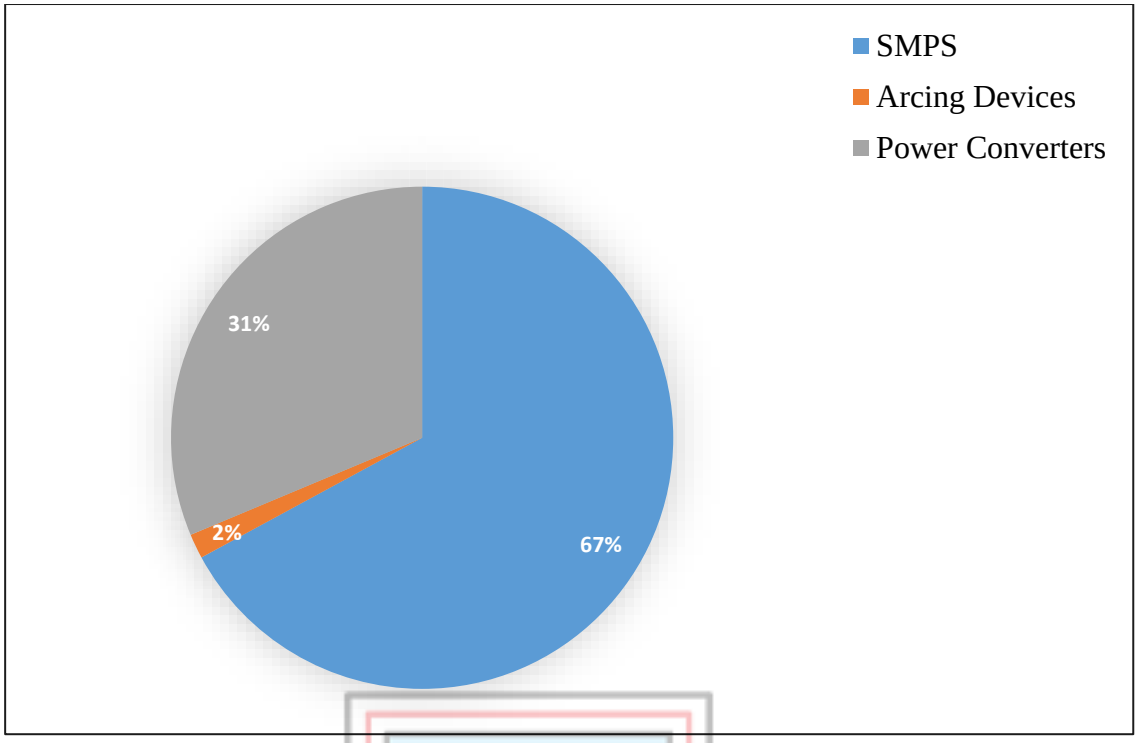

Fig. 3.4 Pie Chart of Special Kinds of Nonlinear Loads on UCC Network

"Other loads" as specified by Fig. 3.3 refer to specialised loads found in areas such the UCC hospital, University press, University filling station, etc. whereas domestic loads are loads typically resident in the bungalows and lodges, etc. on campus.

3.3 Harmonic Measurement Process

The objective of harmonic measurement is to investigate the extent of harmonic disturbances on the distribution network which includes the entire electrical installations and equipment of the University. The harmonic measurements that were undertaken made use of a power quality analysing instrument. To conduct the measurements, extensive lectures and training on the use of the instrument were undertaken at the Energy Foundations, Accra. Permission to open feeder pillars and other switchboards was obtained from the electricity section of the University. Single line diagrams and LV distribution arrangement was also provided.

3.3.1 Measurement Points

Harmonic evaluations were carried out at the PCC in compliance with harmonic limits as prescribed in the IEEE 519-2014 Standard. The point of common coupling according to the standard was taken as "the point in the electrical power system closest to the user, where other users are also connected.

For the commercial users supplied through a common service transformer, the PCC is the LV bus of the transformer whereas the HV side of the dedicated transformer is commonly the PCC for industrial users such as a production plant" as depicted in Fig. 3.5 and Fig. 3.6.

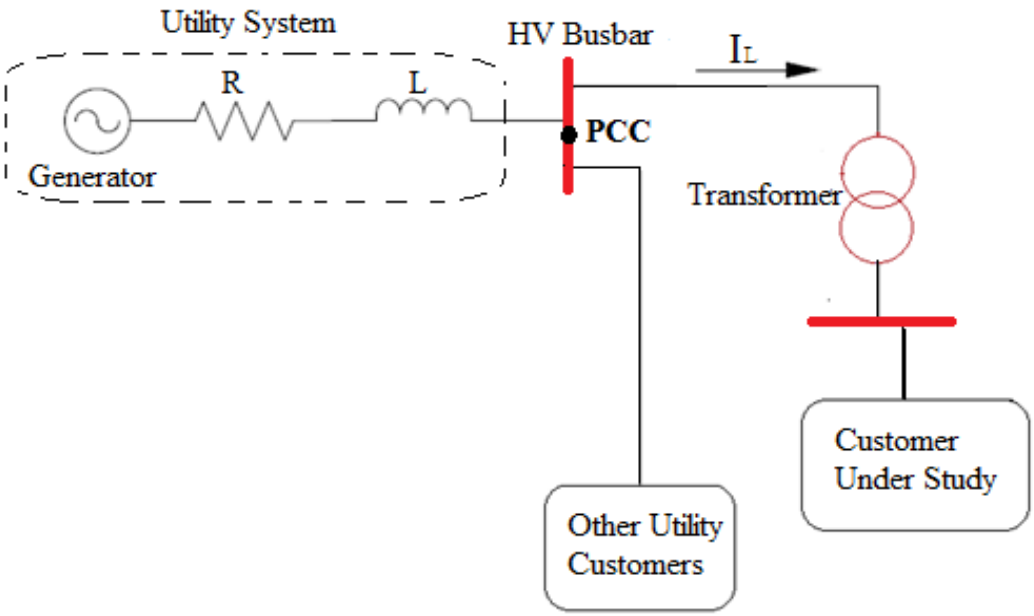

Fig. 3.5 Location of PCC for Industrial Customers

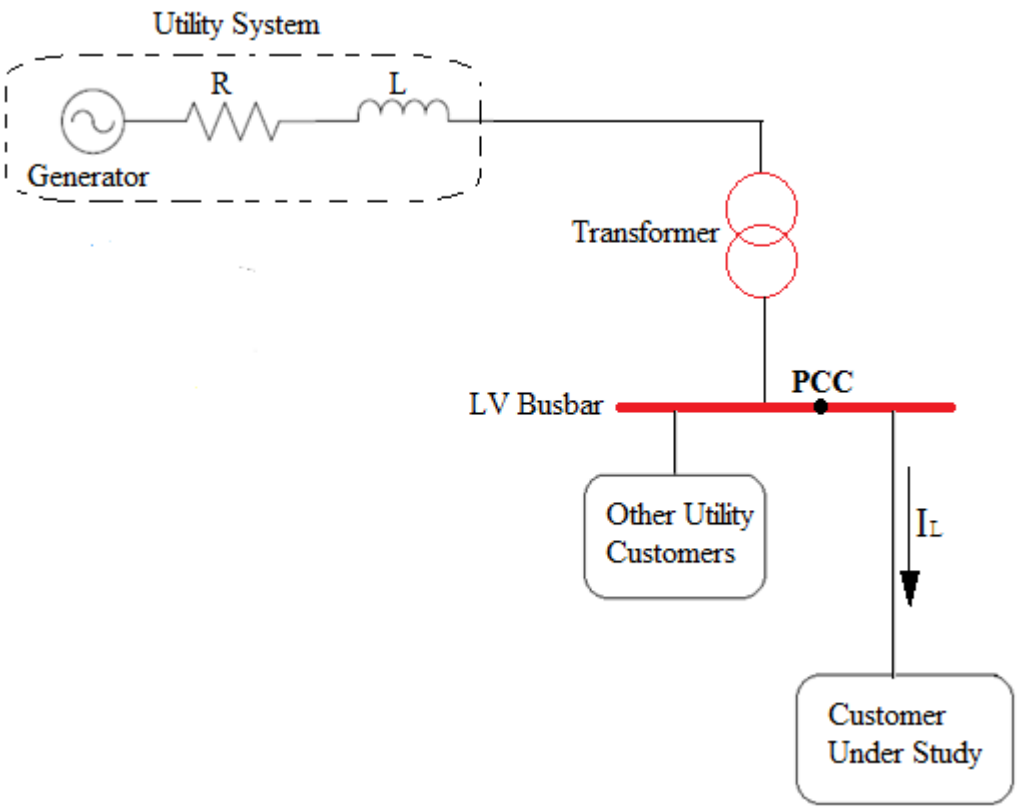

Fig. 3.6 Location of PCC for Commercial Customers

The PCCs on the University distribution network at which measurements were conducted are illustrated by Fig. A1 of Appendix A. Additional measurements were taken at other locations within some facilities known as Special Installations.

Special installations refer to facilities with specialised equipment such as that found at the University Hospital or the University Press. Measurements within these facilities are to characterise the time-varying nature of harmonic currents created, and to gain insight into the behaviour of the aggregated nonlinear loads on the circuit branches. Additionally, these measurements help illustrate the cancellation and attenuation achieved as a result of harmonic injection from various nonlinear loads within the circuit branch or branches of that particular facility.

Fig. 3.7, Fig. 3.8 and Fig. 3.9 give the single line diagrams illustrating typical LV distribution arrangement of the Science Complex, University Hospital and Atlantic substation LV networks, respectively. The PCCs at these typical facilities are identified.

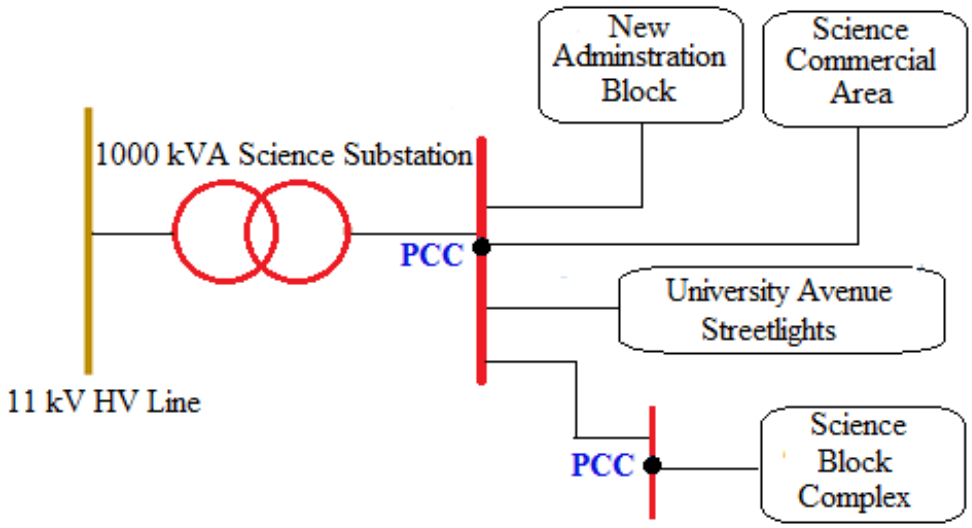

Fig. 3.7 Typical Distribution Arrangement showing the PCCs at Science Complex LV Network

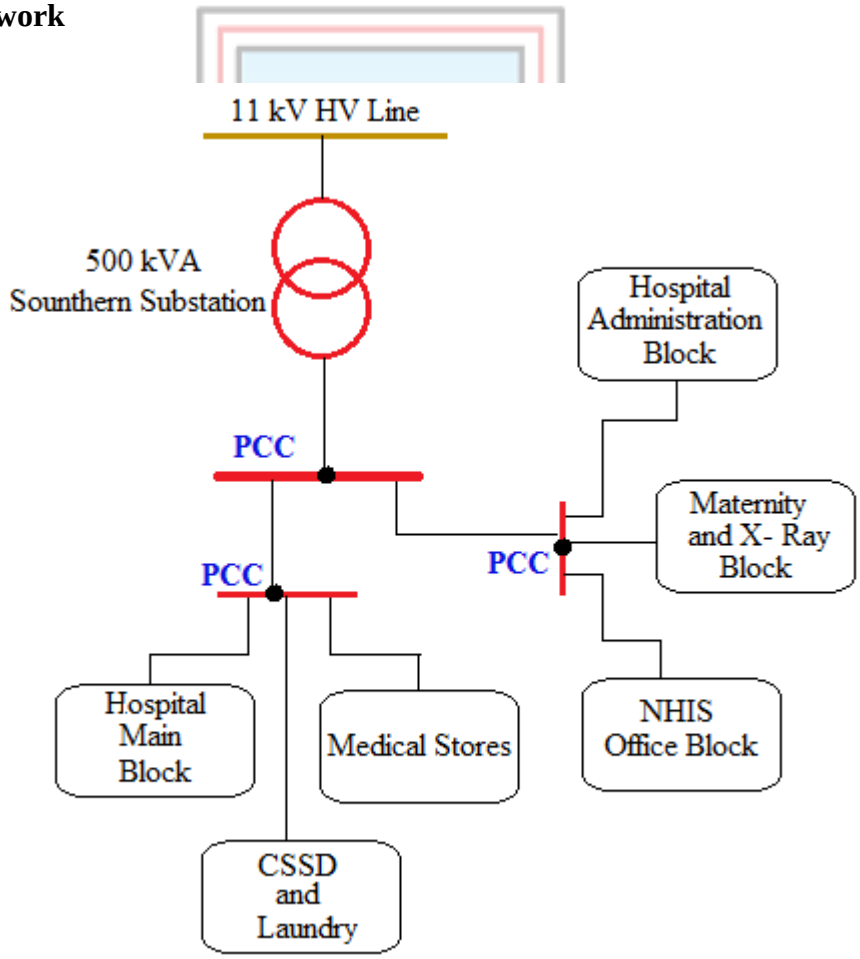

Fig. 3.8 Typical Distribution Arrangement showing the PCCs at University Hospital LV Network

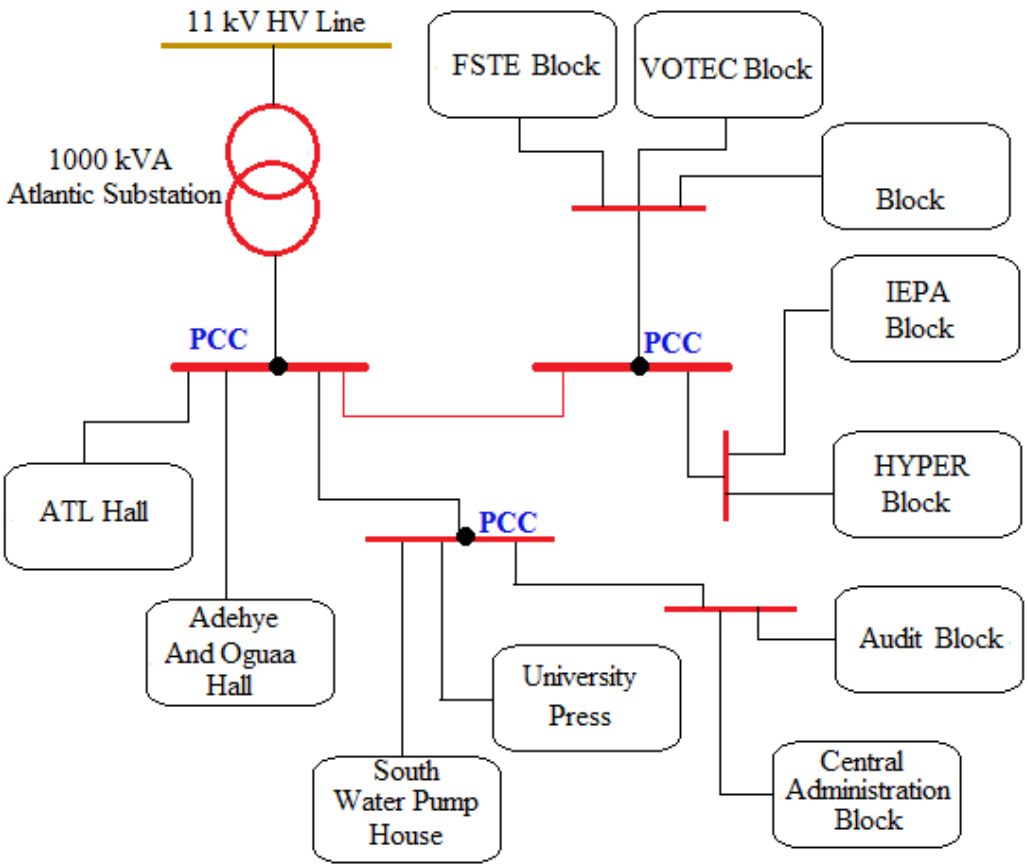

Fig. 3.9 Typical Distribution Arrangement showing the PCCs on the Branch Circuits of Atlantic Substation LV Network

3.3.2 Measurement Procedure

The measurement procedure is illustrated in the flow chart of Fig. 3.10.

Locating transformers and LV feeder pillars

The transformers are strategically located close to the load centres on the University campus where the LV sides of the transformer are hooked directly onto the feeder pillars. The transformers and LV feeder pillars are housed separately in the same power house.

Choosing PCC and setting up

This involves identifying the PCC as specified by IEEE 519-2014 harmonic standard. Setting up is the process that deals with the correct way of installing the power analysing instrument at the PCC.

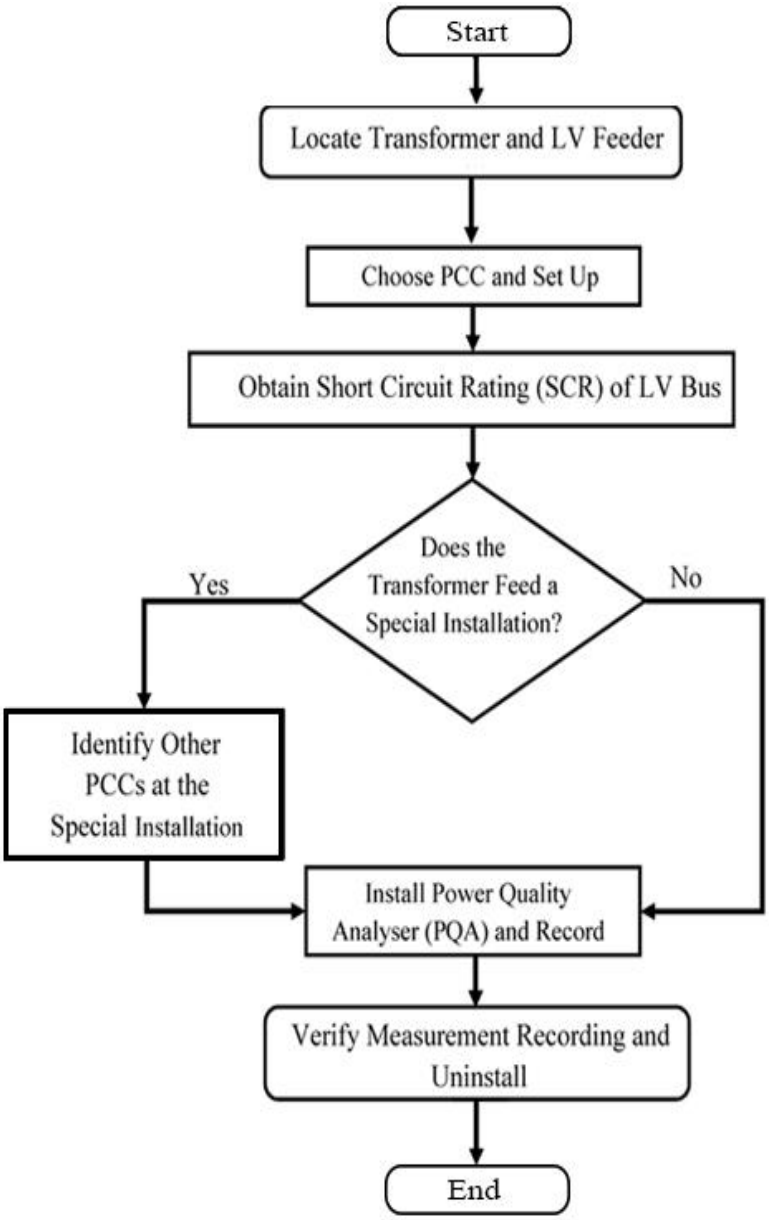

Fig. 3.10 Flowchart illustrating the Harmonic Measurement Procedure

Obtaining the short circuit ratio rating of the LV bus

The Short Circuit Ratio (SCR) at a particular location refers to the ratio of short-circuit current available, in amperes, to the load current, in amperes. The short circuit current I_{SC} is calculated using Equation (3.1).

$$I_{SC} = \frac{kVA \times 100}{\sqrt{3} \times V_{L-L} \times (Z_{P.U} + Z_{System})} \tag{3.1}$$

where, kVA = transformer rating

V_{L-L} = line to line secondary voltage of the transformer at normal tapping

$Z_{P.U}$ = per unit impedance of the transformer at normal tapping

Z_{System} = estimated system impedances comprising service entrance equipment, cables and LV feeder pillars obtained from the UCC Electricity Section as 0.0155 per unit

Equation (3.2) gives the relationship between the load current and short circuit current.

$$SCR = \frac{I_{SC}}{I_L} \tag{3.2}$$

where, I_{sc} = short circuit current calculated from Equation (3.1)

I_L = maximum rated current obtained from the transformer nameplate

The SRC value for each LV bus can then be obtained by applying the parameters given in Table 3.1 using Equation (3.1) and Equation (3.2) as follows:

$$I_{SC} = \frac{1000 \times 100}{\sqrt{3} \times 430 \times (0.0454 + 0.0155)}$$

$$Isc = 22.05 \ kA$$

Therefore, SRC value for LV bus at Auditorium PCC is given as,

$$SCR = \frac{22.05 \times 10^3}{1342}$$

$$SCR = 16.43$$

Similarly, the SCR values in Table 3.2 were calculated for the LV buses at the various PCCs.

Table 3.2 Summary of SCR Values for each Substation

Name of Substation	Transformer Capacity (kVA)	Per Unit Impedance	I_L (A)	I_{SC} (kA)	SCR
Auditorium	1000	0.0454	1342	22.05	16.43
Atlantic	1000	0.0455	1342	22.01	16.40
Science	1000	0.0436	1332	22.56	16.90
Control Station	1000	0.0561	1440	20.19	14.02
CoDE	1000	0.0447	1334	22.15	16.60
SRC/Medical	1000	0.0465	1333	21.51	16.14
Library	1000	0.0456	1342	21.98	16.37
Northern	750	0.0455	1008	16.40	16.42
Casford	750	0.0450	1000	16.53	16.53
Hilltop	630	0.0454	840	13.79	16.42
Superannuation	500	0.0405	696	12.42	17.74
Ghana Hostels	500	0.0441	667	11.19	16.78
Southern	500	0.0400	720	12.01	16.68
Valco-Trust	500	0.0500	667	10.18	15.26
Tech Village	100	0.0428	135	2.30	17.10
Filling Station	50	0.0565	69	1.18	17.20

Since the SCR values are not up to 20, current distortion limits corresponding with values stated in the SCR < 20 category for which the maximum allowable THD_I values for daily 99th percentile is 8%, 4%, 3% and 1.5% for harmonic orders up to the 11th, 17th, 23rd, and 35th respectively shall be applied in this study. Similarly, voltages at the LV buses across the PCCs are less than 1.0 kV. This implies that a recommended THD_V limit of 12% will be applicable in this study.

Transformer feeding a special installation

When the transformer is feeding an installation other than the anticipated loads such as a small concentration of PCs loads, lighting loads etc. and supplies power to loads such as commercial printing press, hospital facility commensurate with a district hospital etc., it becomes necessary to label them as special facilities and determine other PCCs within those

facilities where further measurements could be taken to ascertain their harmonics contribution to the overall anticipated disturbances.

Installation of power quality analyser and measurements recording

A power analyser is installed with appropriate settings to capture measured data over a period of time as specified by IEEE 519-2014 standard. The duration for measurements as prescribed by the standard offers adequate period of time to sufficiently record and characterise the time varying nature of harmonic currents.

Verification of measurements and uninstallation of instrument

To ensure that data are well captured by the device, it is necessary to verify the recorded data by scrolling to the stored data satisfying the presence of the recording before uninstalling the instrument.

3.3.3 Measurement Setup

The following Personal Protective Equipment (PPE) and tools were utilised in the course of setting up for harmonic measurement:

i. 34.5 kV safety gloves ;

ii. Safety boots with antistatic;

iii. Safety goggles;

iv. Work overall;

v. Flashlight; and

vi. Electrical tools set.

Typical measurement setups at some of the substations and facilities of the University are illustrated in Fig. 3.11 to Fig. 3.14.

Fig. 3.11 Measurement Setup at the Science Substation

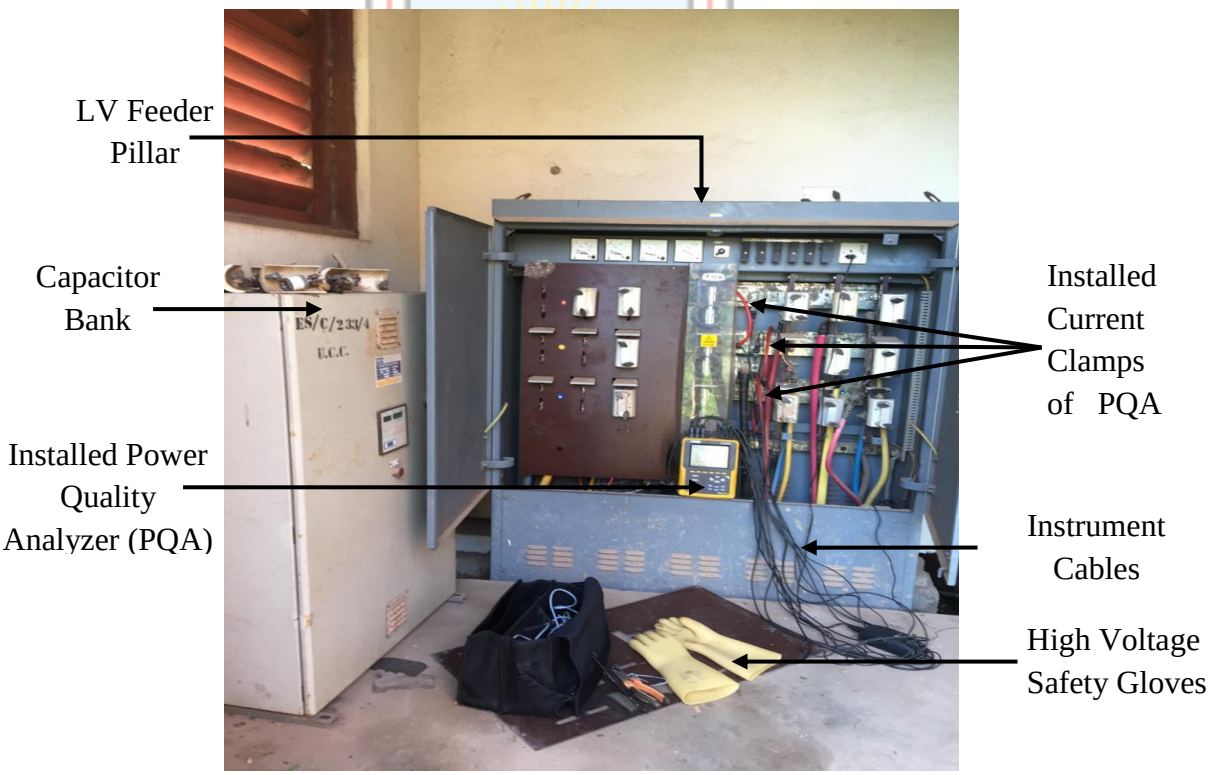

Fig. 3.12 Measurement Setup at the Library Substation

Fig. 3.13 Measurement Setup at the Auditorium Substation

Fig. 3.14 Measurement Setup at the Control Station

3.3.4 Monitoring Duration

Harmonic measurements are performed over a period to characterize the variable nature of the harmonic levels. For very stable conditions such as those encountered in a commercial facility like hospitals, schools and universities, interdepartmental stores and shopping malls, banks and other businesses, measurements over single day are adequate to characterise the varying levels of harmonics.

However, for facilities such as steel plants with arc furnaces or manufacturing and production firms with varying production demands from clients, conducting a weeklong measurement is recommended (Anon., 2014a). Moreover, where operational characteristics vary from day to day, it is recommended to monitor over longer periods. Again, for a University environment, where the load types are similar throughout, the expected spectra content can easily be characterised in short term measurement.

The IEEE 519-2014 Standard recommends the following measurement window widths:

i. Very short time harmonic measurements; and

ii. Short time harmonic measurements.

Very short time harmonic measurements

Very short time harmonic values are assessed over a 3-second interval based on an aggregation of 15 consecutive 12 (10) cycle windows for 60 (50) Hz power systems. Individual frequency components are aggregated based on an rms calculation as shown in Equation (3.3).

$$F_{n,vs} = \sqrt[2]{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^{2}} \tag{3.3}$$

where, F = voltage (V) or current (I), in rms value

n = harmonic order

i = simple counter

vs = “very short”

For very short time harmonic measurements, the duration is 24 hours (1 day) and the 99th percentile value (values should be less than 1.5 times and 2 times for voltages and currents

respectively of the values recommended) should be calculated for each 24-hour period for comparison with the recommended limits in Clause 5 of the IEEE 519- 2014 Standard. This is applied to both voltage and current harmonics.

Short time harmonic measurements

Short time harmonic values are assessed over a 10-minute interval based on an aggregation of 200 consecutive very short time values for a specific frequency component. The 200 values are aggregated based on an rms calculation as shown in Equation (3.4).

$$F_{n,sh} = \sqrt[2]{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),1}^{2}} \tag{3.4}$$

where, F = voltage (V) or current (I), in rms value

n = harmonic order

i = simple counter

sh = "short"

The duration for short time harmonic measurement is a 7-day period (1 week); the 95th and 99th percentile values (i.e., for values exceeding 5% and 1% of the measurement period) should be calculated for each 7-day period for comparison with the recommended limits in Clause 5 of the IEEE 519- 2014 Standard. These statistics should be used for both voltage and current harmonics with the exception that the 99th percentile short time value is not recommended for use with voltage harmonics (Anon., 2014a).

In this work, the "very short time" measurement duration was found optimal and was selected in view of time constraints, resources, similarity of electric loads and the large area to be considered for the measurement. Furthermore, the stable operating conditions prevailing on the distribution network of the University permits the adoption of the "very short time" measurement method.

3.3.5 Recommended Harmonic Limits

The IEEE 519-2014 prescribes the daily percentile values of each harmonic and THD at the PCC for voltage and current limits.

Voltage limits

Limits for line-to-neutral voltage harmonics in 415 V systems with daily 99th percentile very short time (i.e., 3 s) harmonic currents are applied with respect to Table 3.3.

Table 3.3 Voltage Distortion Limits

Bus Voltage at PCC	Individual Harmonic (%)	Total Harmonic Distortion THD (%)
V ≤ 1.0 kV	7.5	12

(Source: Anon., 2014a)

Current limits

Limits for the current distortion by odd harmonics in 415 V systems daily 99th percentile very short time (3 s) harmonic currents are applied according to the ratio $\frac{I_{SC}}{I_L}$ shown in Table 3.4.

Table 3.4 Current Distortion Limits

Maximum Harmonic Current Distortion in Percent of I_L					
Individual Harmonic Order (Odd Harmonics)					
$\frac{I_{SC}}{I_L}$	3 ≤ h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	TDD
< 20	8.0	4.0	3.0	1.2	10.0
20 < 50	14.0	7.0	5.0	2.0	16.0
50 < 100	20.0	9.0	8.0	3.0	24.0
100 < 1000	24.0	11.0	10.0	4.0	30.0
>1000	30.0	14.0	12.0	5.0	40.0

(Source: Anon., 2014a)

3.3.6 System Condition Considerations during Measurements

In addition to the random time variations of harmonic levels, it is noteworthy to consider the impact of various system conditions on harmonic levels within the facility and on the power system. Crucial system conditions considered in the harmonic measurement included:

i. Impact of alternative sources of power (e.g. mains and standby generator);

ii. Influence of different load combinations;

iii. Effect of power factor correction capacitor in the facility;

iv. Effect of power factor correction capacitor on the utility supply system;

v. Influence of harmonic filter or other harmonic mitigation device out of service; and

vi. Impact of neighbouring facility with significant harmonic production.

3.3.7 Power Quality Analyser

Power Quality Analyser (PQA) is a multifunction power-analysing device capable of measuring precisely direct current, alternating current, AC-voltage, DC-voltage, the intensity of DC or AC phase rotation, apparent and true power. A typical PQA is also equipped with the capabilities of capturing and recording data on many power quality indices such as transients, unbalance, distortions, fluctuations etc. and even neutral currents.

Chauvin Arnoux CA 8335 energy analyser qualistar+

Chauvin Arnoux CA 8335 energy analyser qualistar+ was employed for the purposes of harmonic measurements for this work owing to its impact/shock resistant and rugged built including the ergonomics and simplicity of its interface which makes it simple and intuitive to use.

The instrument is a three-phase AC+DC 1000 V_{RMS} category III and 600 V_{RMS} category IV (IEC 61010-1) colour graphic display network analyser with built-in rechargeable battery. Fig. 3.15 and Fig. 3.16 show the general view of the power analyser and an example of its display screen, respectively.

Fig. 3.15 General View of Chauvin Arnoux CA 8335 Power Quality Analyser

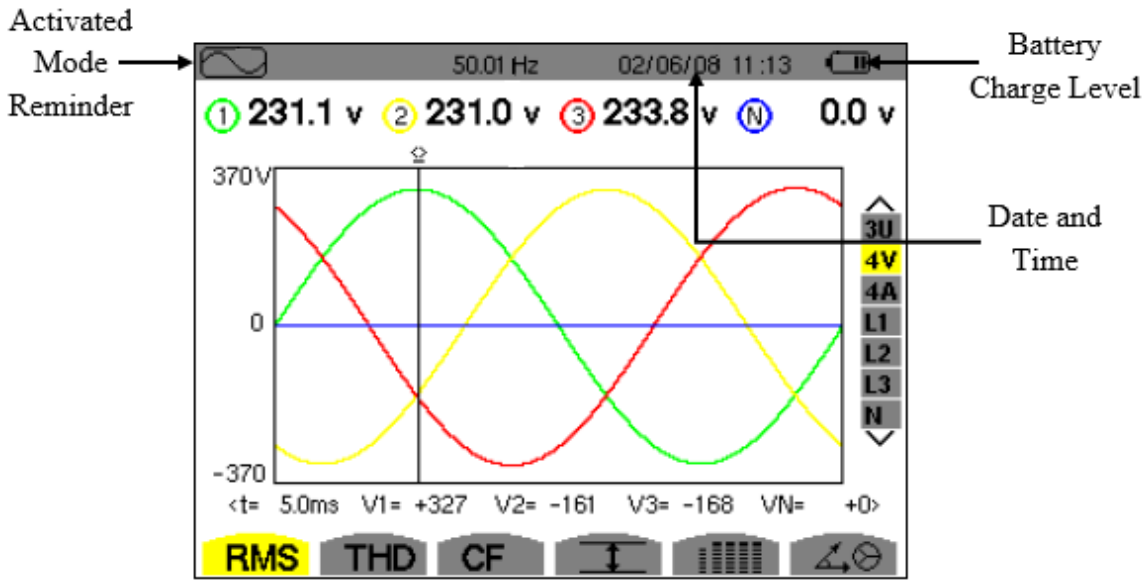

Fig. 3.16 Example of Display Screen of the CA 8335 Power Quality Analyser

The instrument plays three roles, and could be used to measure the RMS values, powers, and disturbances of electric distribution networks and permits these measurements in real-time simultaneously. It can also deliver a snapshot and allows real-time studying of waveforms, diagram for harmonics, flicker, etc. and other principal characteristics of a three-phase network including tracking the deviations of various parameters over a period.

The principal measurements capabilities of the instrument are:

i. The rms values of AC voltages and currents up to 1000 V and 10,000 A respectively between terminals including neutral;

ii. The DC components of AC voltages and currents (neutral included);

iii. Peak values and peak factors of voltage and current (neutral included);

iv. The frequency of 50 Hz and 60 Hz networks;

v. Calculation of the Harmonic Loss Factor (FHL) and K factor (KF) (application to transformers in the presence of harmonic currents);

vi. Measurement of total harmonic distortion with respect to the fundamental of the currents and of the voltages (excluding neutral);

vii. Active, reactive (capacitive and inductive), non-active, distortion, and apparent power, by phase and cumulative (excluding neutral);

viii. PF and DPF (excluding neutral);

ix. Measurement of the short-term (PST) and long-term (PLT) flicker of the voltages (excluding neutral);

x. Current and voltage harmonics (excluding neutral) up to order 50

xi. Harmonics for apparent power up to order 50 (excluding neutral): percentages in relation to the fundamental, minimum and maximum; and

xii. Inrush currents of motor starting.

3.3.8 Instrument Compliance

The measurement process emphasizes the compliance with certain characteristics of recording instruments to ensure the capture of representative samples.

For the purposes of assessing harmonic levels for comparison with the recommended limits established in the IEEE 519-2014 standard, the instrument in section 3.3.7 i.e. Chauvin Arnoux C.A 8335 Energy Analyser (Qualistar +) employed for this research, complies with the specifications of IEC 61000-4-7 and IEC 61000-4-30.

3.4 Modelling and Simulation Software

Complexities arise from harmonics studies in relation to its propagation and interaction of voltage and current distortions where the impedance is shared including partial cancellation due to diversity of phase angles. Owing to this, it is necessary to model the affected network and conduct harmonic analysis to examine and identify possible violations of harmonic distortions limits including designing and testing filters for mitigation.

Several software are employed for power system analysis. In this thesis, ETAP 16.0.0 is chosen to model the UCC distribution network and to conduct harmonic load flow studies.

3.4.1 ETAP 16.0.0 Software Overview

ETAP stands for Electrical Transients Analysis Program and provides an assembly of completely integrated electrical engineering software solutions. Its modular functionality can be adapted to suit the needs of any large or small power systems.

In order to perform harmonic analysis, ETAP software is chosen for the project. It is a user-friendly software and easy to model harmonic sources. ETAP can also perform the following types of analysis:

i. Transient stability analysis;

ii. Load flow analysis;

iii. Unbalanced load flow analysis;

iv. Short circuit analysis;

v. Motor acceleration analysis;

vi. Harmonic analysis;

vii. Star-Protective device coordination;

viii. Optimal power flow analysis;

ix. Reliability assessment; and

x. DC load flow analysis.

3.4.2 Harmonic Analysis Module

By switching to the harmonic analysis mode, harmonic current and voltage sources can be simulated to categorise problems of harmonics nature. Harmonic filters can also be designed and tested including a report on harmonic distortion limit violations in accordance to IEEE and IEC harmonics standards.

ETAP uses the current injection method to carry out load flow at each harmonic frequency for any present harmonic source. The harmonic load flow study performs a load flow calculation using either Accelerated Gauss Seidel Method or the Newton Raphson Method. The results of the fundamental load flow sets the base for the fundamental bus voltages and branch currents which are used later to determine different harmonic indices. The harmonic frequencies measured are all the low order frequencies from the 2nd to the 15th, the characteristic harmonics from the 17th up to the 73rd with the component's impedance adjusted based on the harmonic frequencies and the types of components. The calculated bus THD and Individual Harmonic Distortions (IHDs) are then matched with the parameters specified in the bus editor. Detected violations are flagged and placed next to the associated bus in the harmonic information section.

Fig. 3.17 shows the harmonic analysis mode activated in ETAP 16.0.0 window.

3.4.3 Harmonic Analysis Tool Bar

In the right hand pane of Fig. 3.18 lies the harmonic analysis tool bar. The commands buttons in the tool bar allows the execution of various harmonic analysis instructions. Fig. 3.18 shows each button and the associated commands.

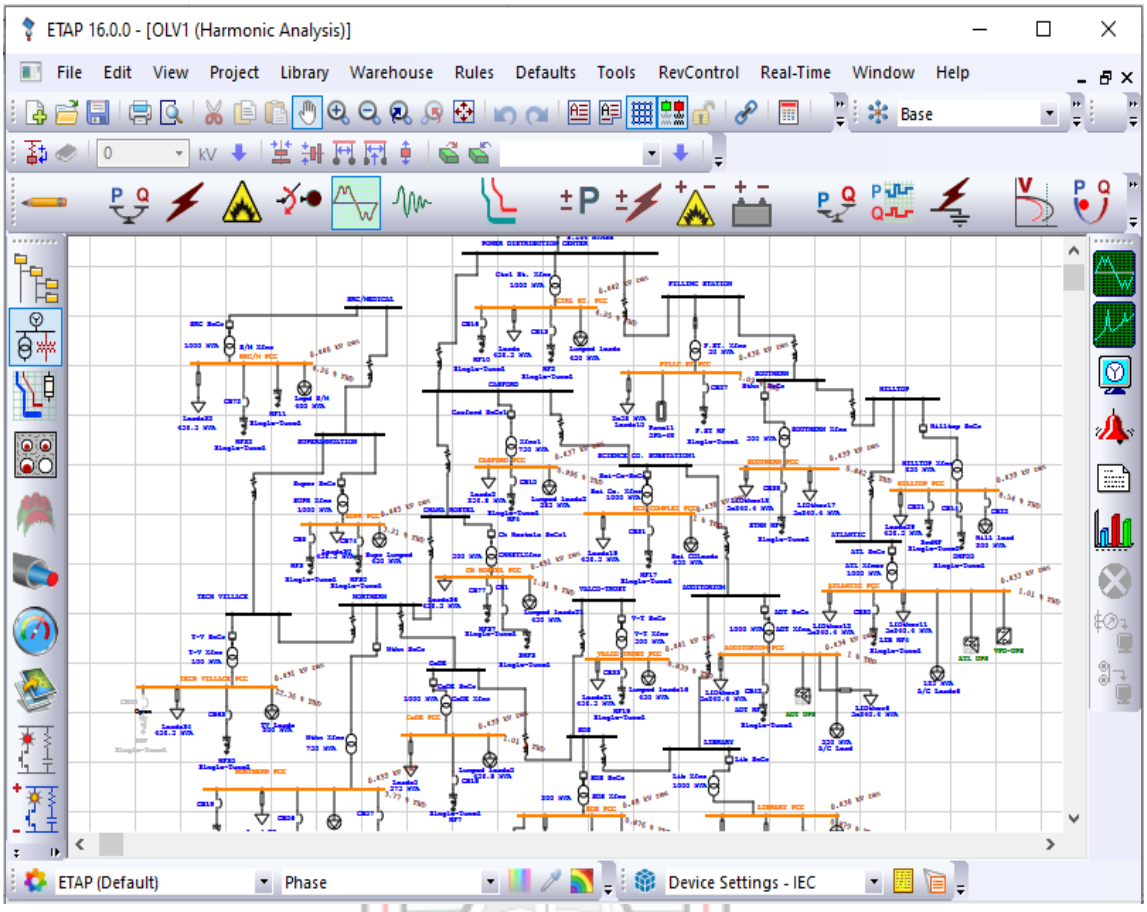

Fig. 3.17 Harmonic Analysis Mode Activated in ETAP 16.0.0 Window

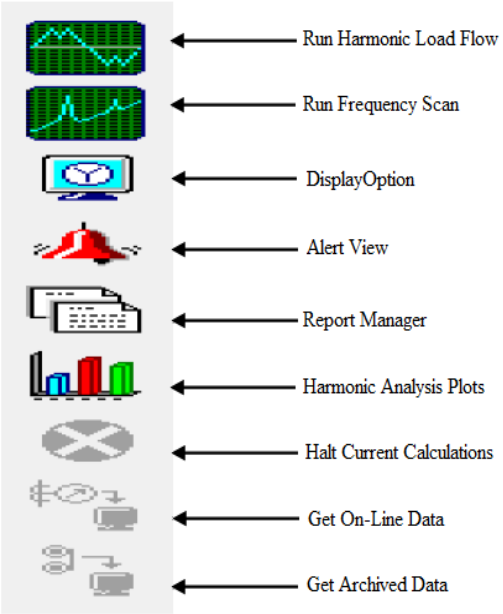

Fig. 3.18 Harmonic Analysis Tool Bar

Run harmonic load flow

The ‘run harmonic load flow’ button will effect a harmonic load flow study. The output results is shown on the single line diagram and can be viewed in output report text after the harmonic load flow calculation ends.

Run frequency scan

The run frequency scan button will perform a harmonic frequency scan study which calculates all the impedance angles and magnitude. The results of the frequency scan study are also displayed on the single line diagram.

Display options

The display options button allows the user to customize the type of result to be displayed on the single line diagram under the harmonic analysis study mode.

Alert view

The alert view lists all equipment with critical and marginal violations centered on the settings in the study case for example the IEEE519 Standard set in ETAP after running a harmonic load flow study or frequency scan.

Report manager

In the report manager, the user is allowed to select a suitable file format for viewing a number of predefined results provided in PDF, MS Word, Rich Text, MS Excel formats etc.

Harmonic analysis plots

The harmonic analysis plots button allows user to graphically represent the result from the selected output plot file. The plot files for harmonic load flow and harmonic frequency scan are given the file extensions .hfp and .fsp respectively after performing the calculations. The impedance magnitude and impedance angle curve can be plotted also by using this button.

3.4.4 Harmonic Component Modelling in ETAP

The nonlinear loads are typically modelled as current and voltage sources with harmonic frequencies because they are basically either injecting harmonic currents into the system or

applying harmonic voltages at the common bus. Power sources like the grid or generators are modelled as voltage source with harmonic frequencies, if harmonic components are present in their fixed voltages. Also, nonlinear loads such as transformers, static loads, UPS, chargers/converters, Static Var Compensators (SVCs), and VFDs are modelled as a harmonic current source in ETAP.

To model a nonlinear component as a harmonic current source, an appropriate harmonic current library via the library button and harmonic library quick pick editor at the harmonic page of that component is selected. Fig. 3.19 gives the harmonic page of a static load as nonlinear load.

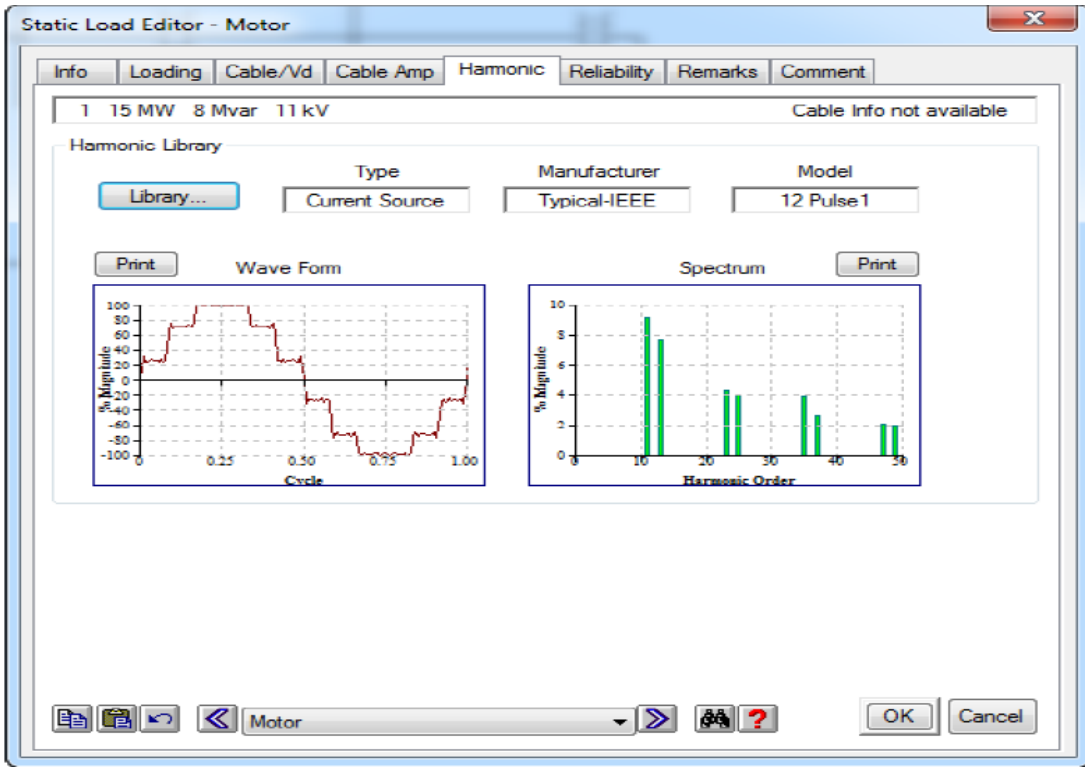

Fig. 3.19 Static Load Editor in ETAP

3.4.5 Harmonic Elimination in ETAP

Presently, ETAP provides six filters adopted in the power industry for harmonics mitigation. These are: By-pass filter, high-pass filter (damped), high-pass (undamped), single tuned filter, 3rd order damped filter and 3rd order C-type filter. A filter sizing program is also available in the harmonic editor for the single tuned filter type, with which users can optimise the filter parameters based on different installation or operation criteria. Fig. 3.20 shows a dialog box of the harmonic filter editor in ETAP.

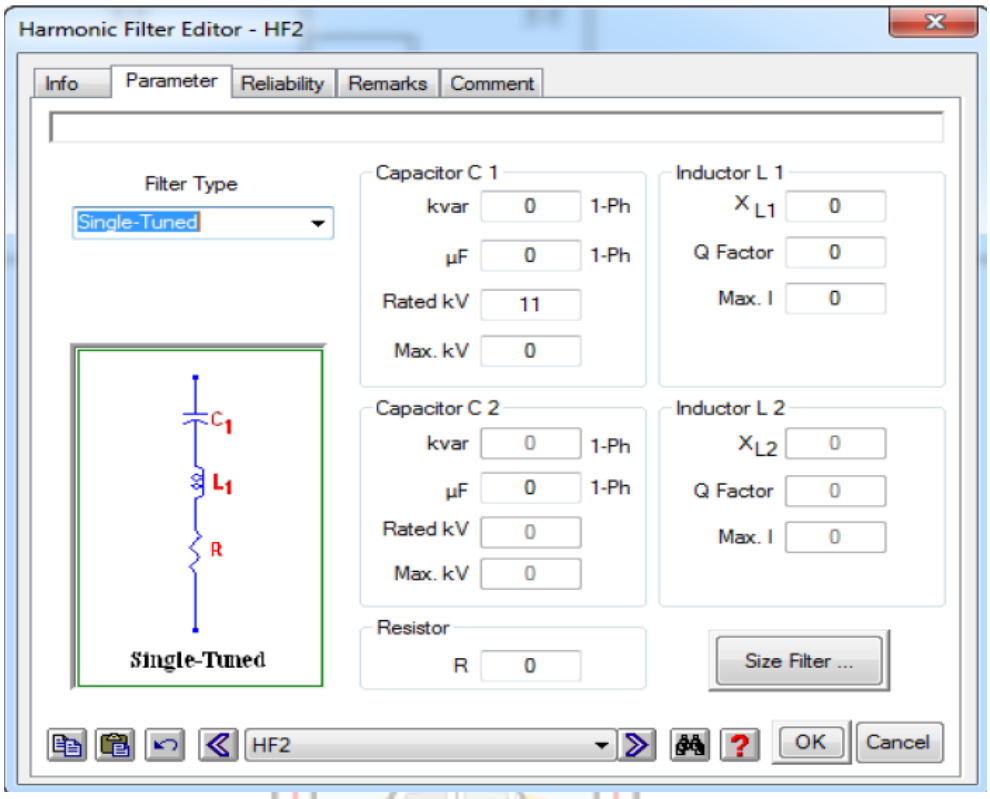

Fig. 3.20 Harmonic Filter Editor

3.5 Summary of Chapter

Seventeen (17) distribution substations on the electrical distribution network were monitored and evaluated at the University of Cape Coast. A single line diagram of the high tension network was obtained to gain perspective of distribution arrangement of the distribution network and subsequently to locate the point of common coupling in line with the IEEE 519 harmonic standard.

Load tables were created and analysed for every physical infrastructure on the University campus to theoretically ascertain the harmonic-producing trends of each facility occasioned by the presence of nonlinear loads.

Facilities with different equipment from the anticipated loads of an academic facility, labelled as “special loads”, were further monitored to establish their contribution to the overall disturbances and to gain insight into the harmonic attenuation or cancelling effects of the loads.

An IEC 61000 harmonic series-compliant power analyser was installed for harmonic

monitoring. The “very short” time duration method was employed based on the considerations that the prevailing conditions that characterised the variable nature of harmonic levels were fairly stable. This makes measurements over a single day adequate to capture every significant level of harmonic disturbances.

The recorded data were downloaded and the outcomes of the analyses in relation to its economic implications are presented in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results and discussions of the research. Field study and simulation results obtained from harmonic measurement using PQA and harmonic analysis using ETAP software as indicated in the preceding chapter are further analysed, represented graphically and interpreted. Other pertinent numerical values pertaining to these data are provided in Appendix C and Appendix D. The economic analysis of harmonic disturbances impact at the University of Cape Coast is also discussed.

4.2 Results

Two results are presented. Results obtained from a harmonic field study conducted at PCCs located at 16 substations including 5 special installations identified and results obtained from ETAP simulations of the modelled UCC distribution network.

4.2.1 Results for Harmonic Field Study at PCCs Located at the 16 Distribution Substations and at 5 Identified Special Installations

Summary of field study results are presented in Table 4.1 and Table 4.2 for the main PCCs and special installation PCCs respectively. This captures the 99th percentile values of THD_V and THD_I as specified by the very short time measuring method prescribed by the IEEE 519-2014 Standard. The bolded values in Table 4.1 and Table 4.2 are those which did not violate the limits set by the harmonic standard.

Fig. 4.1 and Fig. 4.2 show the waveforms of THD_I and THD_V respectively at the Auditorium PCC, while their corresponding harmonic spectra up to the 15th harmonic order are displayed in Fig. 4.3 and Fig. 4.4. The results for the remaining 15 substations in addition to 5 special installations are provided by Fig. C1 to Fig. C80 in Appendix C.

Table 4.1 Summary of Field Results on Three Phase System at Main PCCs

Location of Main PCCs	99th Percentile Values of Current and Voltage THD (%)					
	THD_I			THD_V		
	A1	**A2**	**A3**	**V1**	**V2**	**V3**
Auditorium	14.5	18.7	24.3	13.0	**6.8**	**9.5**
Atlantic	70.5	34.2	34.8	**1.6**	**1.6**	**1.5**
Science	9.8	**7.7**	11.2	**1.9**	**2.4**	**1.5**
Control Station	8.5	9.2	10.1	**1.7**	**1.5**	**1.5**
CoDE	10.4	**7.9**	12.0	**2.3**	**2.2**	**2.4**
SRC/Medical	11.2	11.2	10.0	**1.5**	**1.6**	**1.6**
Library	**6.3**	**6.7**	**7.4**	**1.9**	**1.5**	**1.4**
Northern	10.2	8.6	10.0	**2.9**	**2.5**	**2.6**
Casford	18.4	16.0	12.3	**1.4**	**1.9**	**1.6**
Hilltop	**7.3**	**6.6**	**7.6**	**1.1**	**1.1**	**1.1**
Superannuation	22.9	16.6	24.6	**1.7**	**1.5**	**1.5**
Ghana Hostels	21.9	24.4	68.4	**1.8**	**2.1**	**1.7**
Southern	17.9	31.3	23.6	**2.7**	**2.2**	**2.6**
Valco-Trust	9.8	9.6	6.9	**1.5**	**1.6**	**1.4**
Tech Village	8.0	**7.2**	8.5	**2.4**	**1.6**	**1.7**
UCC Filling St.	17.0	11.7	28.1	**1.9**	**1.7**	**1.9**

Table 4.2 Summary of Field Results obtained from Special Installations PCCs

Location of Special Installation PCCs	99th Percentile Values of Current and Voltage THD (%)					
	THD_I			THD_V		
	A1	**A2**	**A3**	**V1**	**V2**	**V3**
Central Administration	26.8	261.9	82.9	18.6	52.8	85.3
University Hospital	17.0	14.4	20.7	**2.4**	**1.6**	**1.7**
University Press	39.2	28.4	25.9	**2.5**	**2.0**	**2.2**
ICT Centre	32.6	27.6	26.8	15.2	23.2	8.0
Streetlights	16.7	15.8	20.4	**2.5**	**2.0**	**2.2**

Table 4.3 Summary of Averages for Field Results on Three Phase System at Main PCCs

Location of Main PCCs	Average THD_I (%)	Average THD_V (%)
Auditorium	19.17	9.77
Atlantic	46.50	1.57
Science	9.57	1.93
Control Station	9.27	1.57
CoDE	10.10	2.30
SRC/Medical	10.80	1.57
Library	6.80	1.60
Northern	9.60	2.67
Casford	15.57	1.63
Hilltop	7.17	1.10
Superannuation	21.37	1.57
Ghana Hostels	38.23	1.87
Southern Substation	24.27	2.50
Valco-Trust	8.77	1.50
Tech Village	6.80	1.60
UCC Filling St.	18.93	1.83
Average THD	**16.43**	**2.29**

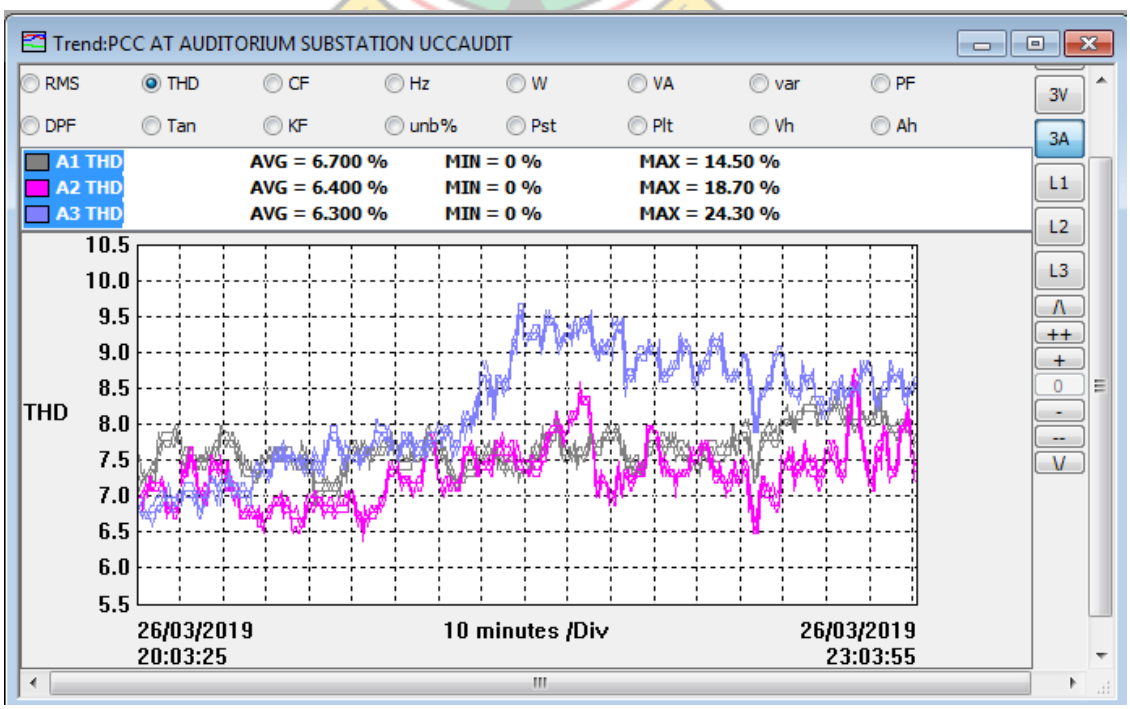

Fig. 4.1 Waveforms of THD_I at the Auditorium PCC

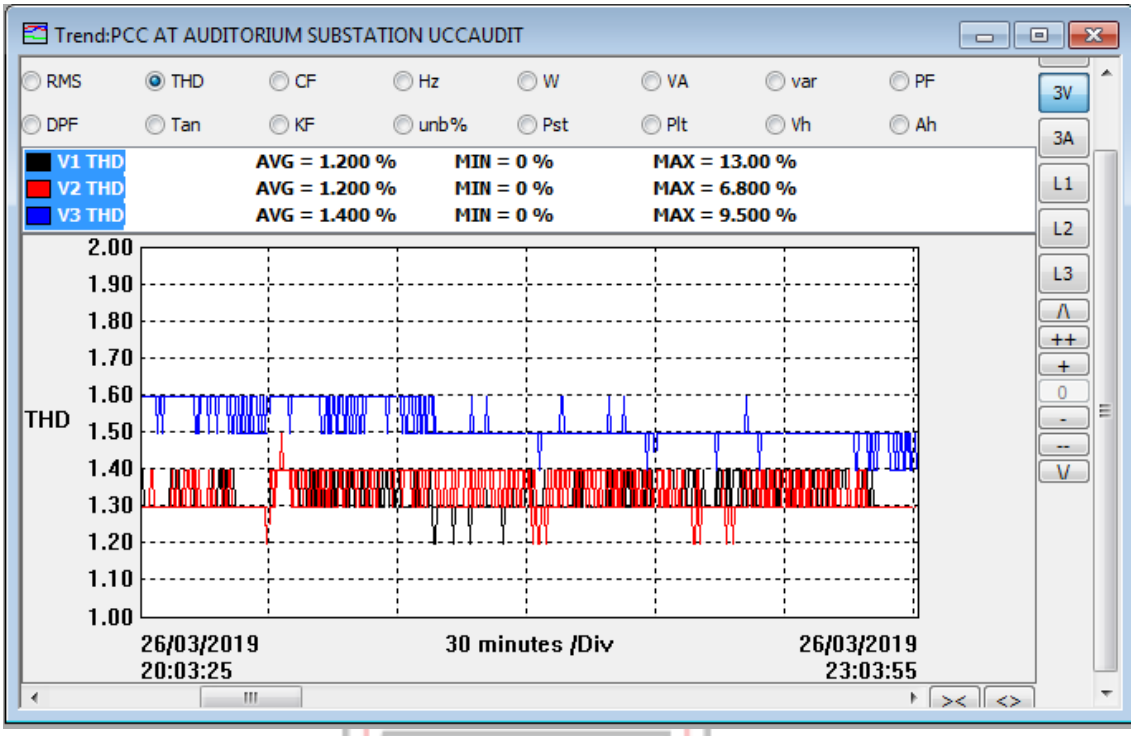

Fig. 4.2 Waveforms of THDv at the Auditorium PCC

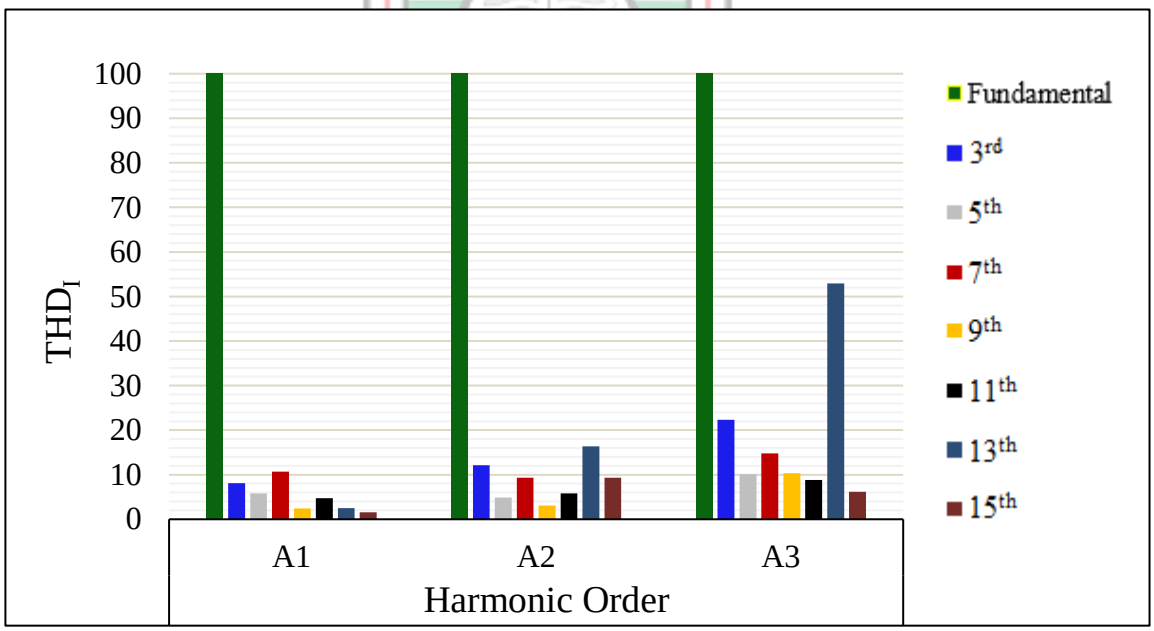

Fig. 4.3 THDI Harmonic Spectrum for Auditorium PCC

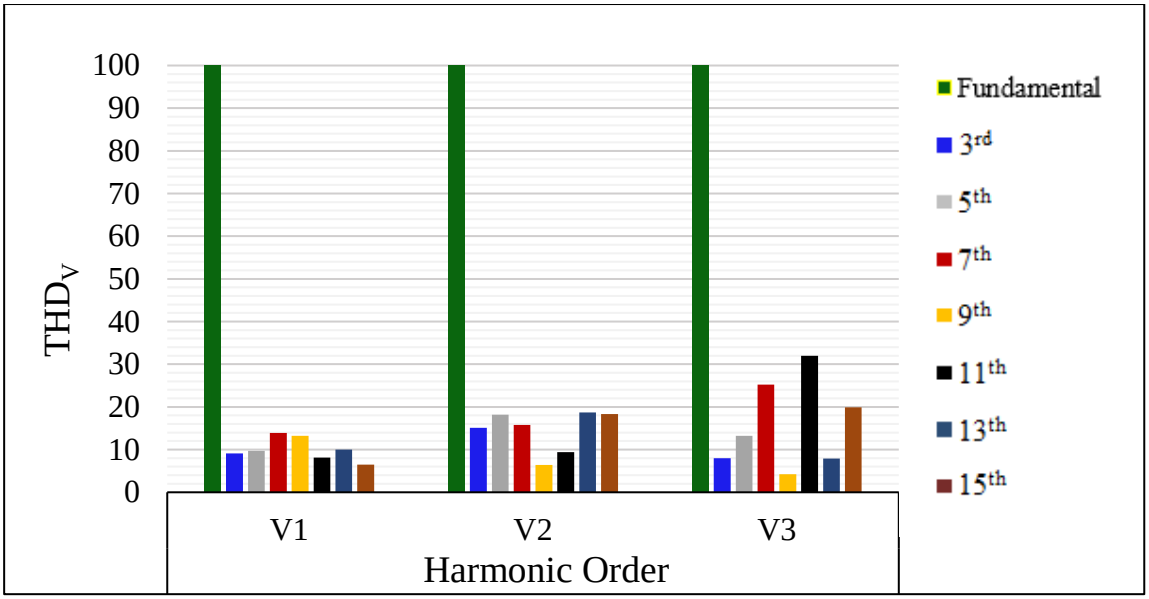

Fig. 4.4 THDv Harmonic Spectrum for Auditorium PCC

4.2.2 Results from Harmonic Analysis and Simulation Using ETAP Software

Harmonic spectrum and waveforms of 8 PCCs and 9 PCCs obtained from simulation were plotted at a time to offer clarity. Harmonic spectrum and their respective waveforms of 8 LV buses and 9 LV buses with filters switched OFF are depicted in Fig. 4.5 to Fig. 4.8. Similarly, the harmonic spectrum and waveforms of 8 LV buses and 9 LV buses with filters switched ON are dpicted in Fig. 4.9 to Fig. 4.12

The modelled single line diagram of UCC distribution network depicted in Fig. D1 of Appendix D was used to perform the harmonic and load flow analysis. The load flow analysis helped to determine the power rating and power factor when sizing the filters. Fig. D2 to D4 in Appendix D depict the modelled single line diagrams for both load flow and harmonic analysis displaying the simulation results.

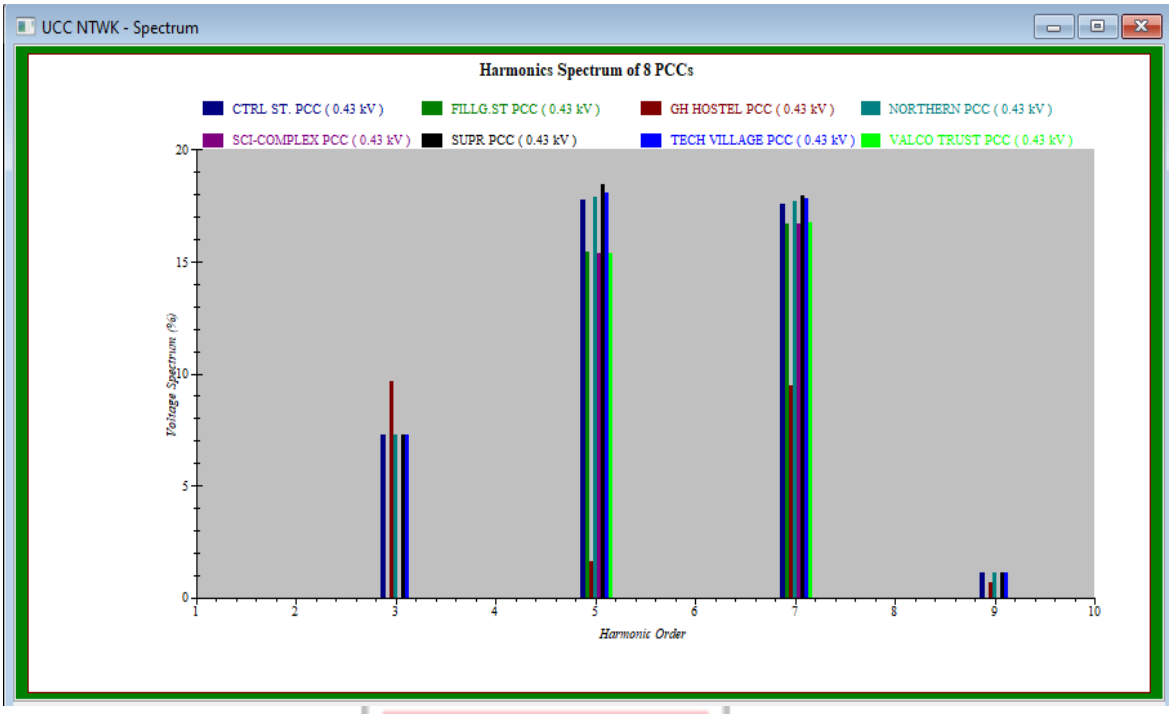

Fig. 4.5 Harmonic Spectrum of Eight (8) LV Buses with Filters Switched-OFF

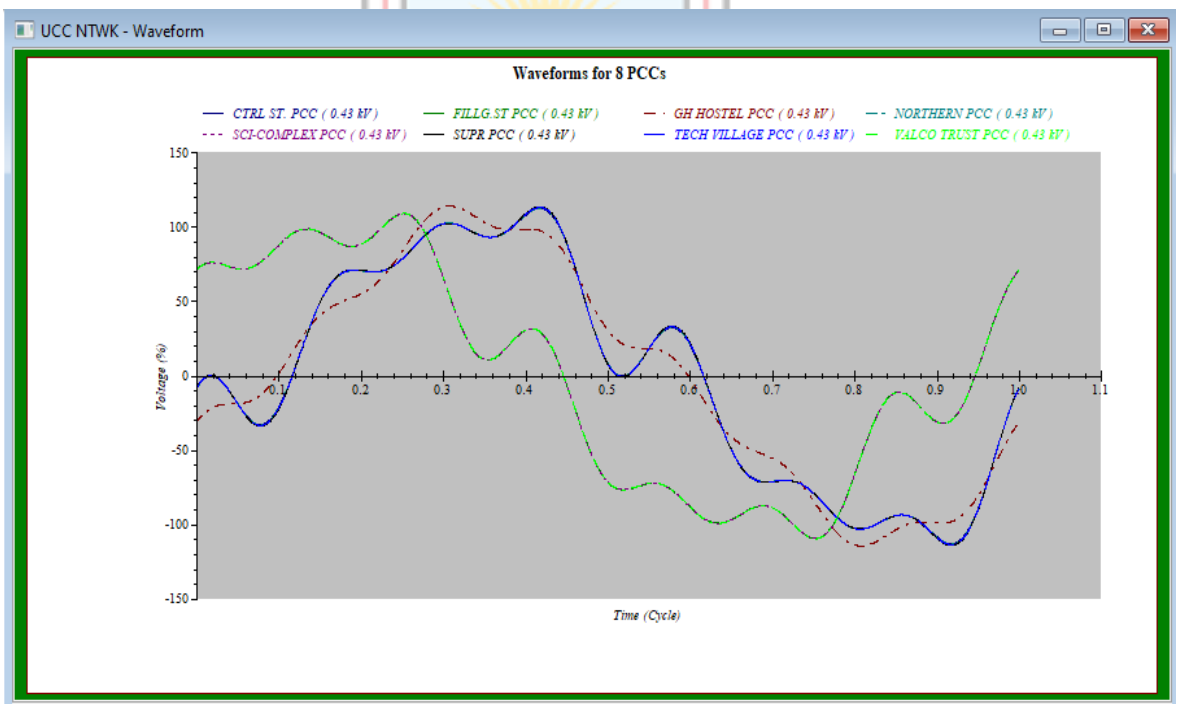

Fig. 4.6 Waveforms of Eight (8) LV Buses with Filters Switched-OFF

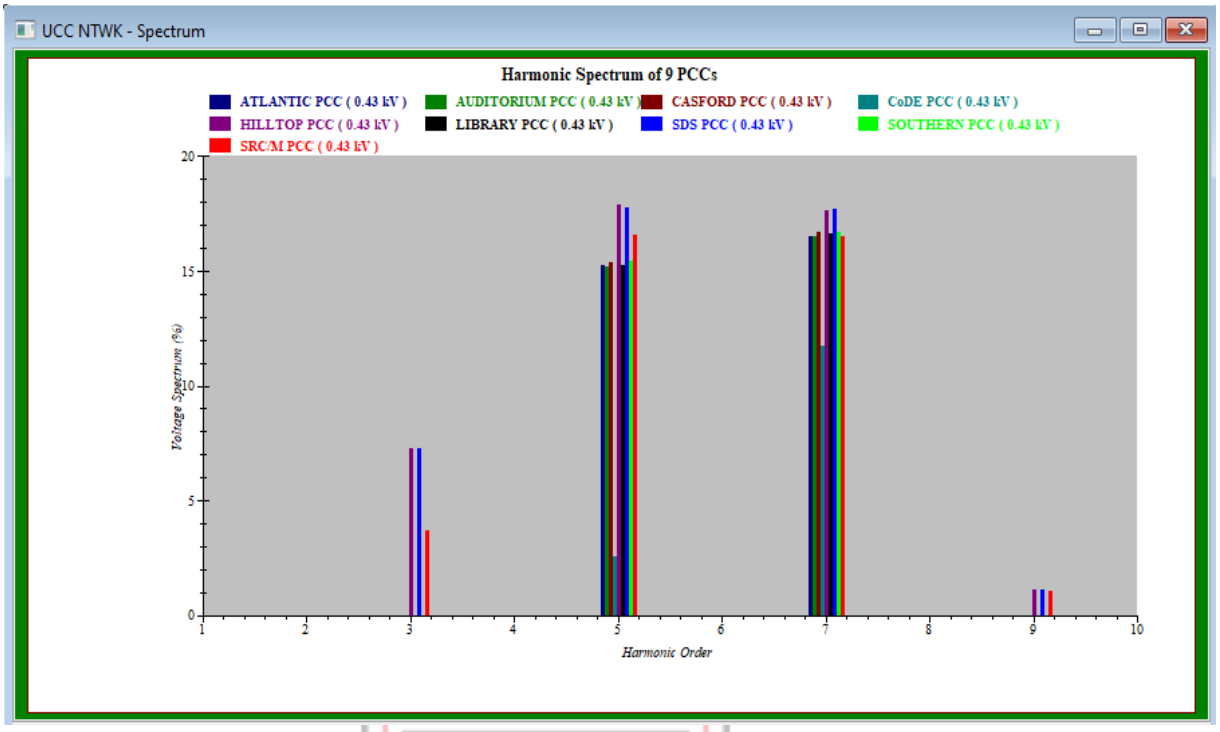

Fig. 4.7 Harmonic Spectrum of Nine (9) LV Buses with Filters Switched-OFF

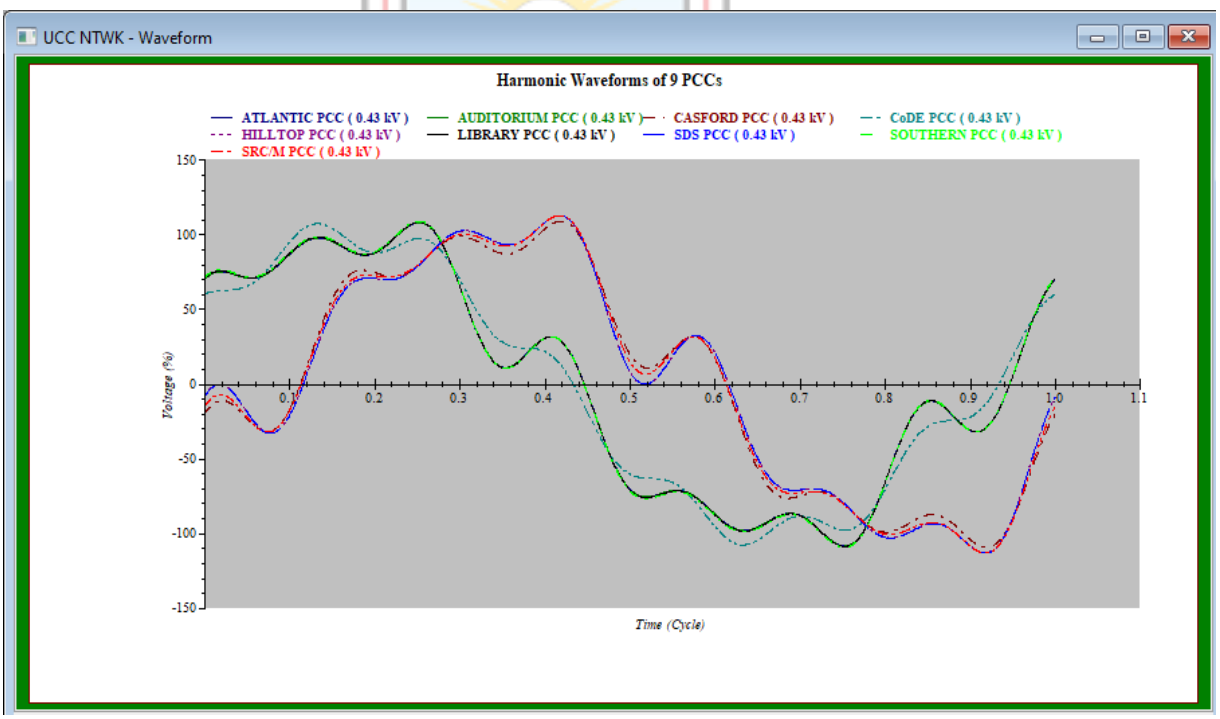

Fig. 4.8 Waveforms of Nine (9) LV Buses with Filters Switched-OFF

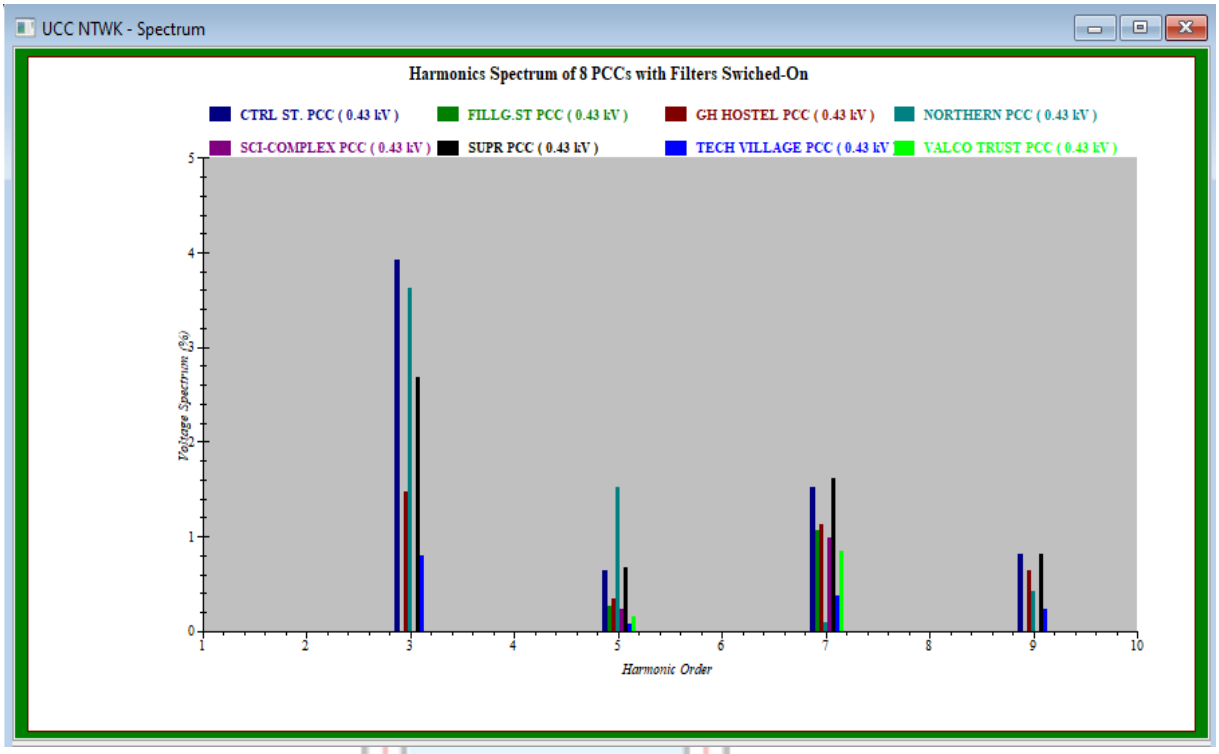

Fig. 4.9 Harmonic Spectrum of Eight (8) LV Buses with Filters Switched-On

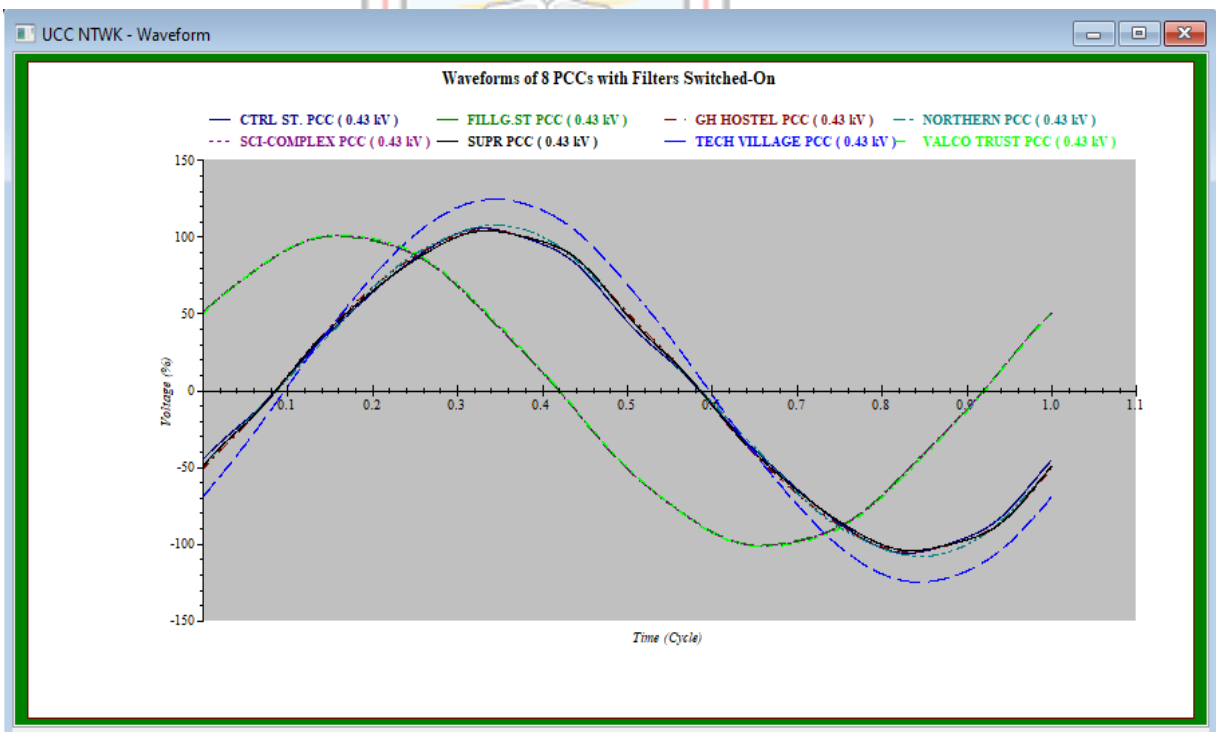

Fig. 4.10 Waveforms of Eight (8) LV Buses with Filters Switched–On

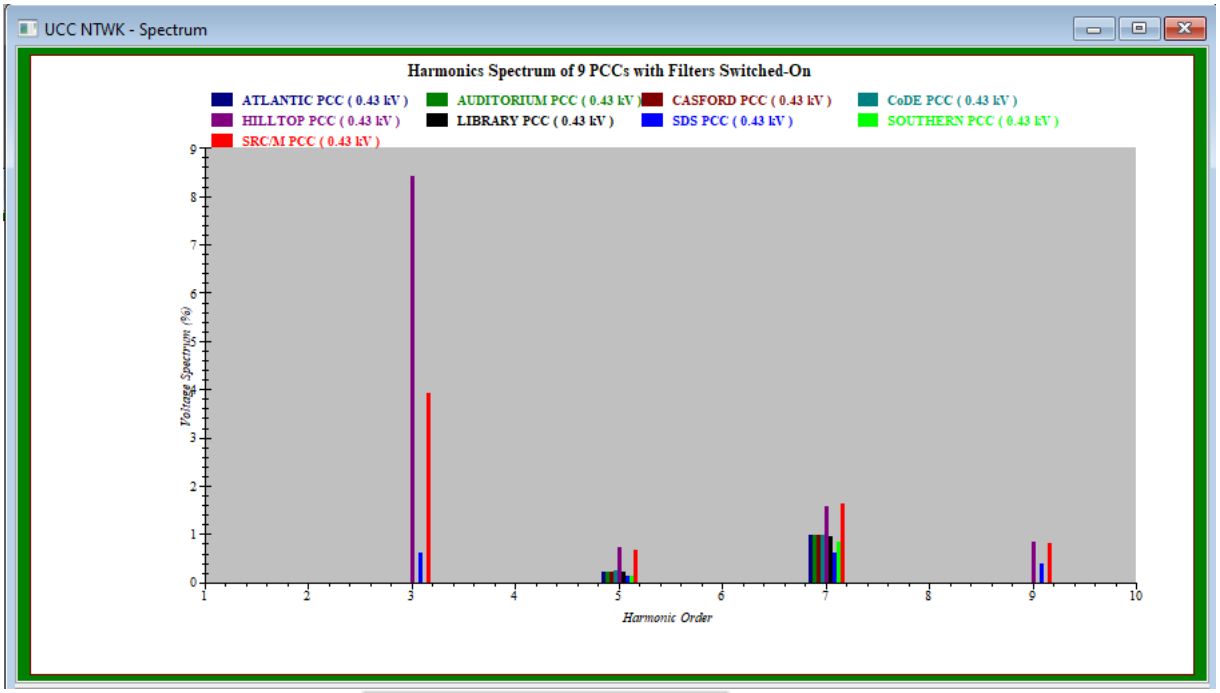

Fig. 4.11 Harmonic Spectrum of Nine (9) LV Buses with Filters Switched-On

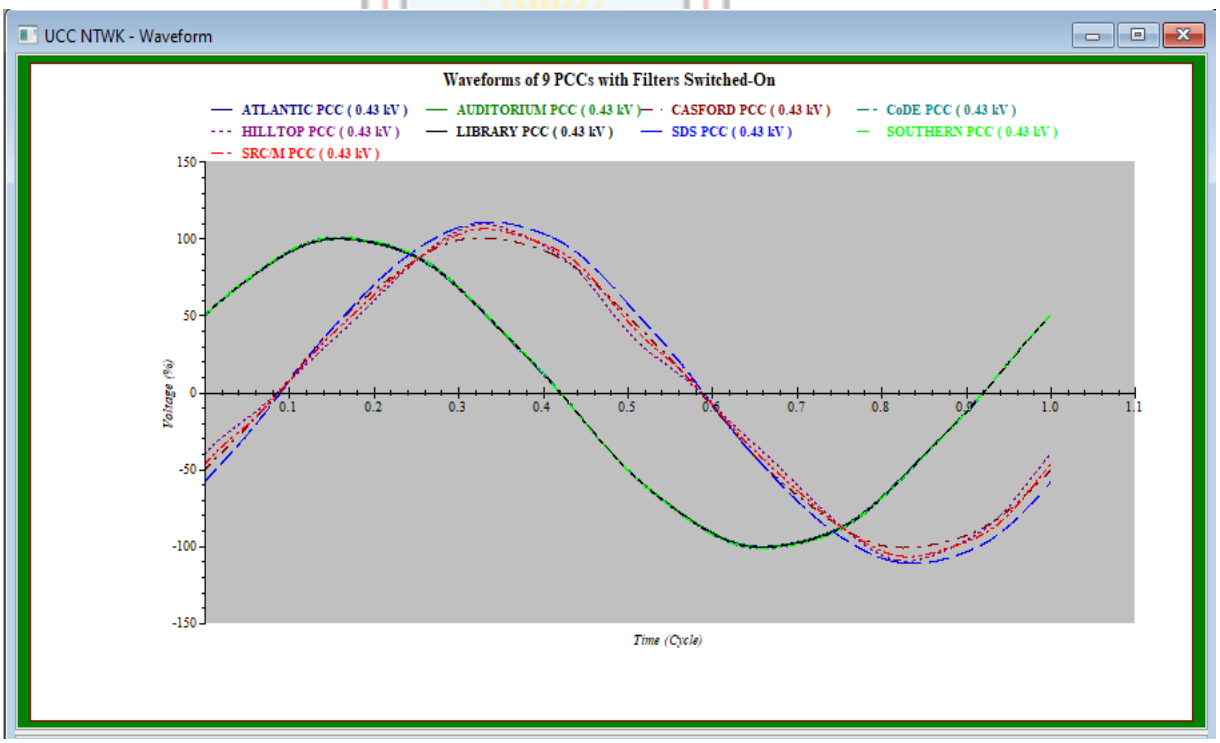

Fig. 4.12 Waveforms of Nine (9) LV Buses with Filters Switched-On

4.3 Discussions

Discussions of the results are presented in two folds. That is, discussions of the field study results and ETAP software simulation results.

4.3.1 Discussion of Results from Harmonic Field Study

The field results obtained are weighted against the bus voltages of the PCCs and SCR values calculated for each LV bus at the PCCs to determine the respective voltage and current distortion limits prescribed in Table 3.3 and Table 3.4 by IEEE 519-2014 harmonic standard.

In accordance with current distortion limits of Table 3.4, field results for THD_I obtained for Auditorium substation in Fig. 4.1 clearly are in violation of the prescribed limits. The 99th percentile (maximum) values recorded exceeds 8%. Similarly, THD of voltage harmonics results for Auditorium substation depicted in Fig. 4.2 marginally exceeded the recommended 12% limit stated in Table 3.3.

Fig. 4.3 and Fig. 4.4 illustrates the respective harmonic spectrums for THD_I and THD_V levels of the individual harmonic order up to the 15th order where significant values were recorded for Auditorium substation . The successive harmonics recorded from the 17th order to the 50th order were less pronounced and as such not included in the bar charts.

The results obtained from the monitoring at Auditorium, Atlantic, Science, Control Station, CoDE, SRC/Medical, Library, Northern, Casford, Hilltop, Superannuation, Ghana Hostels, Southern, Valco-Trust, Tech Village and Filling Station substations including results for Special Installations are summarised in Table 4.1 and Table 4.2. The voltages and currents waveforms and the respective harmonic spectrums for only Auditorium substation are shown in Fig. 4.1 to Fig. 4.4. The waveforms and their corresponding harmonic spectrums for the remaining substations are provided in Appendix C where it can be observed that the 3rd, 5th, 7th, 9th, 11th, 13th and 15th harmonics are the dominant harmonic orders which recorded significant values. The other harmonic orders from the 17th to the 50th mostly recorded values of less significance. The calculated average current harmonics distortions on the UCC distribution network from Table 4.3 is 16.43%.

4.3.2 Discussion of Results for ETAP Simulation

The results of the unbalanced load flow and harmonic analysis are displayed on the single line diagrams of Fig. D2 and Fig. D3 of Appendix D. Fig. D4 of Appendix D also shows the results of harmonics analysis with passive filters switched on.

The results similarly show that the harmonics of the 3rd, 5th, 7th and 9th orders are dominant whereas the higher order harmonics from 11th to the 50th presented docile or no values. This is because of the typical harmonic components (nonlinear loads) modelling available in the ETAP software.

Mitigation of harmonics using filters

Upon switching on the filters, in the harmonic load flow study, it can be seen in the modelled single line diagram depicted by Fig. D4 in Appendix D that a significant reduction in the total harmonic distortion was achieved across all buses (PCCs).

A single-tuned passive filter paralleled with other filters singly tuned to a different harmonic order was selected, designed and connected to the PCCs to reduce the harmonics on the modelled network. Table 4.4 shows the levels of THD reduction achieved when filters were connected to the network.

Table 4.4 Summary of Simulation Results with Filters Switched ON and OFF

LV Bus (PCC)	Simulated Results of THD		Filter Tuned Harmonic Order
	Filter OFF	Filter ON	
Auditorium	10.44	1.00	3rd
Atlantic	10.28	1.01	3rd
Science	10.06	0.99	5th
Control Station	13.88	4.25	3rd , 5th
CoDE	10.31	1.01	7th
SRC/Medical	14.92	4.20	3rd , 5th
Library	10.27	0.98	5th
Northern	15.81	3.77	3rd , 5th, 7th
Casford	9.82	0.99	3rd
Hilltop	13.50	8.54	5th, 7th
Superannuation	14.85	3.21	3rd , 5th

Table 4.4 Cont'd

LV Bus (PCC)	Simulated Results of THD		Filter Tuned Harmonic Order
	Filter OFF	Filter ON	
Ghana Hostels	13.27	1.91	3rd , 5th
Southern	9.80	0.84	5th
Valco-Trust	9.25	0.84	5th
Tech Village	10.47	0.74	5th, 7th
UCC Filling St.	9.46	1.09	5th
SDS	13.33	0.88	3rd , 5th

A complete generated report of the harmonic analysis from ETAP, detailing 2-winding transformer input data, branch connections, harmonic library, bus input data, cable input data, filter input data, and harmonic source from library is provided in the Appendix E.

4.4 Economic Analysis of Harmonic Disturbances at the University of Cape Coast

The economic consequences of harmonics are occasioned by many factors including derating of equipment, premature ageing of electrical equipment, misoperation of electrical systems, reduced power factor, etc. In this thesis, cost of harmonics due to reduced equipment lifespan of selected loads and cost of harmonic disturbances due to reduced true power factor are considered.

4.4.1 Cost of Harmonics due to Reduced Equipment Lifespan

Table 4.5 gives the estimated quantities of the selected harmonic loads replaced in 2017, 2018 and 2019 and total associated costs for academic and administrative facilities only. The selected harmonic loads at the University are evaluated in this thesis due to the rate of repairs and replacements performed on them. The harmonic loads include: 23 W CFLs, 100 W LED floodlights, 28 W electronic ballasts, 2.5 μF fan capacitors, 45 μF A/C capacitors, power supply units for computers and circuit boards for UPS.

Table 4.5 Annual Cost Estimation of Selected Harmonic Loads Replacement

Selected Harmonic Loads	Year of Replacement								
	2017			2018			2019		
	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)	Unit Cost (Gh¢)	Qty	Total Cost (Gh¢)
CFLs	11.00	243	2673.00	12.50	176	2200.00	13.20	210	2772.00
100 W LED Lights	655.00	54	35370.00	699.00	54	37746.00	720	42	30240.00
28 W Electronic Ballasts	25.00	874	21850.00	26.50	652	17278.00	29.50	785	23157.50
250 W Choke	70.53	268	18902.00	77.25	200	15450.00	80.34	165	13256.10
2.5 µF Fan Capacitor	10.50	284	2982.00	12.10	165	1996.50	15.40	183	2818.20
45 µF A/C Capacitors	42.00	68	2856.00	48.00	71	3408.00	56.00	64	3584.00
PC PSUs	230.00	87	20010.00	246.00	52	12792.00	288.00	56	16128.00
800 VA UPS	505.00	175	189375.00	103.00	308	216524.00	287.00	150	91500.00
Total			**193 018.00**			**166 795.00**			**183 455.80**

Based on the assumption that the service life of single phase loads operated in harmonic environment exceeding 10% THD_I are reduced by 32.5% (Anon., 2018a; Ajenikoko and Ojerinde, 2015), this thesis therefore safely assumes that 32.5% of the replacements effected on the selected loads are occasioned by the adverse effects of harmonics disturbances in the University since the average total harmonic distortion is found to be 16.43% THD_I as depicted in Table 4.3. The selected harmonic loads were expected on the average to be in service for the stated duration depicted in Table 2.2 before attaining obsolescence.

Therefore in 2017,

cost due to harmonics = 32.5% of total cost of replacement in 2017

$$= \frac{32.5}{100} \times 193,018.00$$

$$= 62,730.85$$

This implies that the University incurred Gh¢62 731.00 in 2017 as avoidable cost due to harmonics. Similar computations revealed that, Gh¢54 208.20 and Gh¢59 623.10 for 2018 and 2019, respectively, were lost due to frequent replacement exacerbated by harmonics.

4.4.2 Cost Savings of Improved True Power Factor by Harmonics Mitigation

Power factors, which are usually indicated on utility bills, are not the actual or true power factors but rather displacement power factors. The distortion power factor obtained from the harmonic field measurement indicates an average of 0.944 across all PCCs as shown in Table 4.6. Table 4.7 shows a summary of 2017 SLT billing elements recorded for UCC energy consumption at an energy charge of Gh¢0.7809. However, the Contracted kVA Demand for UCC is 2109.5.

Table 4.6 Field Results for Measured Power Factors at Main PCCs

Location of Main PCC	**Displacement Power Factor (DPF)**	**Distortion Power Factor (δPF)**	**True Power Factor (TPF)**
Auditorium	0.989	0.967	0.854
Atlantic	0.987	0.864	0.896
Science	0.992	0.908	0.927
Control Station	0.994	0.935	0.879
CoDE	0.996	0.884	0.985
SRC/Medical	0.998	0.989	0.981
Library	0.997	0.983	0.954
Casford	0.988	0.957	0.924
Hilltop	0.985	0.935	0.927
Northern	0.991	0.941	0.930

Table 4.6 cont'd

Location of Main PCC	Displacement Power Factor (DPF)	Distortion Power Factor (δPF)	True Power Factor (TPF)
Superannuation	0.992	0.939	0.959
Ghana Hostels	0.988	0.943	0.932
Southern	0.989	0.967	0.956
Valco-Trust	0.985	0.941	0.927
Tech Village	0.993	0.965	0.958
Filling Station	0.979	0.958	0.938
Average Power Factors Measured at Main PCCs	**0.991**	**0.944**	**0.935**

Table 4.7 Summary of Registered Power Components of Monthly Electricity SLT Bill for UCC in 2017

Month	Active Energy Consumed (kWh)	Apparent Energy Consumed (kVAh)	Maximum Demand (kVA)	Displacement PF (DPF)	Distortion PF (δPF)	True PF (TPF)
Jan	513887.87	529411.00	1779.11	0.971	0.955	0.927
Feb	680594.96	695640.00	2119.16	0.978	0.948	0.928
Mar	818970.91	830763.00	2083.00	0.986	0.942	0.929
Apr	763126.00	775512.00	2099.00	0.984	0.945	0.930
May	744062.57	755843.00	2010.73	0.984	0.946	0.931
Jun	545832.18	557596.00	1593.73	0.979	0.952	0.932
Jul	507789.66	519783.00	1291.90	0.977	0.955	0.933
Aug	458425.89	470685.00	1170.57	0.974	0.958	0.933
Sep	640079.41	651703.00	1632.91	0.982	0.951	0.934
Oct	796549.44	807790.00	1936.63	0.986	0.948	0.935
Nov	806671.03	816848.81	2016.99	0.988	0.948	0.936
Dec	686504.00	698015.00	1717.00	0.984	0.953	0.937

Other incidental charges, such as demand billing factor, monthly service charge, government subsidy, government levy, street lighting and taxes (VAT and NHIL), which appear every month on the SLT bill, are unaffected variables and as such not included in the subsequent analysis.

The distortion power factor is determined from Equation (4.1) and relates to the true power factor and displacement power factor by Equation (4.2) as follows:

$$\delta PF = \frac{1}{\sqrt{1+THD^2}} \tag{4.1}$$

$$TPF = DPF \times \delta PF \tag{4.2}$$

where, TPF = true power factor

DPF = displacement power factor

δPF = distortion power factor

To reduce the THD_I from the recorded average of 16.43% to 8% (8% being the recommended limit for daily 99th percentile monitoring method for harmonics orders up to 11th harmonics), the distortion PF must be improved from an average of 0.9424 to 0.9968 in the distribution system.

A distortion power factor ≥ 0.9968 suggests a THD of 8% or less. Therefore, a multiplier K can be derived by plugging 8% into Equation (4.1) as follows:

$$\delta PF = \frac{1}{\sqrt{1+(0.08)^2}} = 0.9968$$

But,

$$K = \frac{1}{\delta PF} \tag{4.3}$$

Hence,

$$K = \frac{1}{0.9968} = 1.003195$$

Multiplying K to the displacement power factors in Table 4.7 yields the improved values of new true power factor (New TPF) in Table 4.8 and the corresponding potential cost savings of Gh¢690 360.43 calculated in Table 4.9.

Table 4.8 Calculated Consumption Elements of Monthly Electricity Bill for UCC in 2017

Month	Energy Charge @ 0.7809	Calculated Reactive Energy (kVArh1)	New True Power Factor (New TPF)	Apparent Energy Consumed ($kVAh_2$)	Reactive Energy Consumed ($kVArh_2$)	$kVArh_{(diff)}$ ($kVArh_1$-$kVArh_2$)
Jan	401295.04	127260.61	0.974	500413.63	120053.52	7207.10
Feb	531476.60	143894.09	0.981	668002.78	132770.67	11123.43
Mar	639534.38	139476.92	0.989	809925.67	122738.29	16738.63
Apr	595925.09	138049.16	0.987	753337.07	123421.41	14627.75
May	581038.46	132926.79	0.988	734805.98	118475.13	14451.67
Jun	426240.35	113932.13	0.982	536023.69	104896.50	9035.63
Jul	396532.95	111013.64	0.980	497658.01	102984.72	8028.92
Aug	357984.78	106724.28	0.977	447912.60	99905.76	6818.53
Sept	499838.01	122536.32	0.985	630671.71	110969.19	11567.13
Oct	622025.46	134289.51	0.989	787974.86	117830.13	16459.39
Nov	629929.41	128545.08	0.991	799165.26	110817.45	17727.63
Dec	536090.97	126242.62	0.987	677340.04	113307.94	12934.68

Table 4.9 Calculated Energy Savings from Monthly Electricity Bill for UCC in 2017

Month	New True Power Factor (New TPF)	$kVArh_{(diff)}$ Converted to kWh	Energy Charge @ 0.7809 (GH¢)
Jan	0.974	30849.91	24 090.69
Feb	0.981	57019.74	44 526.71
Mar	0.989	111688.43	87 217.49
Apr	0.987	90444.75	70 628.31
May	0.988	90761.20	70 875.42

Table 4.9 Cont'd

Month	New True Power Factor (New TPF)	$kVArh_{(diff)}$ Converted to kWh	Energy Charge @ 0.7809 (GH¢)
Jun	0.982	47017.19	36 715.72
Jul	0.980	39588.42	30 914.59
Aug	0.977	31287.38	24 432.32
Sept	0.985	66720.17	52 101.78
Oct	0.989	111267.93	86 889.13
Nov	0.991	129044.31	100 770.70
Dec	0.987	78367.94	61 197.52
Annual Cost Savings for 2017			**690 360.40**

With similar iterations where 8% THD_I is assumed to be the average harmonic levels in the distribution system, the SLT bills for 2018 and 2019 yielded potential cost savings of Gh¢ 790 276.65 and Gh¢ 1 460 575.27, respectively.

Summary of registered power components of monthly electricity SLT bill, calculated consumption elements of monthly electricity bill and calculated energy savings from monthly electricity bill for 2018 and 2019, respectively, are given in Appendix F.

The estimated average annual cost of harmonic disturbances as shown in Table 4.10 is Gh¢ 1 161 493.71.

Table 4.10 Estimated Average Annual Cost of Harmonic Disturbances

Year	Estimated Annual Cost of Replacement of Selected Harmonic Loads (Gh¢)	Cost Savings of Harmonic Mitigation (Gh¢)	Estimated Total Cost of Harmonic Disturbances (Gh¢)
2017	193 018.00	690 360.40	883 378.40
2018	166 795.00	790 276.65	957 071.65
2019	183 455.80	1 460 575.27	1 644 031.07
Average Annual Cost of Harmonic Disturbances			**1 161 493.71**

4.4.3 Cost-Benefit of Harmonic Mitigation

The cost-benefit analysis attempts to draw economic comparisons between the cost effectiveness of implementing harmonic mitigation schemes at various supply points of the University and the attendant (avoidable) costs of harmonic induced reduction in equipment service life and reduction of the net true power factor of the system where the harmonic distortions are not curbed.

Proposed mitigation equipment

Tuned paralleled passive filters are proposed based on their performance and effectiveness in reducing the resident harmonics as shown by the simulation results of Fig. 4.9 to Fig. 4.12 including other considerations such as lowest cost compared with other harmonics solutions, simplicity of design with fewer components and additional power factor correction. Typical parameters for simulation purposes were selected based on the maximum line currents and the overall kVAr ratings. Since the harmonics of concern are of lower frequency, a high Q factor of 50 at a rated voltage of 0.433 kV is selected with the typical tuning factors as indicated in Table 4.11.

Table 4.11 Parameters for Paralleled Single Tuned Passive Filters

Harmonic Order	Tuning Order	Parameters of Capacitor, C			Parameters of Inductor, L		
		kVAr	μF	V_C (kV)	xL (Ω)	I_L (A)	I_{Max} (A)
3rd	2.95	45.42	771.1	0.629	0.4744	155.1	200
5th	4.81	45.42	771.1	0.526	0.1784	138.7	180
7th	6.73	45.42	771.1	0.492	0.0911	133.8	180
9th	8.66	45.42	771.1	0.472	0.0551	127.3	150
11th	10.59	36.33	616.8	0.466	0.0481	103.8	150
13th	12.51	36.33	616.8	0.454	0.0334	95.69	100
15th	14.44	32.70	555.2	0.451	0.0275	85.78	80

Estimated cost of harmonic mitigation equipment

The pricing obtained for the mitigation equipment is typical and based on available market price at the time of the research (Anon., 2020d; Loucks, 2005). Table 4.11 gives a summary of estimated costs of harmonic mitigation equipment.

The value of kVAr required was typically selected based on the maximum THD_I measured at the PCC under consideration and not on the reactive compensation requirement of the system. This is due to the fact that, a danger of overloading may exists when the need for compensation is low and the production of harmonics is dominant within the distribution system. The selection is also done with recourse to the application data of the filter to be applied and expected load current on a particular circuit branch.

Table 4.12 Estimated Cost of Harmonic Mitigation Equipment

Location of PCC	**Transformer Capacity (kVA)**	**Max THD_I (%)**	**Max Load (A)**	**kVAr Required**	**Cost @ $ 120/kVar**
Auditorium	1000	24.30	1013	650	78000
Atlantic	1000	70.50	684	650	78000
Science	1000	11.20	1051	650	78000
Control Station	1000	10.10	208	650	78000
CoDE	1000	12.00	714	650	78000
SRC/Medical	1000	11.20	432	650	78000
Library	1000	7.40	812	650	78000
Northern	750	10.20	247	400	48000
Casford	750	18.40	171	400	48000
Hilltop	630	7.60	264	315	37800
Superannuation	500	24.60	487	270	32400
Ghana Hostels	500	68.40	357	270	32400
Southern	500	31.30	482	270	32400
Valco-Trust	500	9.80	296	270	32400
Tech Village	100	7.40	72	80	9600
Filling Station	50	17.00	38	30	3600
Total Cost of Mitigation Equipment					**$ 822 600.00**

Economic evaluation of cost of harmonic disturbances

The cost evaluation of harmonic disturbances at the University is estimated at an annual average of Gh¢1,161,493.71 as indicated in Table 4.10. This comprises losses due to reduced service life of equipment and losses due to reduced true power factor of the UCC distribution network. A 25 years life expectancy is assumed for the harmonic mitigating equipment at a total cost of $822,600.00.

The total present values of benefits and cost stand at Gh¢7,122,377.98 and Gh¢4,386,349.98, respectively; giving a NPV of Gh¢2,736,028.00. The NPV yielded a positive figure, suggesting that embarking on a harmonic mitigation venture is worthwhile if considered. Details of economic analysis calculations are shown in Appendix G.

The rule of thumb is to assume a slightly higher figure than the stated inflation for a discount factor. Therefore with inflation of 7.90% (Anon., 2020b), a discount factor of 8% is reasonably selected and a Discounted Payback Period (DPBP) of 6.23 years was calculated as follows.

From Table G2 in Appendix G, the first positive discounted Present Value (PV) occurred at year 7.

Therefore,

$$\text{Discounted Pay Back Period } (\text{DPBP}) = 7 - \left(\frac{318,268.68}{413,459.34}\right)$$

$$\text{DPBP} = 6.23 \text{ Years}$$

Furthermore, the ratio of discounted total benefits and mitigation cost i.e. the BCR was calculated from Table G3 and Table G4 in Appendix G to be 1.62 as follows:

$$\text{Benefit/Cost Ratio (BCR)} = \frac{\sum \text{Benefit PVs}}{\sum \text{Cost PVs}} \tag{4.1}$$

Therefore,

$$\text{BCR} = \left(\frac{7,122,377.98}{4,386,349.98}\right) = 1.62$$

The project is worth undertaking since the benefit outweighs the cost by 1.62 times.

The import of this indicator is to look at the performance of the mitigation equipment over the 25-year expected lifespan. A BCR greater than 1 means the project is economically viable. Table 4.13 shows the summary of results for the economic analysis.

Table 4.13 Summary of Economic Analysis Results

Economic Indicators	Values
Discount Factor, %	8.00
Inflation, %	7.90
Exchange Rate (US$ to Gh¢)	5.3323
Total Cost of Harmonic Mitigating Equipment, US$	822,600.00
Annual Projected Cost of Harmonic Disturbances, Gh¢	1,161,493.71
Total PVs of Benefits, Gh¢	7,122,377.98
Total PVs of Costs, Gh¢	4,386,349.98
NPV, Gh¢	2,736,028.00
Discounted Payback Period, years	6.23
Benefit/Cost Ratio	1.62

From the sensitivity analysis shown in Table G6 of Appendix G, a 10% worse change is assumed. This is built on the prudence concept of economics, which suggests that an entity must not overstate its revenue, assets and profits but must make provisions for possible losses.

$$\text{NPV} = \sum \text{Present Values } (\text{PVs}) = 563,049.19$$

From Table G6, the first positive discounted present value occurred at year 14

Therefore,

$$\text{DPBP} = 14 - \left(\frac{43,497.30}{109,457.80} \right)$$

$$\text{DPBP} = 13.6 \text{ Years}$$

Comparing the reliability of the assumptions, it can be inferred that NPV is the most significant assumption since a slight increase in other assumptions (cost of investment, discount factor, exchange rate and inflation) and a slight decrease in annual projected cash flow can adversely affect the project.

4.5 Summary of Findings

The summary of findings of this research are presented as follows:

i. Dominant harmonic orders measured on the entire distribution network of the University are the 3rd, 5th, 7th, 11th and 13th harmonic orders; harmonics beyond the 15th order to the 50th order recorded insignificant values except where the transformers were overloaded.

ii. The total distortions measured on the network differ from phase to phase owing to the load imbalance on the lines as is noticed throughout the analysis.

iii. Distortions observed at Special Installations PCCs connected upstream of the distribution network minimally affected the overall distortions observed at the main PCCs. This is noticeable at Library-ICT Centre PCCs and Atlantic-Central Administration PCCs.

iv. High pressure sodium lights employed for street lighting at the University contributed high levels of 3rd harmonics of 13.6%, 12.7% and 11.4% across the three phase system. This makes up an average of 64% of the overall THD_I of 16.7%, 15.8% and 20.4% measured at the Casford PCC.

v. The total harmonic distortions measured on the entire network is at an average of 16.43% with reduced true power factor of 0.935.

vi. The reduced true power factor improved to an average of 0.9987 when the average THD of 16.43% was mitigated with a passive filter to 8%.

vii. Annual cost savings of up to Gh¢1,161,493.71 could be made with mitigation equipment installed at a discounted payback period of 6.23 years.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The increasing use of nonlinear loads has given rise to harmonics problems on electrical distribution systems. The proliferation of these harmonic loads on the electrical distribution systems has unquestionable economic consequences on the overall finances of a University. The rate of replacement of susceptible nonlinear loads has been more frequent in the presence of harmonic distortions including an overall reduction in the true power factor of the system. Thus, warranting investigations into the harmonic effects and the attendant cost implications for a typical University setting.

From the results and discussions, the following conclusions were drawn:

i. The calculated average THD_I over the entire distribution network of 16.43% far exceeded the recommended limits set by the IEEE 519-2014 Standard. This is an indication of the extent of harmonic pollution in the distribution network of the University.

ii. The high THD_I resulted in an increase in the distortion power factor, which is a component of the true power factor. This consequently led to a lowered overall true power factor.

iii. A reduced true power factor for a special load tariff consumer such as the University, meant that large sums of money are lost. The analysis showed that by mitigating the harmonics from an average of 16.43% to 8% leads to a significant savings of up to Gh¢1,161,493.71 per annum.

5.2 Recommendations

The following recommendations are made based on the findings and conclusions drawn from the research conducted:

i. In view of the daunting outlay that must be expended in embarking upon harmonics mitigation, the University should consider, as a matter of policy, to

gradually replace nonlinear loads with harmonics-compliant load types as a way of reducing the overall harmonics in the electrical distribution system.

ii. A reconfiguration of the distribution network, which aims to separate shared buses of nonlinear loads and linear loads, is necessary and should be considered with the nonlinear loads bus connected upstream of the network. This will minimise the overall impacts of harmonics at the main feeder bus and consequently reducing the levels of harmonics distortions.

iii. The use of a tuned paralleled passive filter is recommended for harmonics mitigation as it is less expensive and proved effective in reducing the harmonic distortions to tolerable levels.

5.3 Future Research Work

Future works could tackle the following:

i. Evaluating the effectiveness and cost of Active Harmonic Filters (AHF) employed in the harmonic mitigation for a University electrical distribution system.

ii. Assessing the total harmonic distortion levels of harmonic-compliant nonlinear loads employed on the University distribution network as an alternative to harmonics mitigation.

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APPENDICES

APPENDIX A

SINGLE LINE DIAGRAM FOR 11 kV HIGH VOLTAGE DISTRIBUTION NETWORK FOR UCC

SINGLE LINE DIAGRAM TO BE INSERTED

APPENDIX B

ESTIMATED TOTAL POWER OF ELECTRICAL LOADS FOR PHYSICAL INFRASTRUCTURE AT THE UNIVERSITY OF CAPE COAST

Table B1 Estimated Total Power of Electrical Loads for Alumni Hostel

Load Types	Quantity	Total Power (W)
Lighting	525	13288
Office Equipment	10	2375
Heating	327	624300
Cooling	195	24185
Total Power		**664148**

Table B2 Estimated Total Power of Electrical Loads for Kwame Nkrumah Hall

Load Types	Quantity	Total Power (W)
Lighting	1045	51096
Office Equipment	63	33425
Heating	1455	1754500
Cooling	463	108895
Other	124	68000
Total Power		**2015916**

Table B3 Estimated Total Power of Electrical Loads for Valco Hall

Load Types	Quantity	Total Power (W)
Lighting	1036	37360
Office Equipment	84	24185
Heating	1950	3135000
Cooling	668	118000
Other	305	154180
Total Power		**3468725**

Table B4 Estimated Total Power of Electrical Loads for Casely Hayford Hall

Load Types	Quantity	Total Power (W)
Lighting	830	29408
Office Equipment	69	23445
Heating	1158	1891000
Cooling	670	141750
Other	315	158360
Total Power		**2243963**

Table B5 Estimated Total Power of Electrical Loads for Atlantic Hall

Load Types	Quantity	Total Power (W)
Lighting	704	24356
Office Equipment	69	24762
Heating	1328	2179600
Cooling	750	186825
Other	360	182500
Total Power		**2598043**

Table B6 Estimated Total Power of Electrical Loads for Adehye Hall

Load Types	Quantity	Total Power (W)
Lighting	261	7308
Office Equipment	33	12660
Heating	561	928250
Cooling	209	33078
Other	77	34650
Total Power		**1015946**

Table B7 Estimated Total Power of Electrical Loads for Superannuation Hall

Load Types	Quantity	Total Power (W)
Lighting	1737	29251
Office Equipment	48	20825
Heating	2551	3101250
Cooling	842	208785
Other	250	125000
Total Power		**3485111**

Table B8 Estimated Total Power of Electrical Loads for SRC Hall

Load Types	Quantity	Total Power (W)
Lighting	1559	26833
Office Equipment	73	29700
Heating	1878	1999200
Cooling	917	201400
Other	230	115000
Total Power		**2372133**

Table B9 Estimated Total Power of Electrical Loads for Oguaa Hall

Load Types	Quantity	Total Power (W)
Lighting	785	27320
Office Equipment	92	32750
Heating	1516	2156100
Cooling	388	74700
Other	478	170670
Total Power		2461540

Table B10 Estimated Total Power of Electrical Loads for University Hospital

Load Types	Quantity	Total Power (W)
Lighting	646	21244.00
Office Equipment	145	54585.00
Heating	33	33965.00
Cooling	303	152307.00
Other	55	48571.15
Total Power		**310672.15**

Table B11 Estimated Total Power of Electrical Loads for Anatomy, Mortuary and Clinical Lab

Load Types	Quantity	Total Power (W)
Lighting	280	7486
Office Equipment	26	8250
Heating	6	10950
Cooling	105	96972
Other	6	2530
Total Power		**126188**

Table B12 Estimated Total Power of Electrical Loads for C. A. Ackaah Lecture Theater Complex (CAALT)

Load Types	Quantity	Total Power (W)
Lighting	2115	69713
Office Equipment	149	50238
Heating	14	18500
Cooling	285	359425
Other	21	9765
Total Power		**507641**

Table B13 Estimated Total Power of Electrical Loads for Campus Broadcasting Services (CBS)

Load Types	Quantity	Total Power (W)
Lighting	148	6808
Office Equipment	48	16139
Heating	4	7450
Cooling	118	70180
Other	2	1500
Total Power		**102077**

Table B14 Estimated Total Power of Electrical Loads for Sasakawa Restaurant

Load Types	Quantity	Total Power (W)
Lighting	46	1207
Office Equipment	616	282835
Heating	4	6200
Cooling	23	40250
Other	4	4300
Total Power		**334792**

Table B15 Estimated Total Power of Electrical Loads for School of Medical Sciences

Load Types	Quantity	Total Power (W)
Lighting	181	5608
Office Equipment	101	42750
Heating	3	6000
Cooling	101	187725
Other	59	13320
Total Power		**255403**

Table B16 Estimated Total Power of Electrical Loads for Faculty of Social Sciences

Load Types	Quantity	Total Power (W)
Lighting	368	10304
Office Equipment	374	146895
Heating	17	21800
Cooling	264	358450
Other	20	3400
Total Power		**540849**

Table B17 Estimated Total Power of Electrical Loads for Amissah Arthur Language Centre

Load Types	Quantity	Total Power (W)
Lighting	230	5008
Office Equipment	61	19630
Heating	3	3600
Cooling	189	274275
Other	6	1500
Total Power		**304013**

Table B18 Estimated Total Power of Electrical Loads for Communal Block (Dept. of Music)

Load Types	Quantity	Total Power (W)
Lighting	164	4555
Office Equipment	219	88650
Heating	8	10400
Cooling	139	274475
Other	10	3800
Total Power		**381880**

Table B19 Estimated Total Power of Electrical Loads for New Examination Centre (NEC)

Load Types	Quantity	Total Power (W)
Lighting	219	6204
Office Equipment	137	42150
Heating	7	8400
Cooling	64	139950
Other	33	4750
Total Power		**201454**

Table B20 Estimated Total Power of Electrical Loads for Basic Education

Load Types	Quantity	Total Power (W)
Lighting	13	904
Office Equipment	24	7225
Heating	28	36950
Cooling	5	5200
Other	11	4500
Total Power		**54779**

Table B21 Estimated Total Power of Electrical Loads for College of Distance Education

Load Types	Quantity	Total Power (W)
Lighting	695	17332
Office Equipment	150	78875
Heating	8	13950
Cooling	308	336860
Other	16	880
Total Power		**447897**

Table B22 Estimated Total Power of Electrical Loads for Kingdom Books and Stationary

Load Types	Quantity	Total Power (W)
Lighting	25	700
Office Equipment	18	6800
Heating	53	63800
Cooling	21	25625
Other	12	540
Total Power		**97465**

Table B23 Estimated Total Power of Electrical Loads for Primary, UCC

Load Types	Quantity	Total Power (W)
Lighting	446	14930
Office Equipment	140	70775
Heating	985	1232100
Cooling	176	48150
Other	478	170670
Total Power		**1536625**

Table B24 Estimated Total Power of Electrical Loads for VOTEC

Load Types	Quantity	Total Power (W)
Lighting	489	13914
Office Equipment	309	83089
Heating	5	1950
Cooling	310	197373
Other	56	22550
Total Power		**318876**

Table B25 Estimated Total Power of Electrical Loads for School of Business Guest House

Load Types	Quantity	Total Power (W)
Lighting	90	1730
Office Equipment	19	4663
Heating	11	17550
Cooling	58	42948
Other	3	2850
Total Power		**69741**

Table B26 Estimated Total Power of Electrical Loads for Institute of Education Chalets

Load Types	Quantity	Total Power (W)
Lighting	119	3726
Office Equipment	60	10102
Heating	46	7900
Cooling	59	42948
Other	5	5500
Total Power		**70176**

Table B27 Estimated Total Power of Electrical Loads for Senior Club House

Load Types	Quantity	Total Power (W)
Lighting	70	2809.8
Office Equipment	12	2416.0
Heating	7	4000.0
Cooling	21	66700.0
Other	3	5080.0
Total Power		**81005.8**

Table B28 Estimated Total Power of Electrical Loads for Guest House (Sasakawa)

Load Types	Quantity	Total Power (W)
Lighting	44	512
Office Equipment	54	10410
Heating	45	70800
Cooling	126	83970
Other	5	5500
Total Power		**171192**

Table B29 Estimated Total Power of Electrical Loads for Sculpture Workshop

Load Types	Quantity	Total Power (W)
Lighting	32	896
Office Equipment	4	1425
Cooling	14	4360
Total Power		6681

Table B30 Estimated Total Power of Electrical Loads for School of Development Studies

Load Types	Quantity	Total Power (W)
Lighting	88	2464
Office Equipment	119	47200
Cooling	165	167445
Total Power		**217109**

Table B31 Estimated Total Power of Electrical Loads for UCC Fire Service

Load Types	Quantity	Total Power (W)
Lighting	38	1508
Office Equipment	8	2825
Cooling	17	11775
Total Power		**16108**

Table B32 Estimated Total Power of Electrical Loads for Faculty of Arts

Load Types	Quantity	Total Power (W)
Lighting	350	9800
Office Equipment	205	77125
Heating	2	4000
Cooling	288	371640
Total Power		**462565**

Table B33 Estimated Total Power of Electrical Loads for Assembly Hall and Offices

Load Types	Quantity	Total Power (W)
Lighting	70	1960
Office Equipment	2	46
Cooling	29	8840
Total Power		**10846**

Table B34 Estimated Total Power of Electrical Loads for Large Lecture Theatre

Load Types	Quantity	Total Power (W)
Lighting	72	2088
Office Equipment	29	7195
Cooling	42	16850
Total Power		**26133**

Table B35 Estimated Total Power of Electrical Loads for Development Office

Load Types	Quantity	Total Power (W)
Lighting	196	6376
Office Equipment	90	33615
Cooling	67	101385
Total Power		**141376**

Table B36 Estimated Total Power of Electrical Loads for UCC Security Section

Load Types	Quantity	Total Power (W)
Lighting	37	1354
Office Equipment	7	2250
Cooling	13	14750
Total Power		**18354**

Table B37 Estimated Total Power of Electrical Loads for Central Administration

Load Types	Quantity	Total Power (W)
Lighting	527	17180
Office Equipment	621	287575
Heating	22	33600
Cooling	304	530050
Total Power		**868405**

Table B38 Estimated Total Power of Electrical Loads for HYPER

Load Types	Quantity	Total Power (W)
Lighting	29	812
Office Equipment	38	10423
Heating	53	63800
Cooling	37	3888
Total Power		**78923**

Table B39 Estimated Total Power of Electrical Loads for Education Foundations

Load Types	Quantity	Total Power (W)
Lighting	55	1540
Office Equipment	18	13825
Heating	1	2100
Cooling	47	48162
Total Power		**65627**

Table B40 Estimated Total Power of Electrical Loads for IEPA

Load Types	Quantity	Total Power (W)
Lighting	75	2100
Office Equipment	95	33789
Heating	1	2100
Cooling	63	98625
Total Power		**136614**

Table B41 Estimated Total Power of Electrical Loads for UCC Police Station

Load Types	Quantity	Total Power (W)
Lighting	44	1676
Office Equipment	4	1625
Cooling	10	10950
Total Power		**14251**

Table B42 Estimated Total Power of Electrical Loads for Grounds and Gardens

Load Types	Quantity	Total Power (W)
Lighting	21	1920
Office Equipment	5	2260
Cooling	4	345
Total Power		**4525**

Table B43 Estimated Total Power of Electrical Loads for Main Library

Load Types	Quantity	Total Power (W)
Lighting	260	7280
Office Equipment	797	415613
Cooling	203	176625
Other	5	450
Total Power		**599968**

Table B44 Estimated Total Power of Electrical Loads for CoDE Multipurpose Complex

Load Types	Quantity	Total Power (W)
Lighting	110	2430
Office Equipment	24	17445
Cooling	124	41815
Total Power		**61690**

Table B45 Estimated Total Power of Electrical Loads for Institute of Education

Load Types	Quantity	Total Power (W)
Lighting	141	3936
Office Equipment	72	28642
Heating	1	2000
Cooling	50	72519
Total Power		**107097**

Table B46 Estimated Total Power of Electrical Loads for KG, UCC

Load Types	Quantity	Total Power (W)
Lighting	141	4092
Office Equipment	4	1625
Cooling	35	10150
Total Power		**15867**

Table B47 Estimated Total Power of Electrical Loads for Central Stores

Load Types	Quantity	Total Power (W)
Lighting	30	1360
Office Equipment	19	7665
Cooling	27	21400
Total Power		**30425**

Table B48 Estimated Total Power of Electrical Loads for Teaching and Research Farm

Load Types	**Quantity**	**Total Power (W)**
Lighting	73	3640
Office Equipment	27	11000
Heating	1	2400
Cooling	23	5375
Other	2	5580
Total Power		**27995**

APPENDIX C

HARMONIC WAVEFORMS AND SPECTRUM OF CURRENTS AND VOLTAGES OBTAINED AT MAIN PCCs AND SPECIAL INSTALLATION PCCs

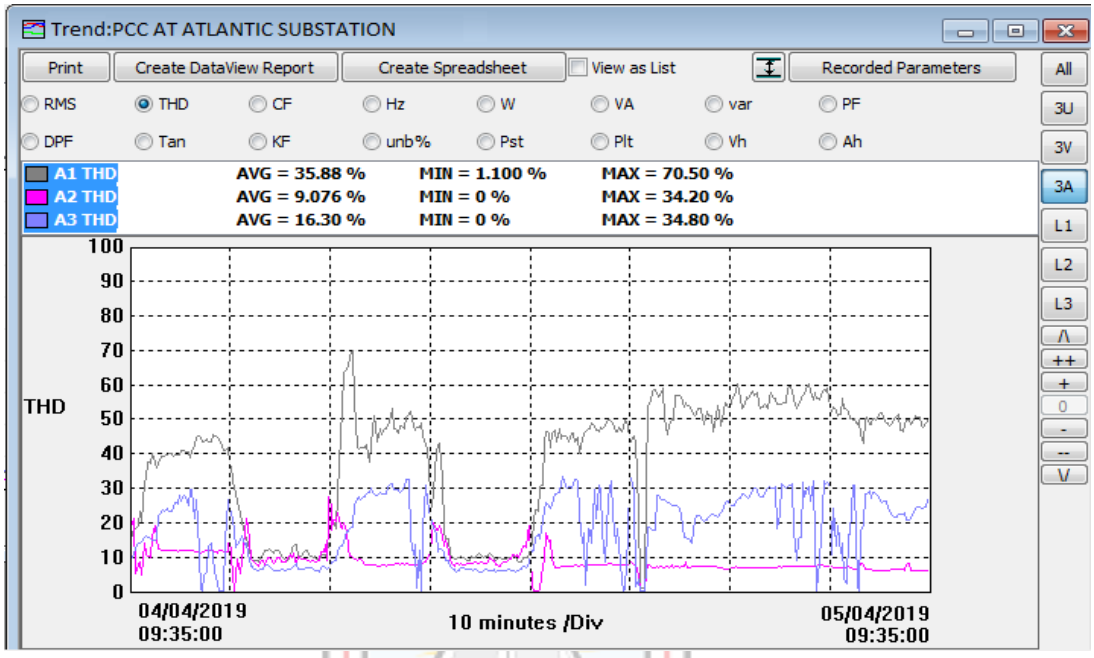

Fig. C1 Waveforms of THD_I Obtained at the Atlantic PCC

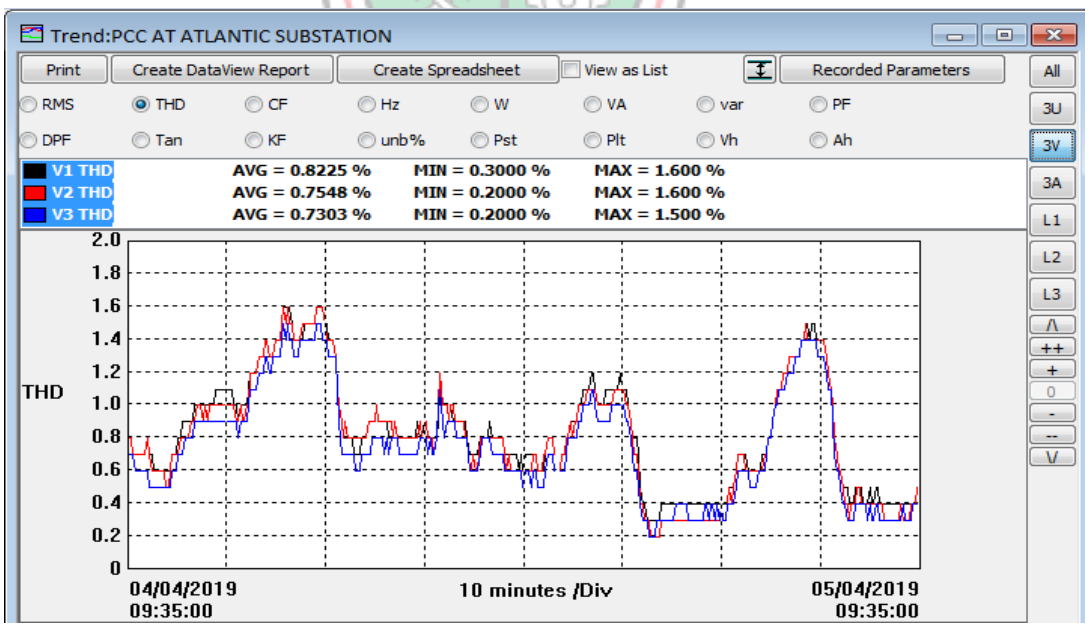

Fig. C2 Waveforms of THD_V Obtained at the Atlantic PCC

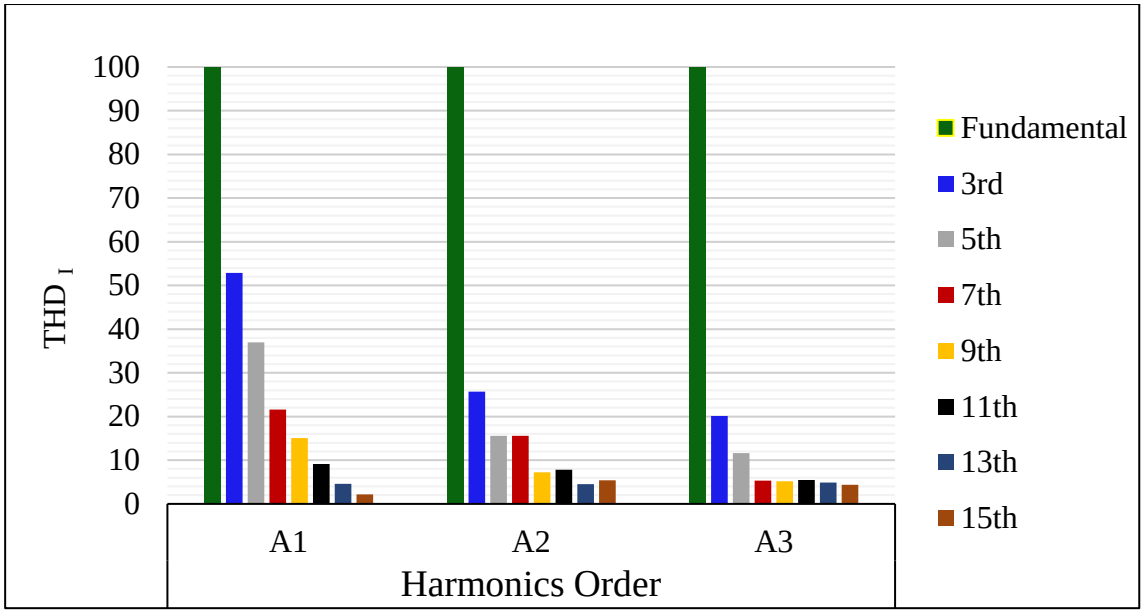

Fig. C3 Harmonic Current Spectrum for Atlantic PCC

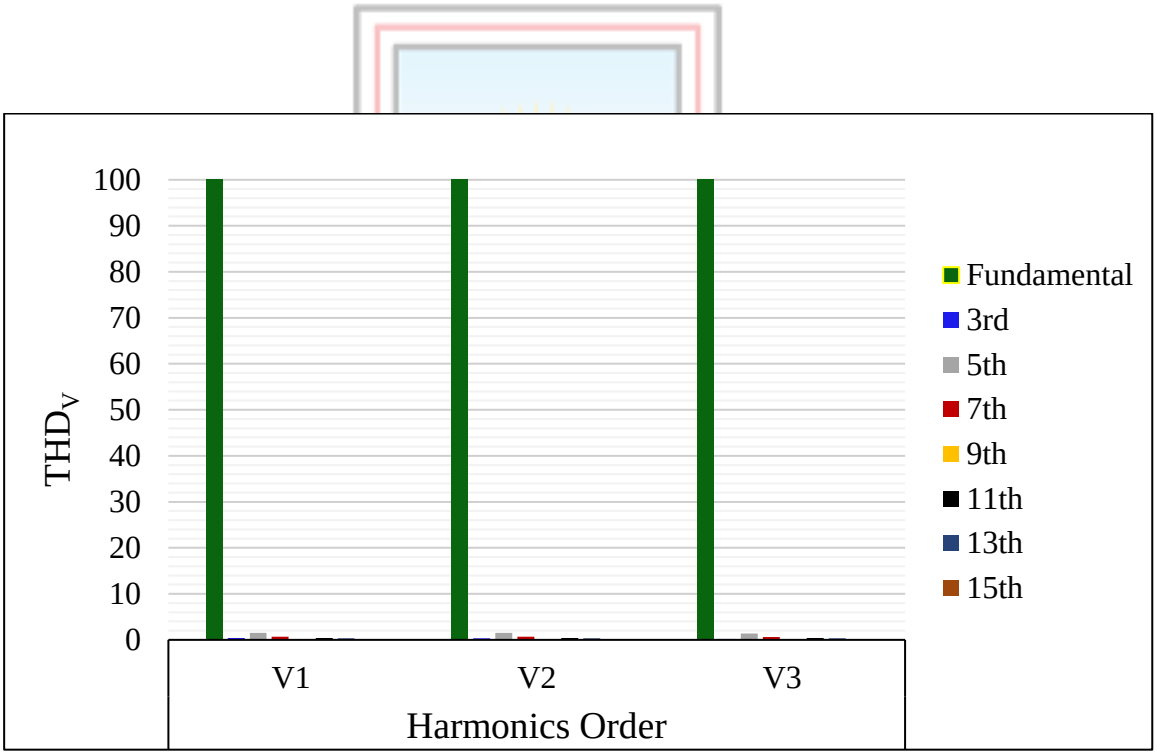

Fig. C4 Harmonic Voltage Spectrum for Atlantic PCC

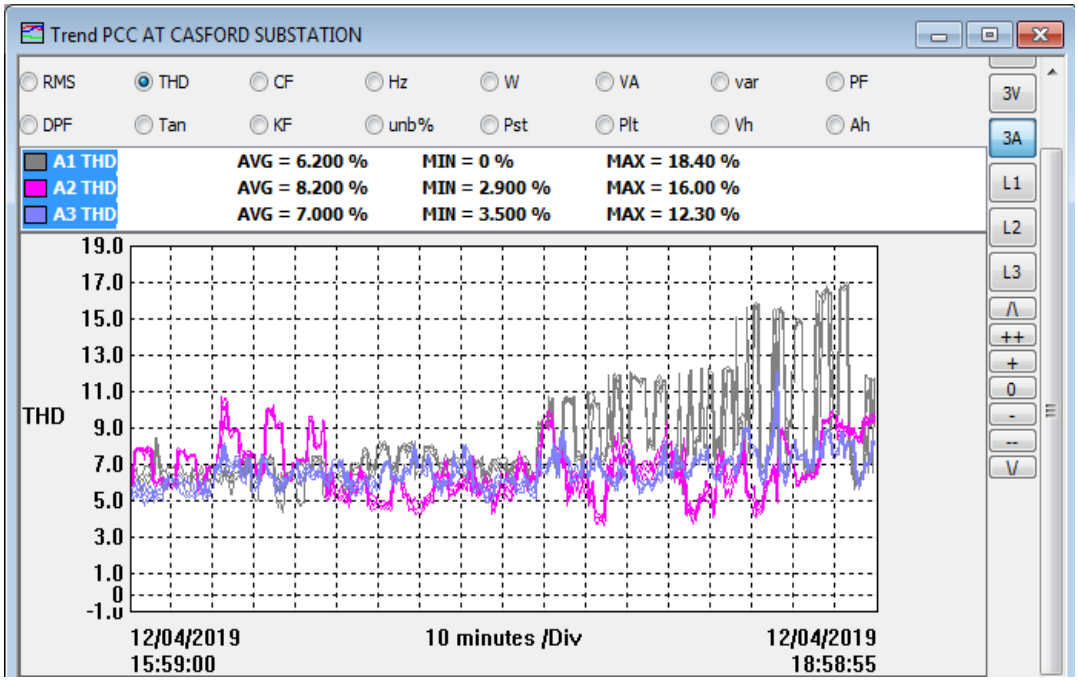

Fig. C5 Waveforms of THD_I Obtained at the Casford PCC

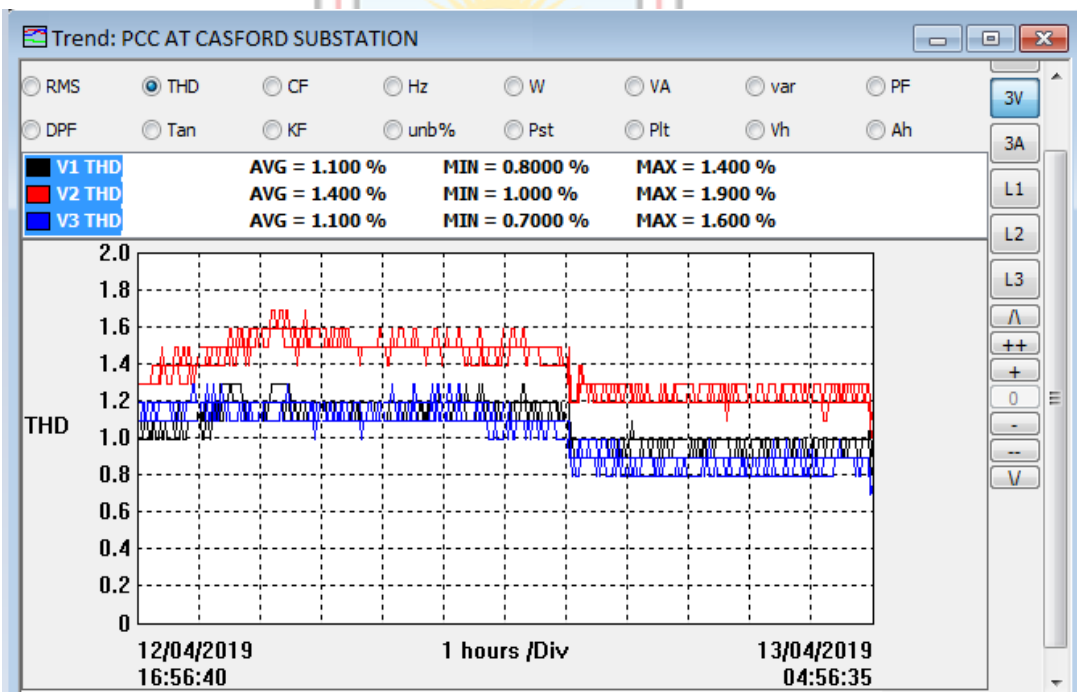

Fig. C6 Waveforms of THD_V Obtained at the Casford PCC

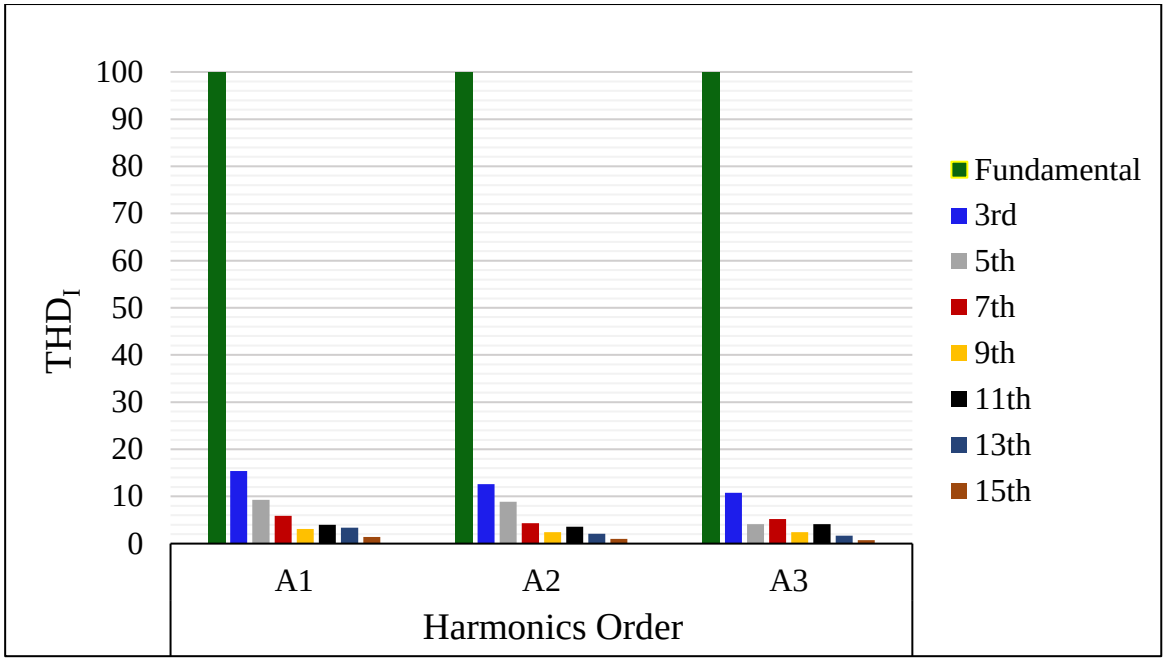

Fig. C7 Harmonic Current Spectrum for Casford PCC

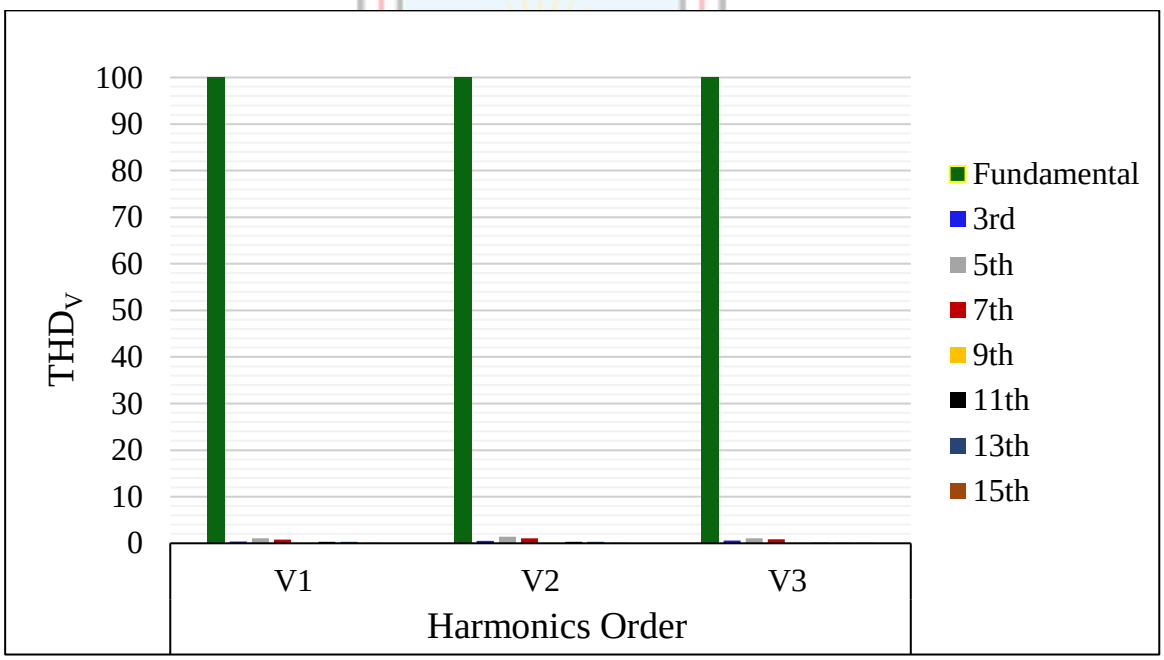

Fig. C8 Harmonic Voltage Spectrum for Casford PCC

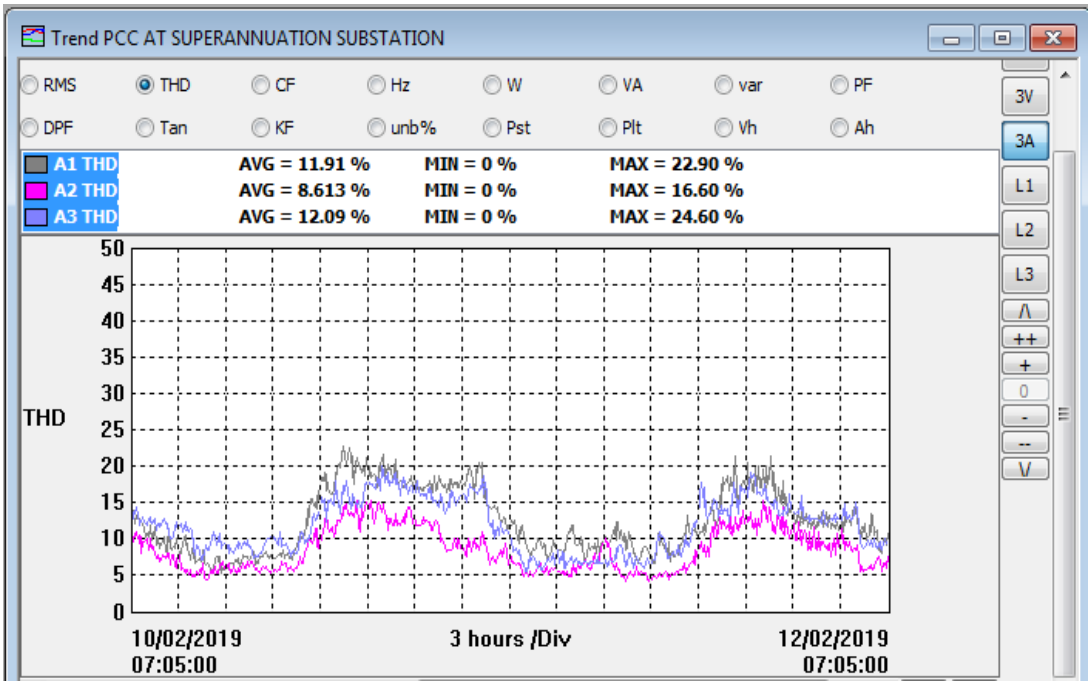

Fig. C9 Waveforms of THDI Obtained at the Superannuation PCC

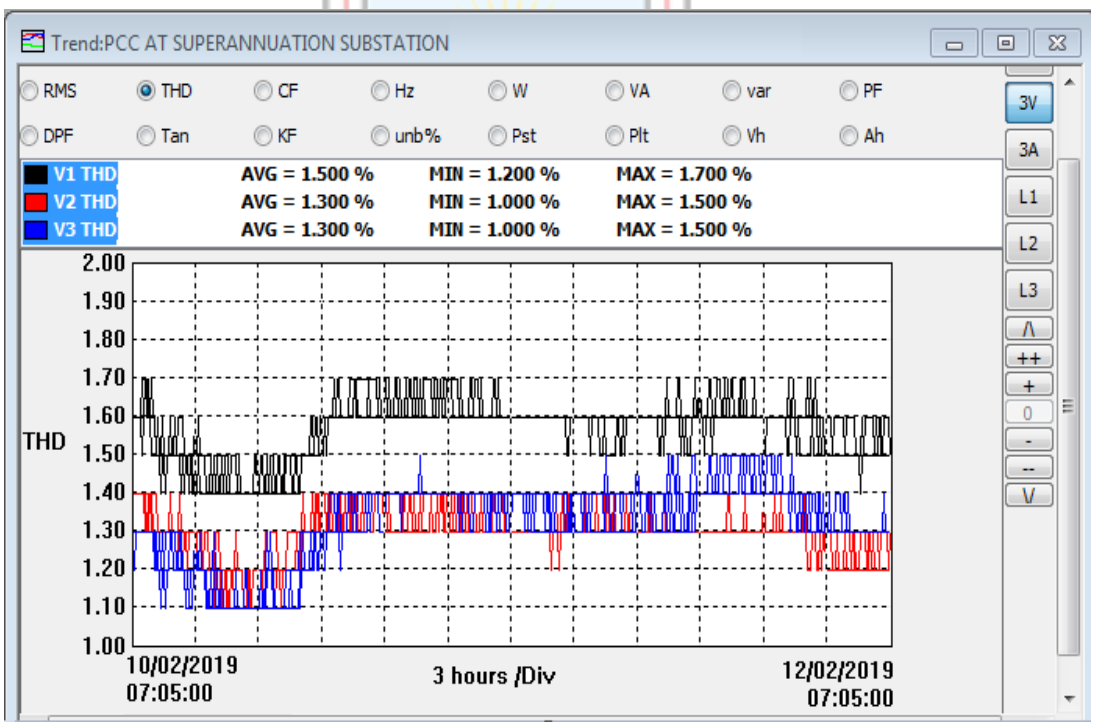

Fig. C10 Waveforms of THDV Obtained at the Superannuation PCC

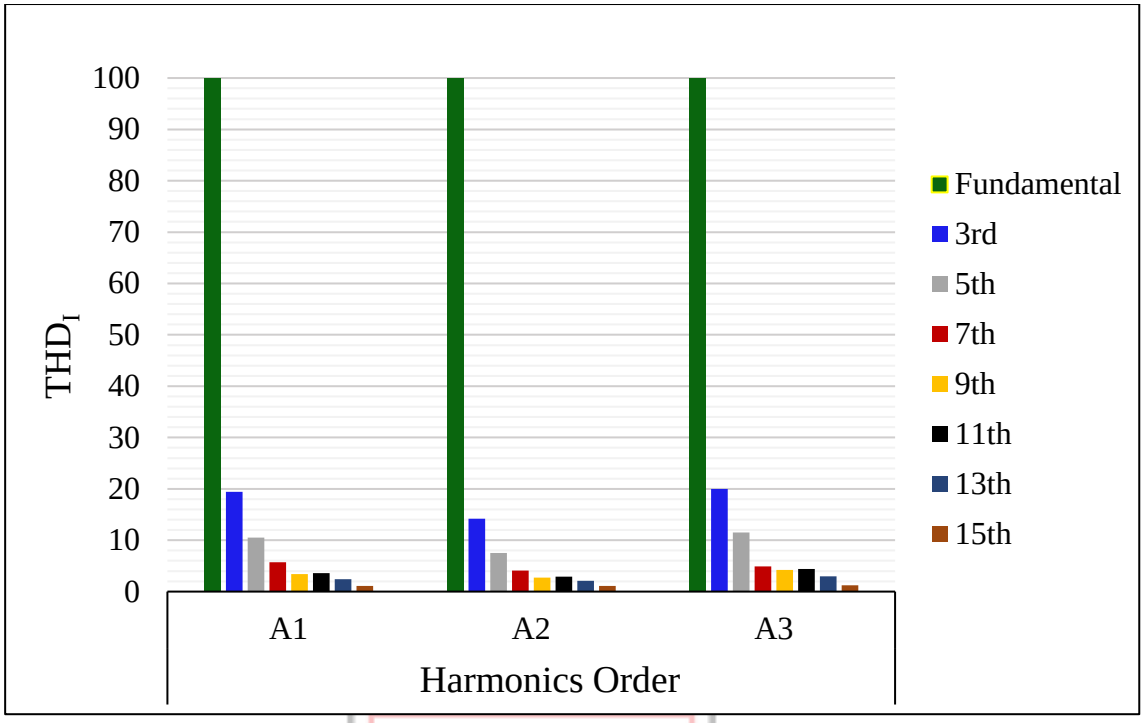

Fig. C11 Harmonic Current Spectrum for Superannuation PCC

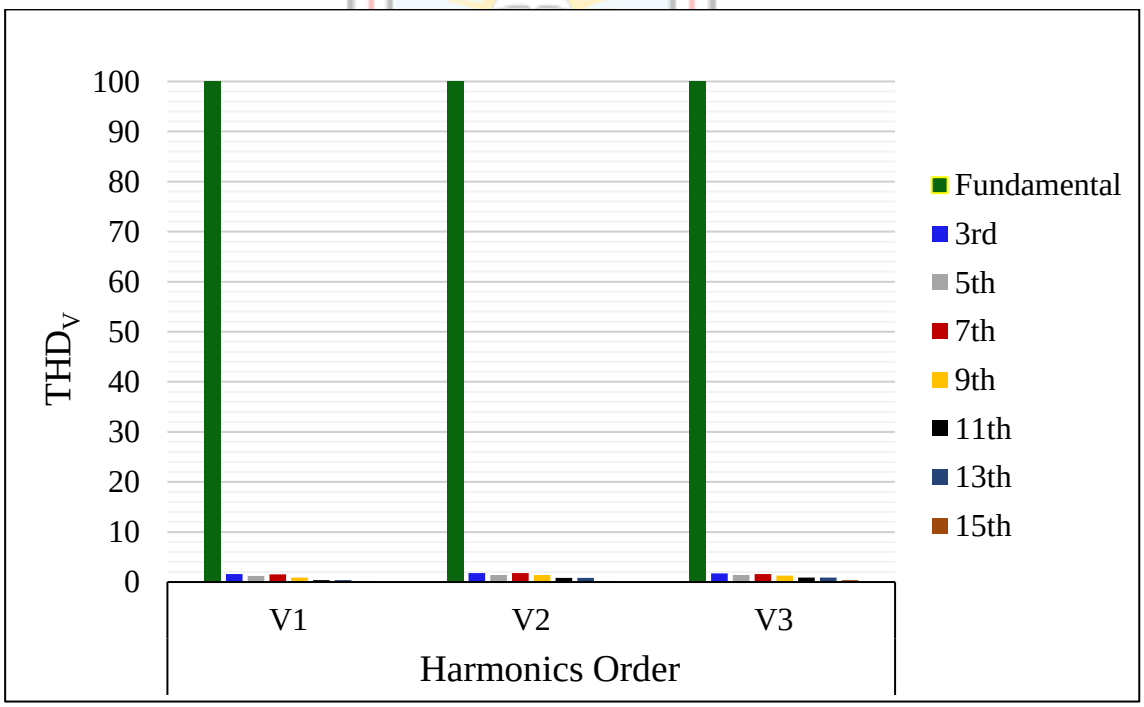

Fig. C12 Harmonic Voltage Spectrum for Superannuation PCC

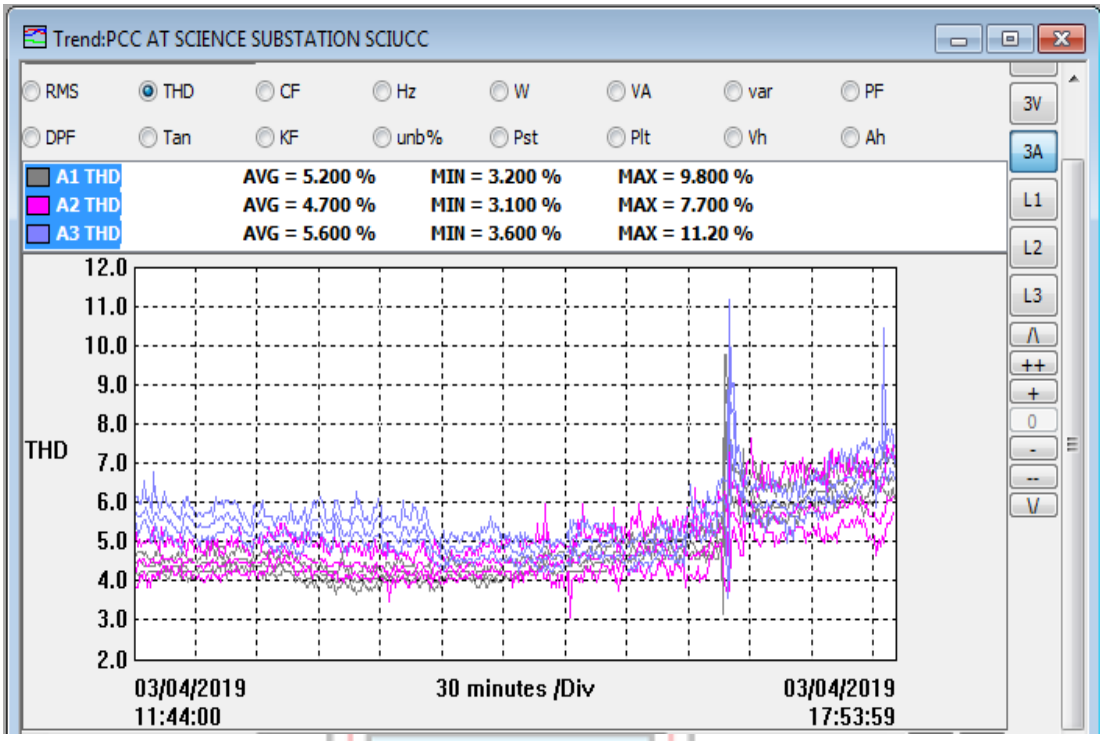

Fig. C13 Waveforms of THD_I Obtained at the Science PCC

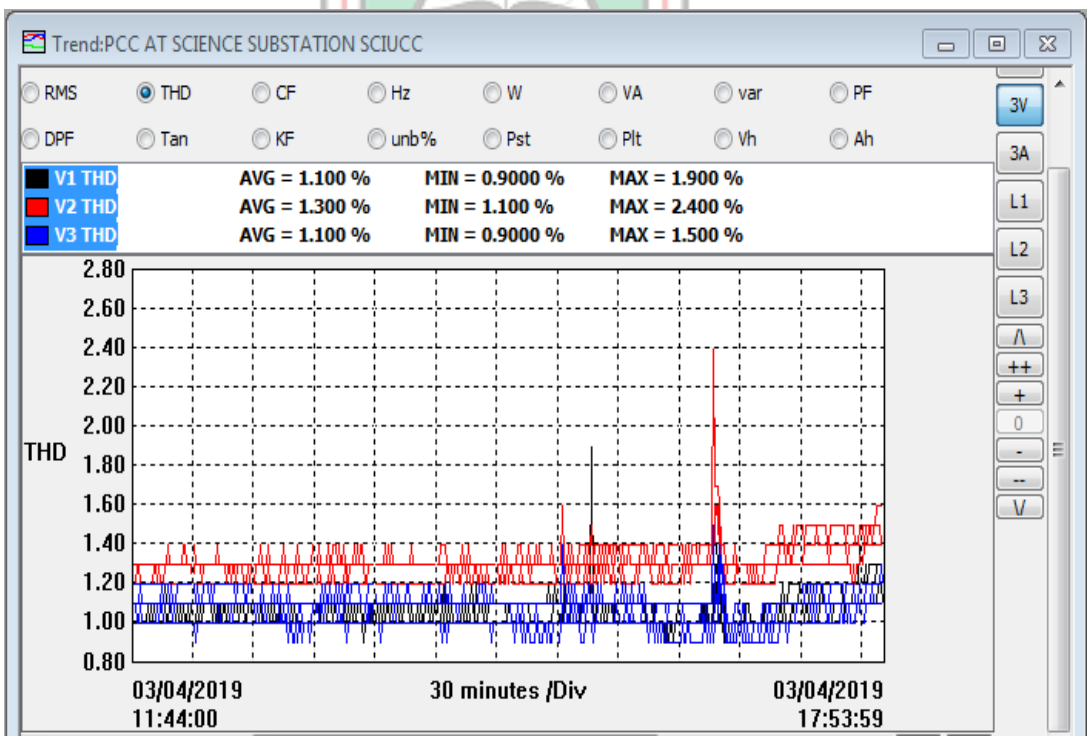

Fig. C14 Waveforms of THD_V Obtained at the Science PCC

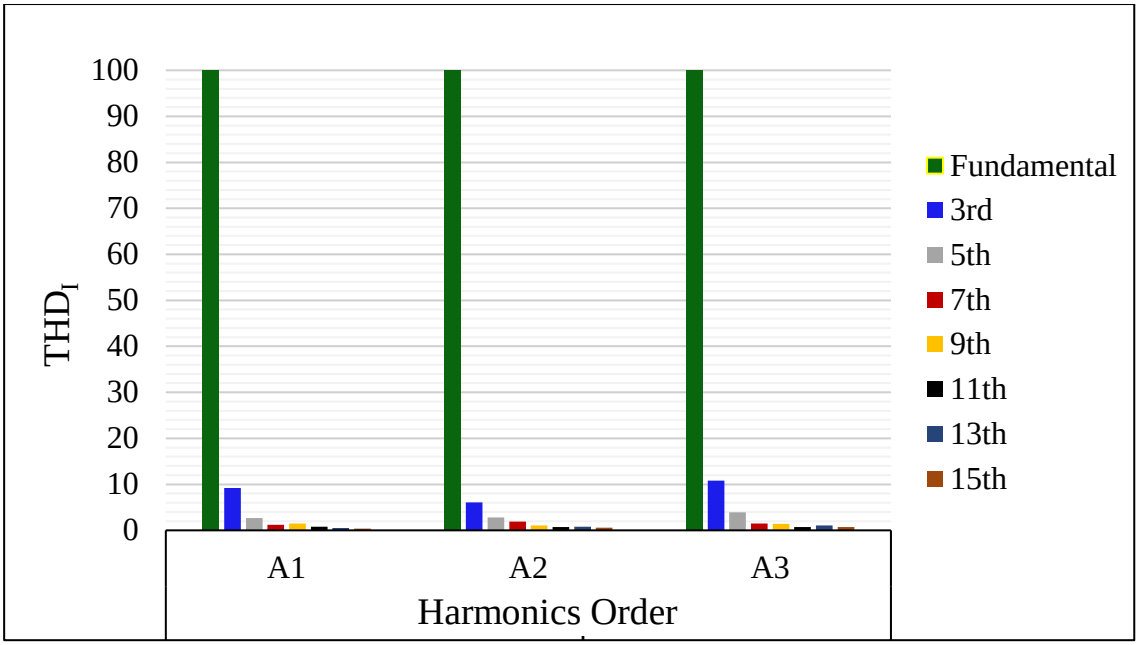

Fig. C15 Harmonic Current Spectrum for Science PCC

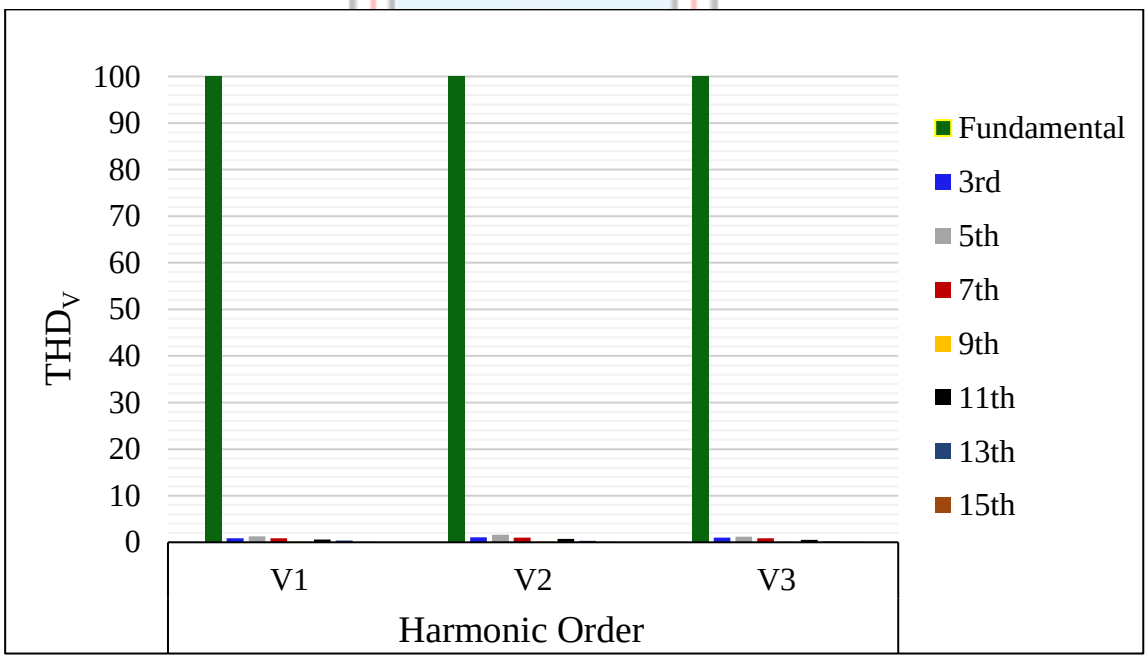

Fig. C16 Harmonic Voltage Spectrum for Science PCC

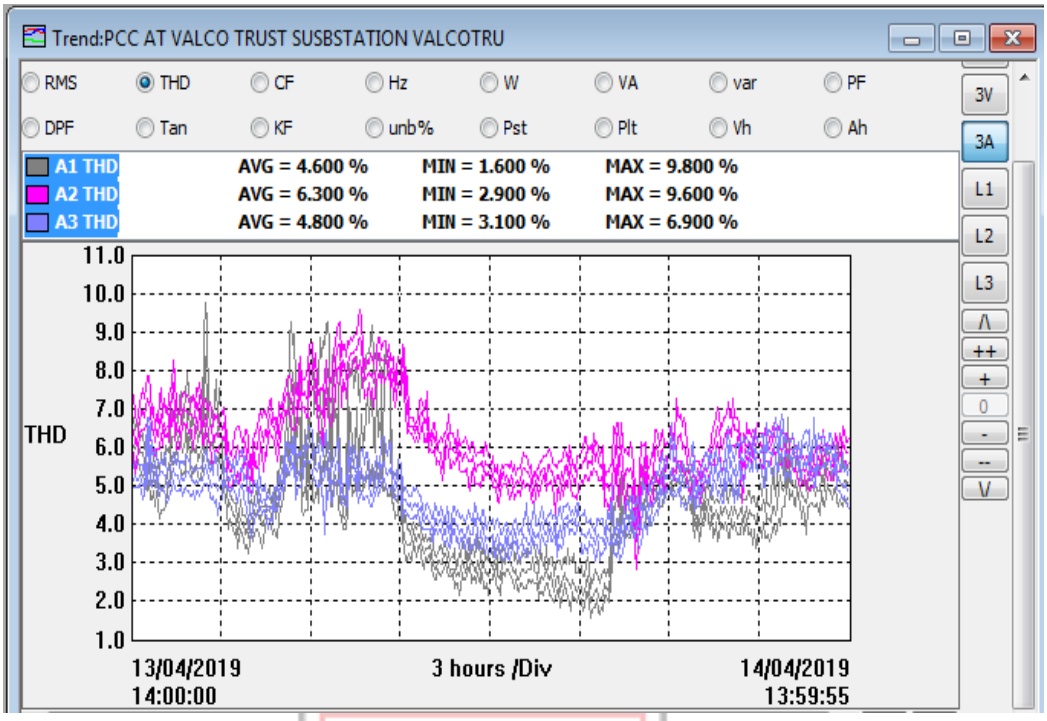

Fig. C17 Waveforms of THD_I Obtained at the Valco-Trust PCC

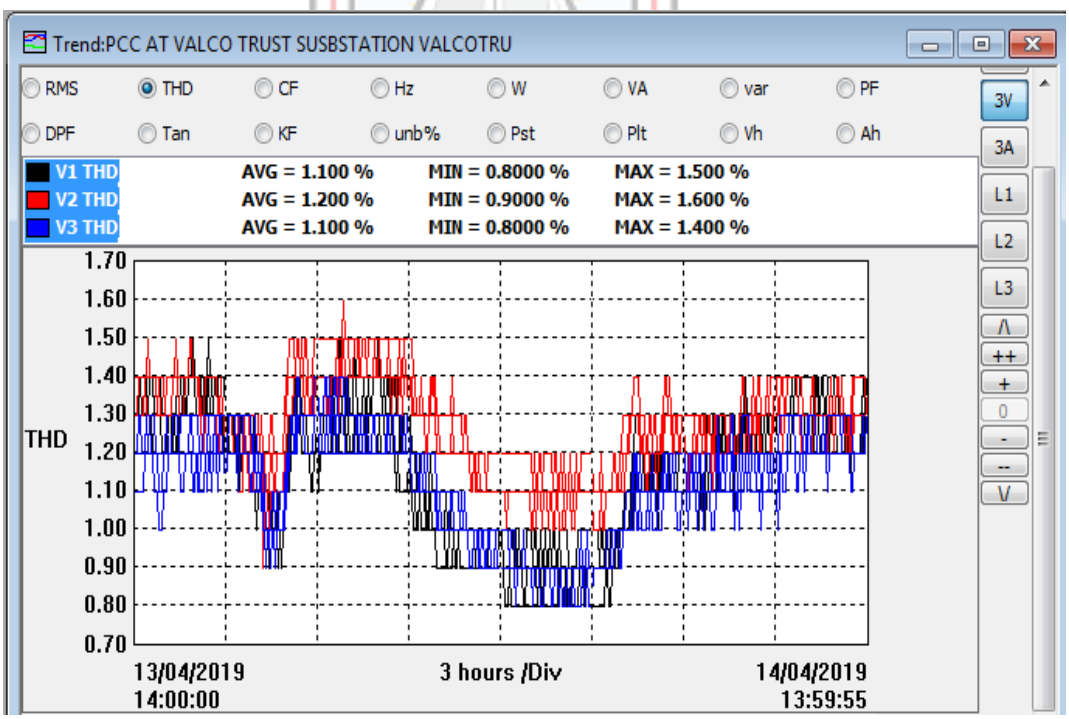

Fig. C18 Waveforms of THD_V Obtained at the Valco-Trust PCC

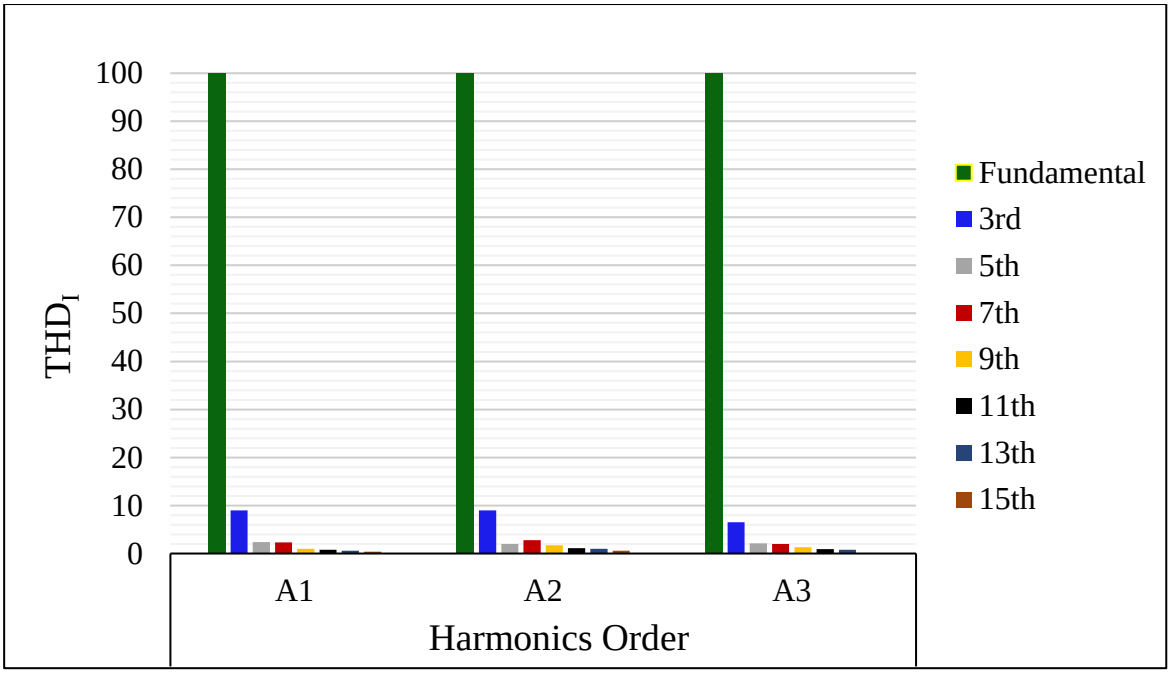

Fig. C19 Harmonic Current Spectrum for Valco-Trust PCC

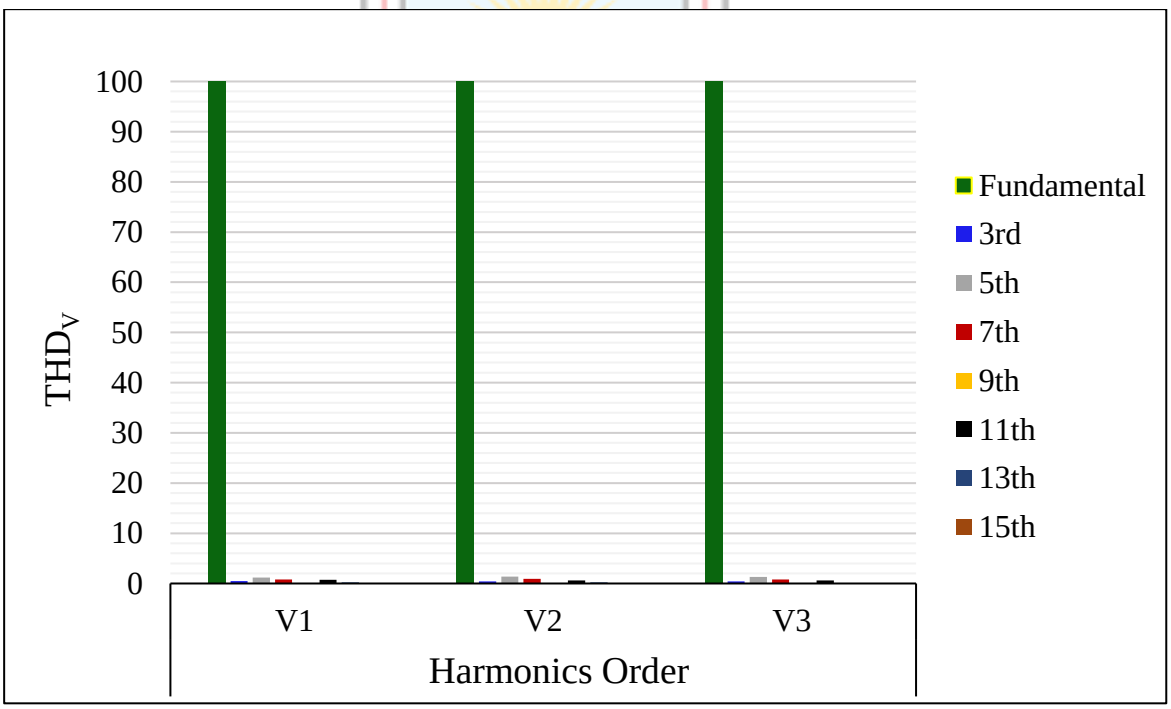

Fig. C20 Harmonic Voltage Spectrum for Valco-Trust PCC

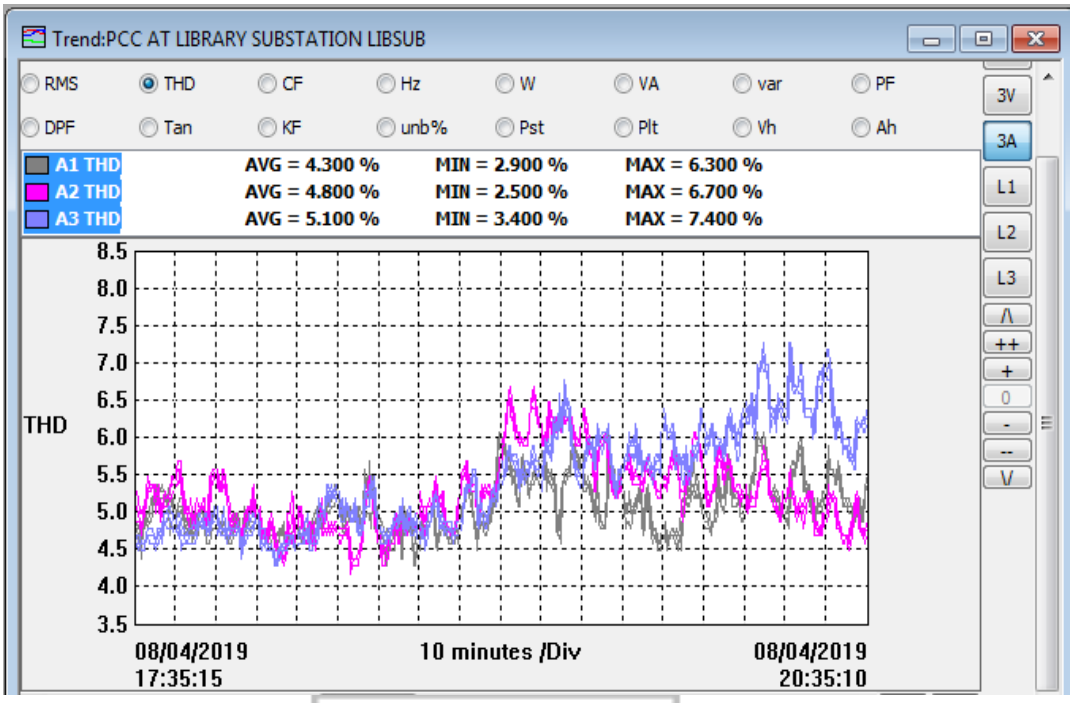

Fig. C21 Waveforms of THD_I Obtained at the Library PCC

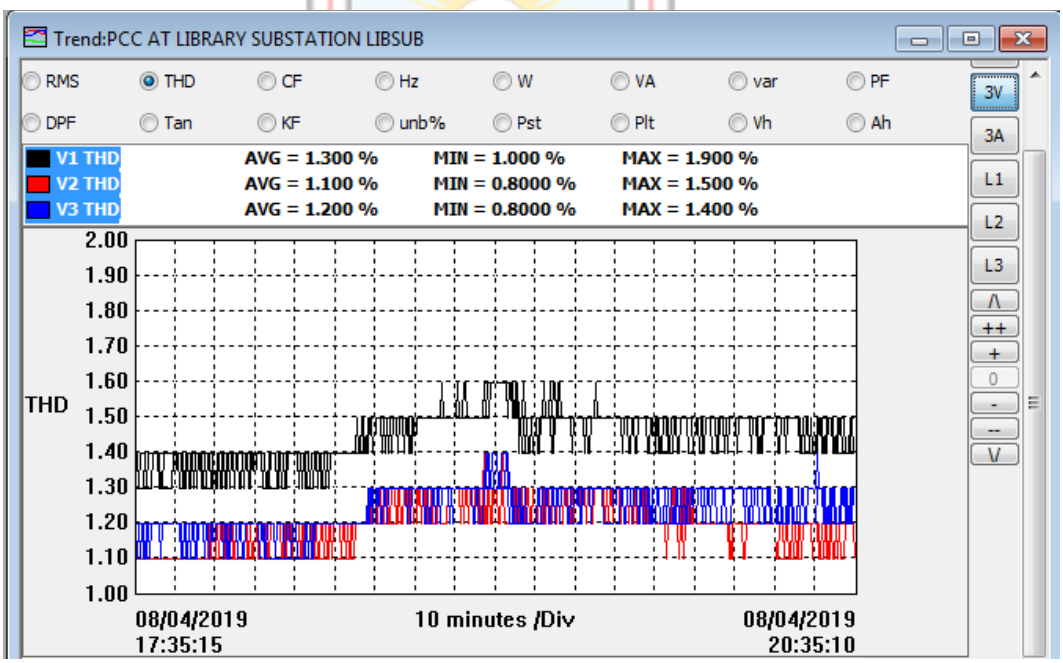

Fig. C22 Waveforms of THD_I Obtained at the Library PCC

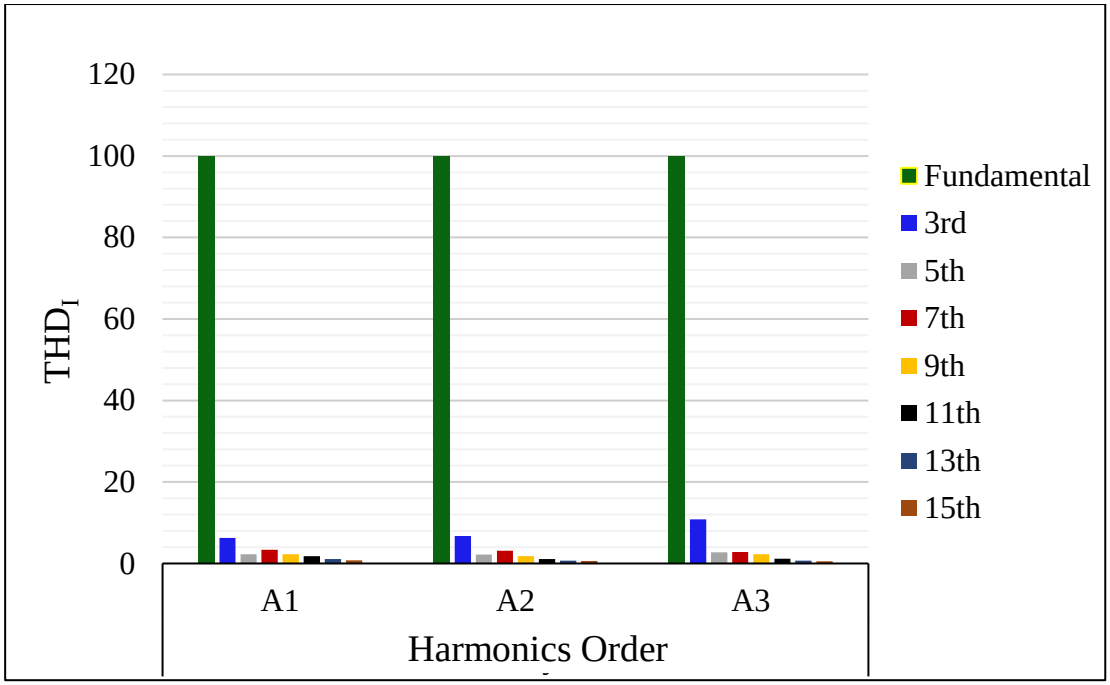

Fig. C23 Harmonic Current Spectrum for Library PCC

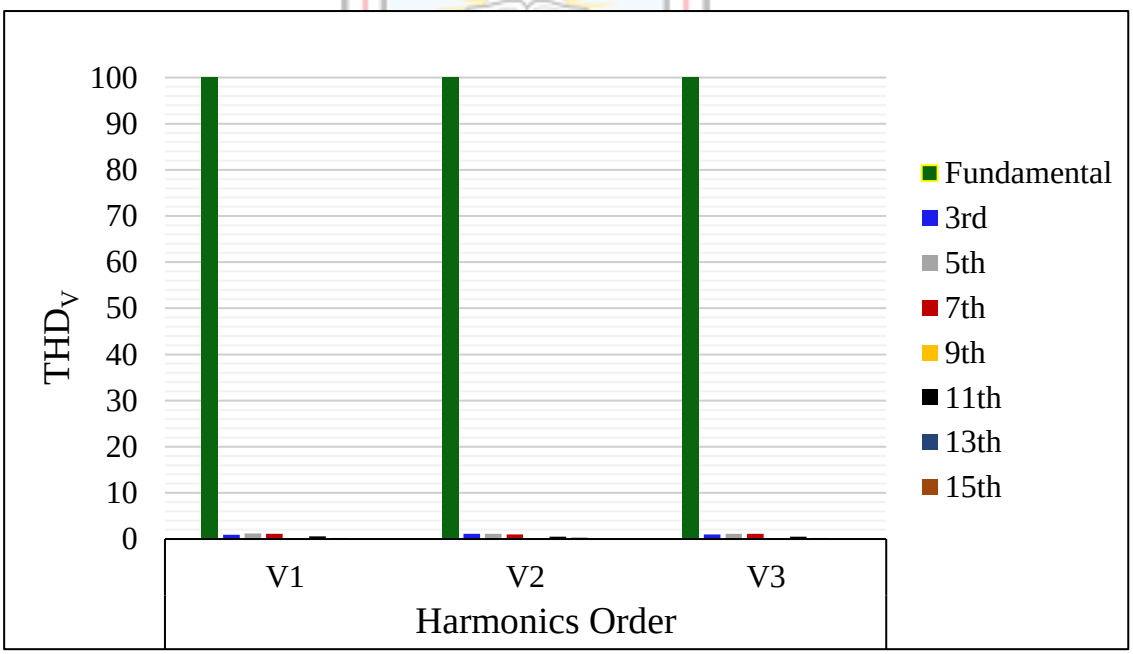

Fig. C24 Harmonic Voltage Spectrum for Library PCC

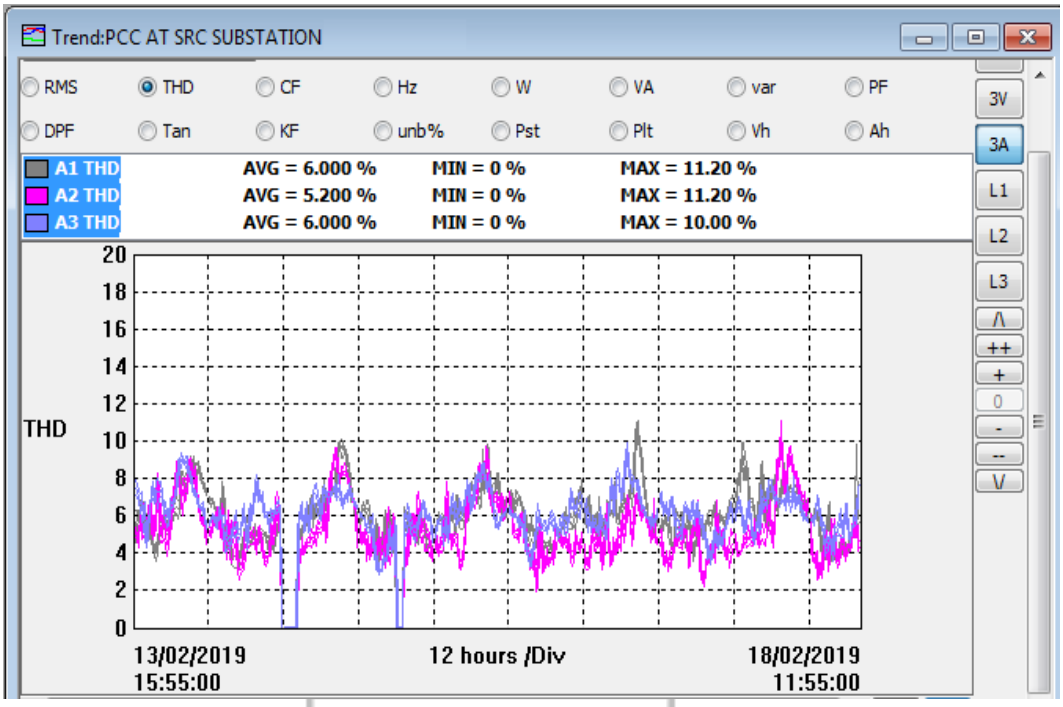

Fig. C25 Waveforms of THD_I Obtained at the SRC PCC

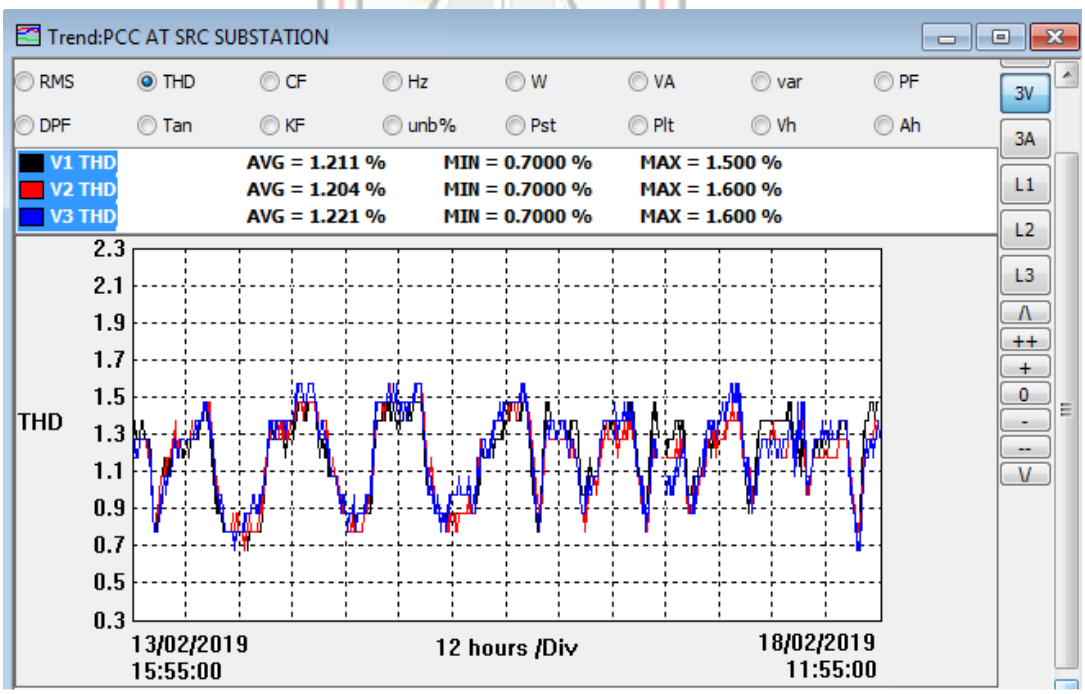

Fig. C26 Waveforms of THD_V Obtained at the SRC PCC

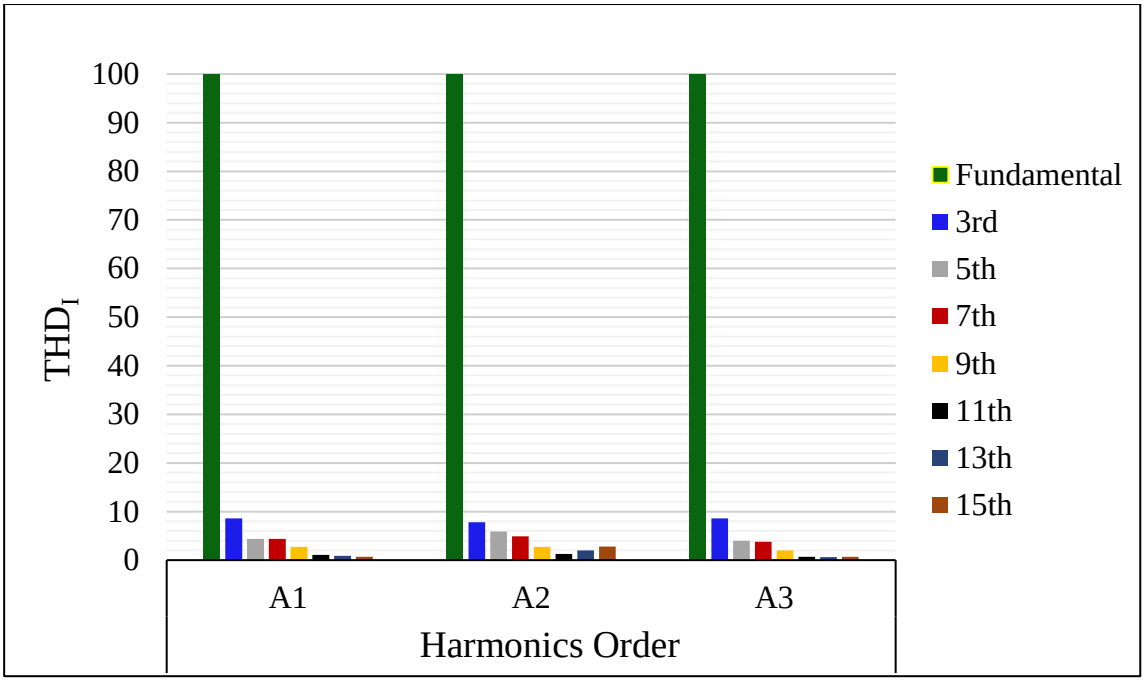

Fig. C27 Harmonic Current Spectrum for SRC PCC

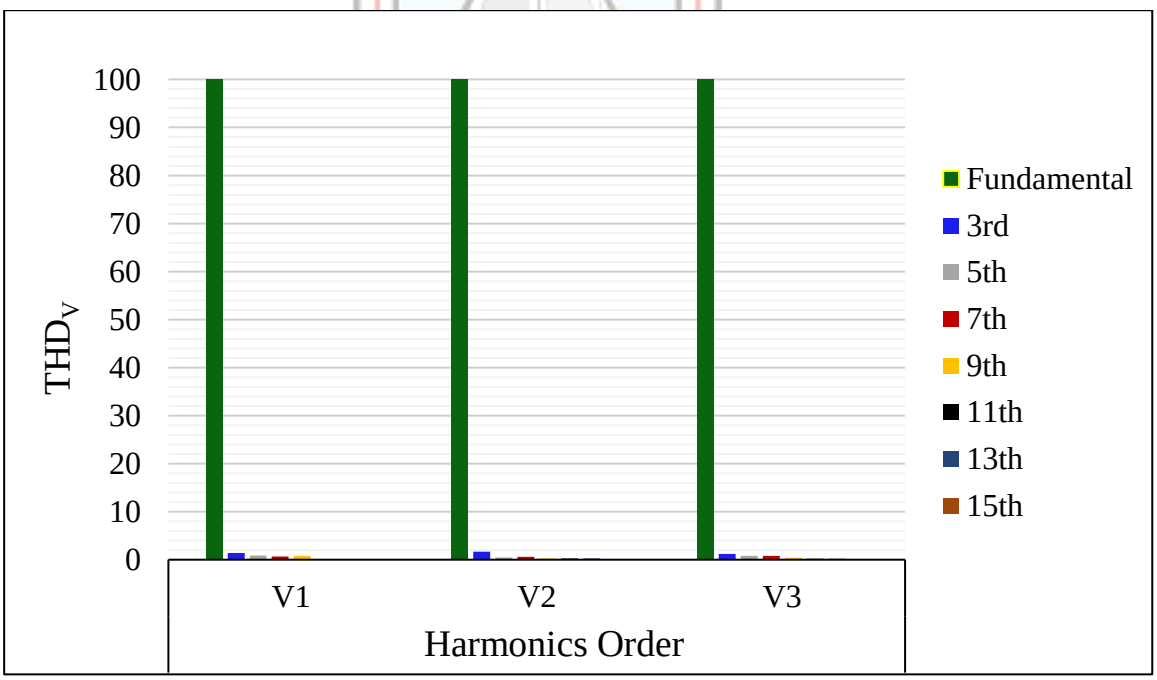

Fig. C28 Harmonic Voltage Spectrum for SRC PCC

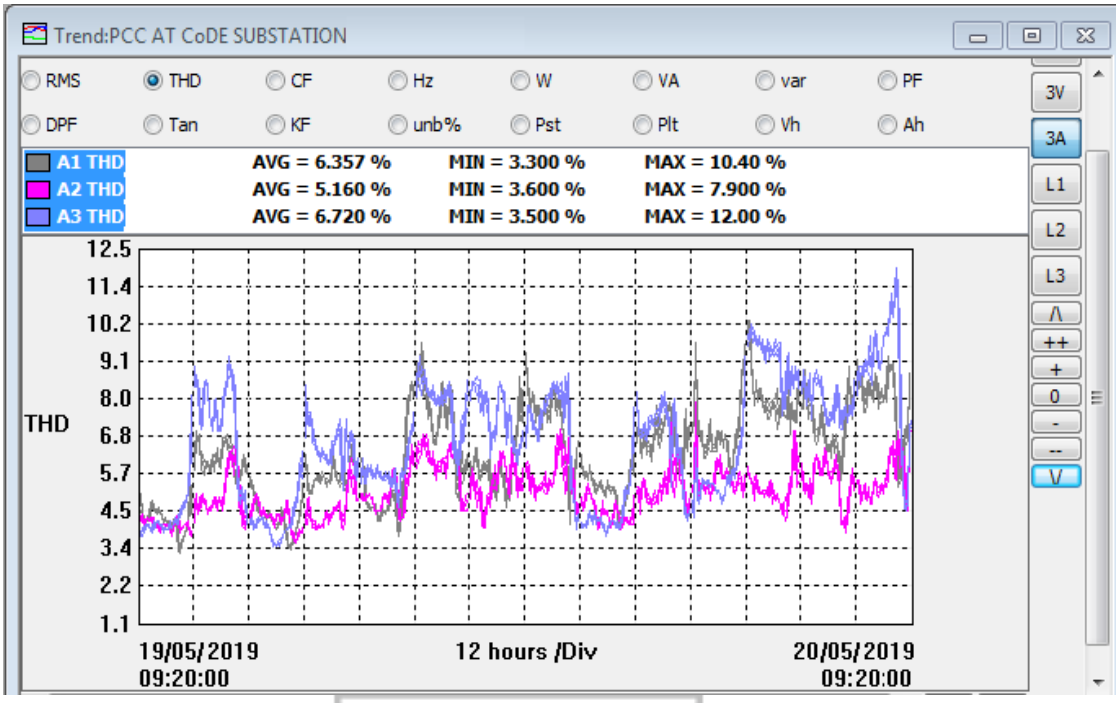

Fig. C29 Waveforms of THD_I Obtained at the CoDE PCC

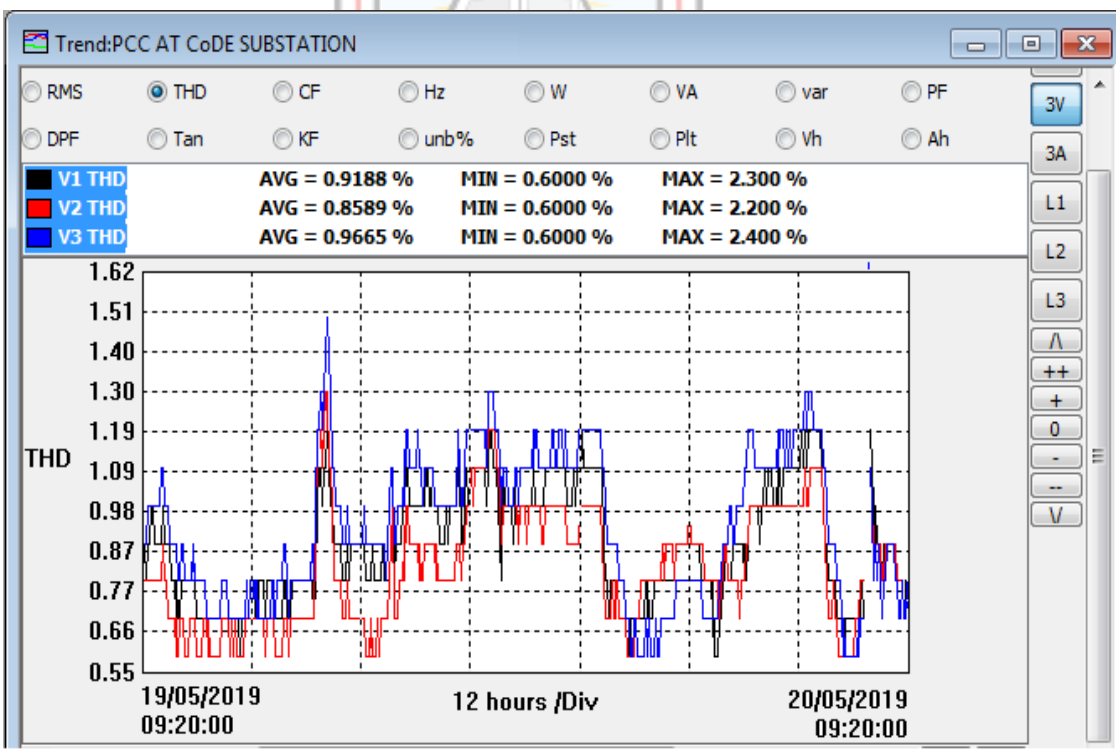

Fig. C30 Waveforms of THD_V Obtained at the CoDE PCC

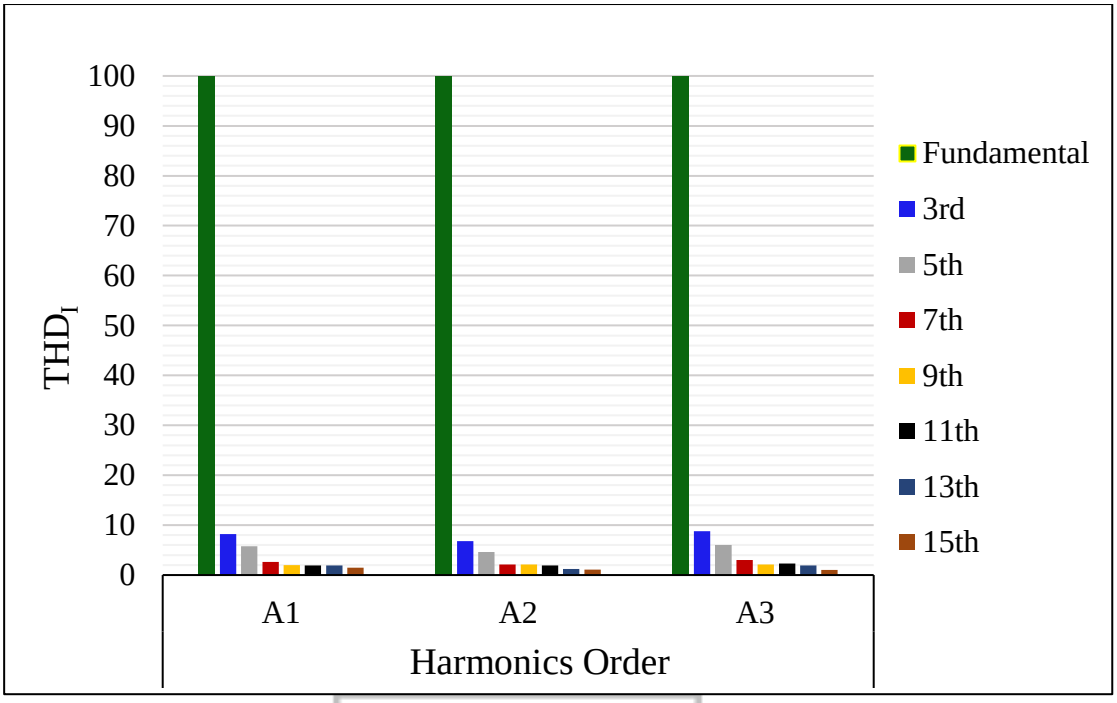

Fig. C31 Harmonic Current Spectrum for CoDE PCC

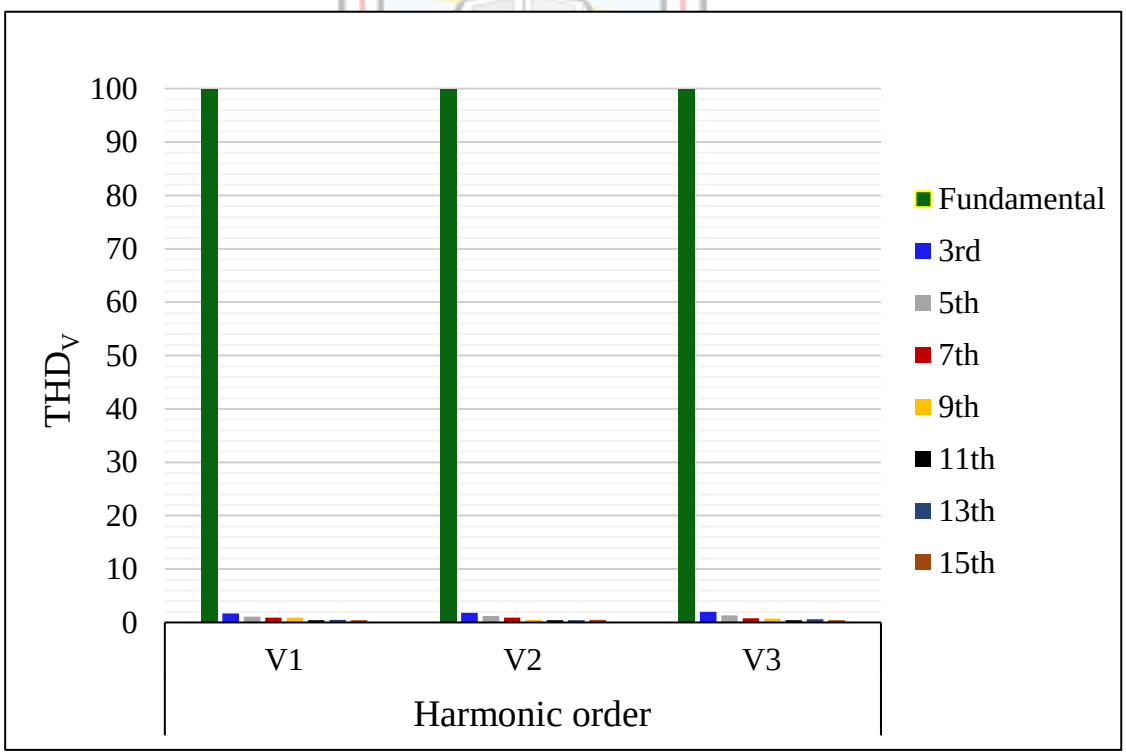

Fig. C32 Harmonic Voltage Spectrum for CoDE PCC

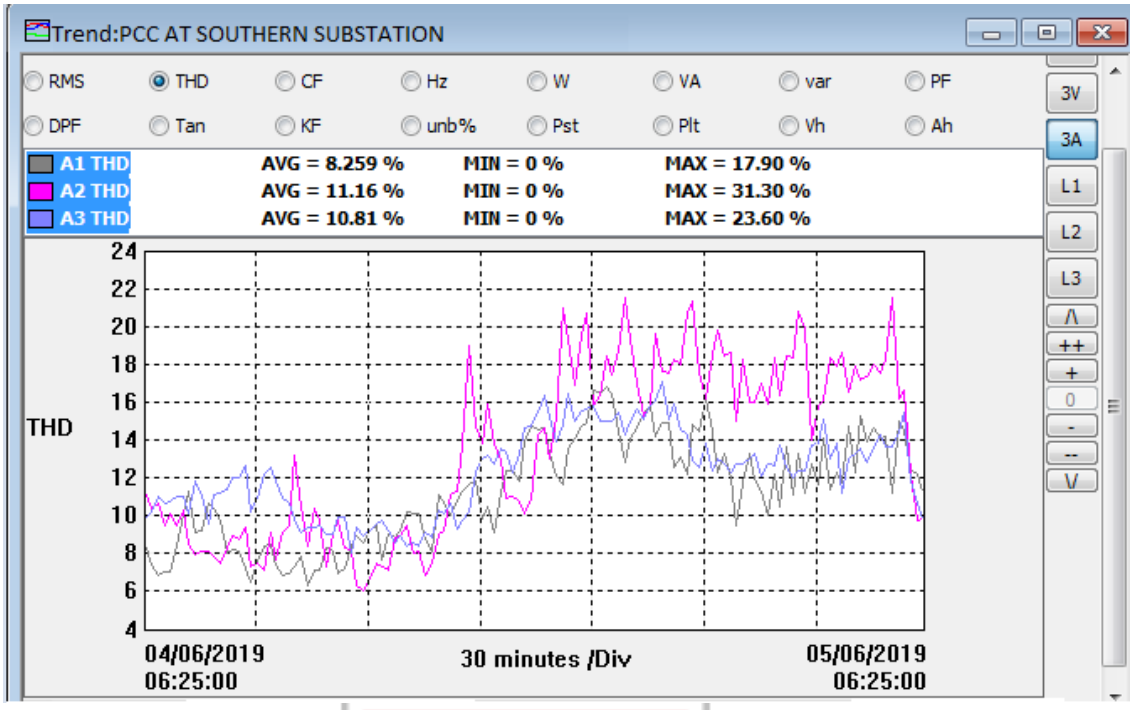

Fig. C33 Waveforms of THD_I at the Southern PCC

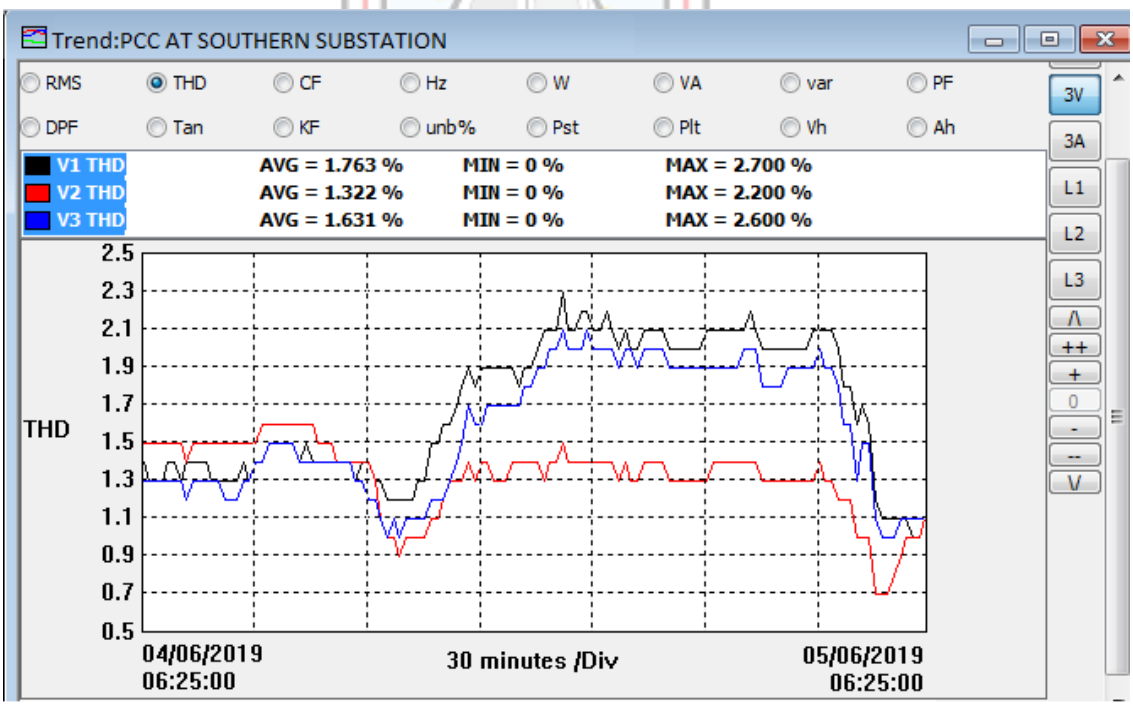

Fig. C34 Waveforms of THD_V at the Southern PCC

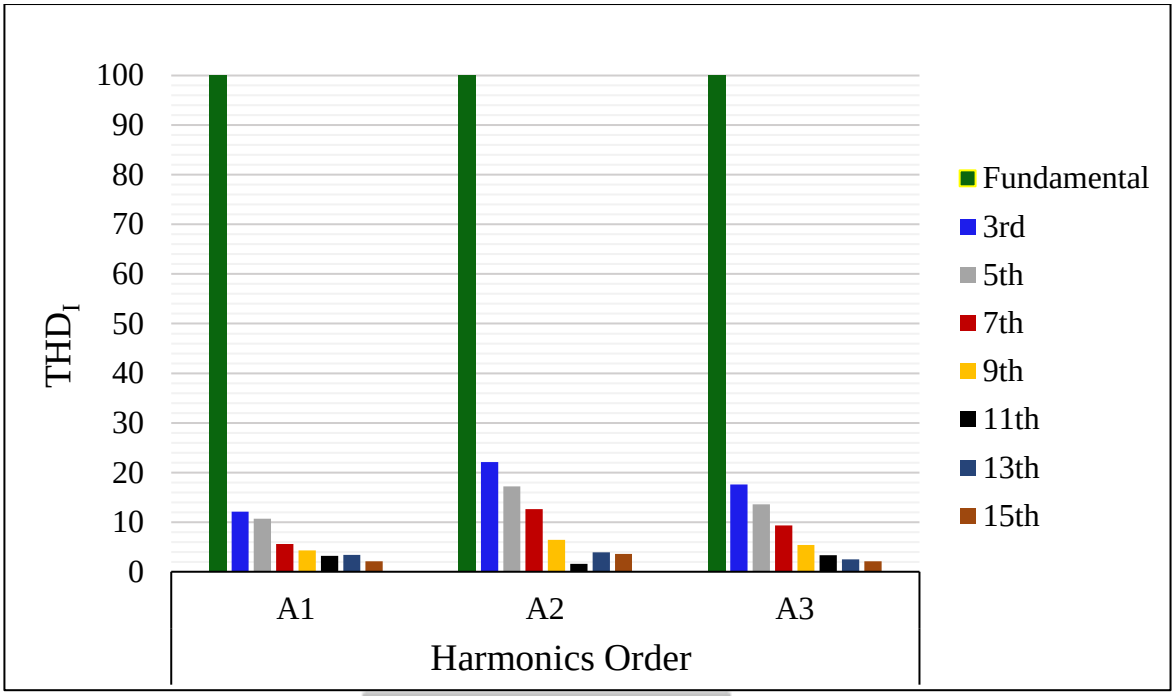

Fig. C35 Harmonic Current Spectrum for Southern PCC

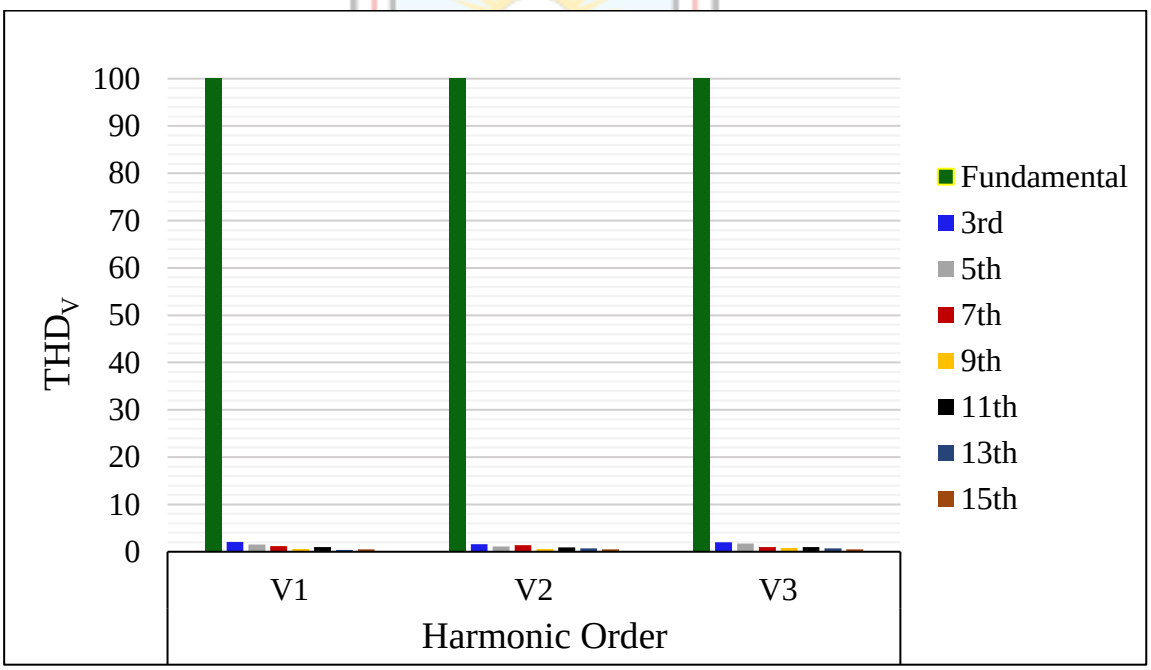

Fig. C36 Harmonic Voltage Spectrum for Southern PCC

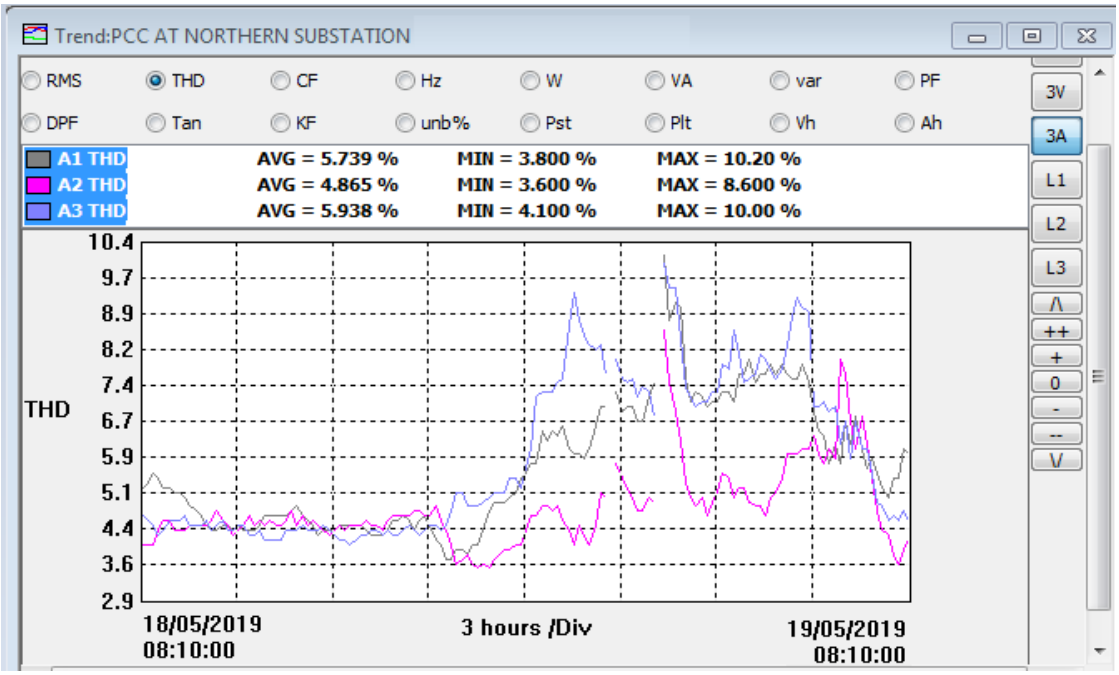

Fig. C37 Waveforms of THD_I obtained at the Northern Substation PCC

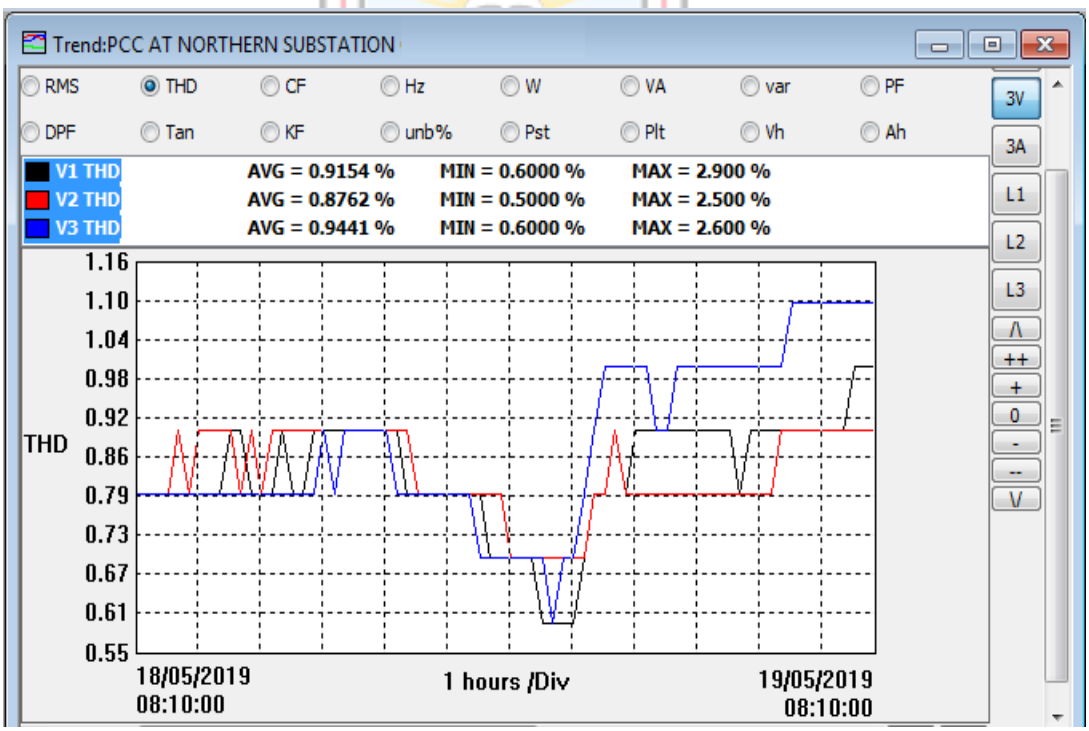

Fig. C38 Waveforms of THD_V at the Northern PCC

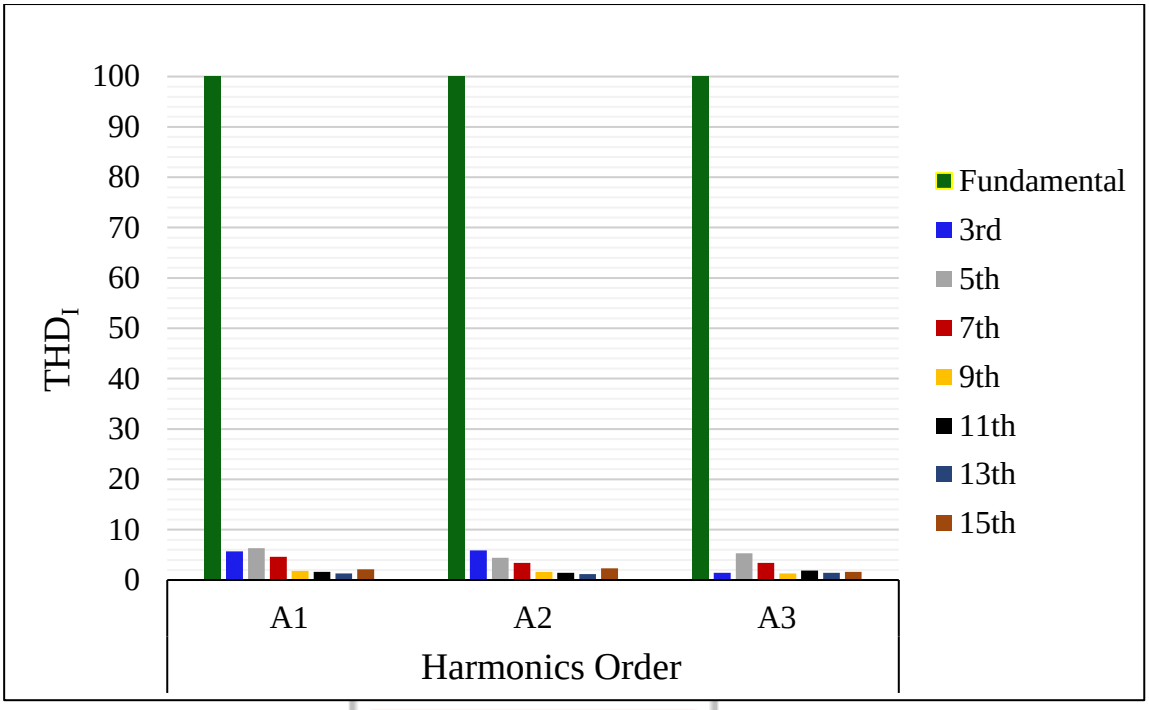

Fig. C39 Harmonic Current Spectrum for Northern PCC

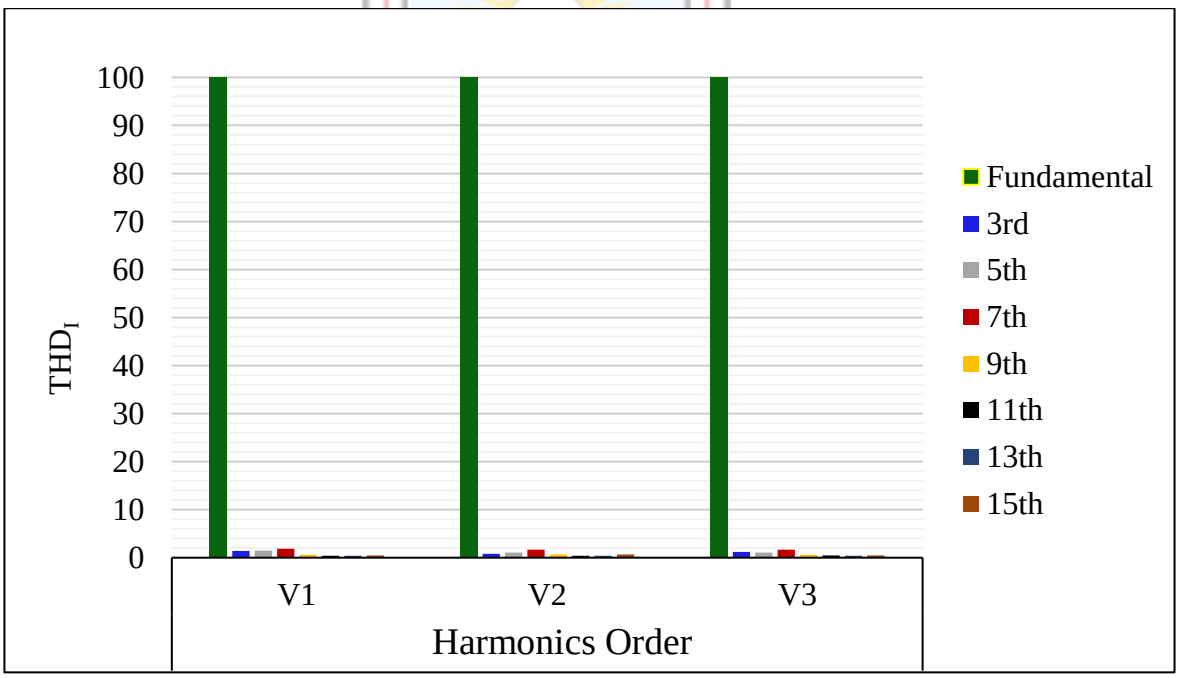

Fig. C40 Harmonic Voltage Spectrum for Northern PCC

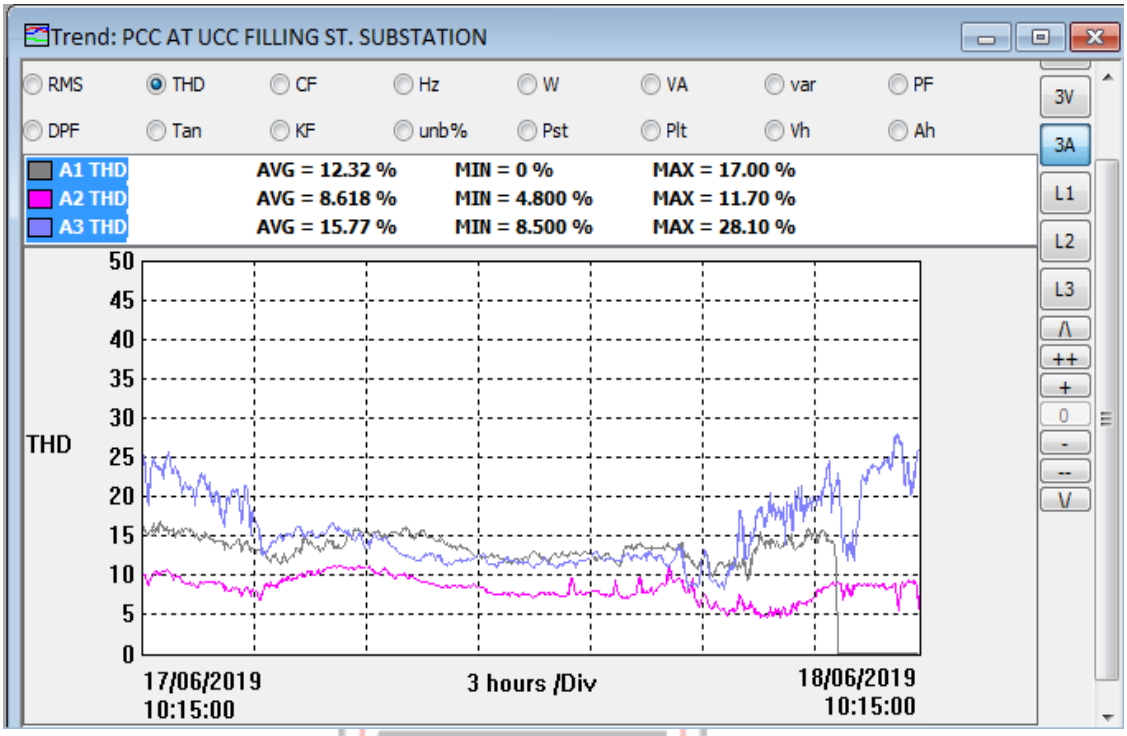

Fig. C41 Waveforms of THD_I at the UCC Filling St. PCC

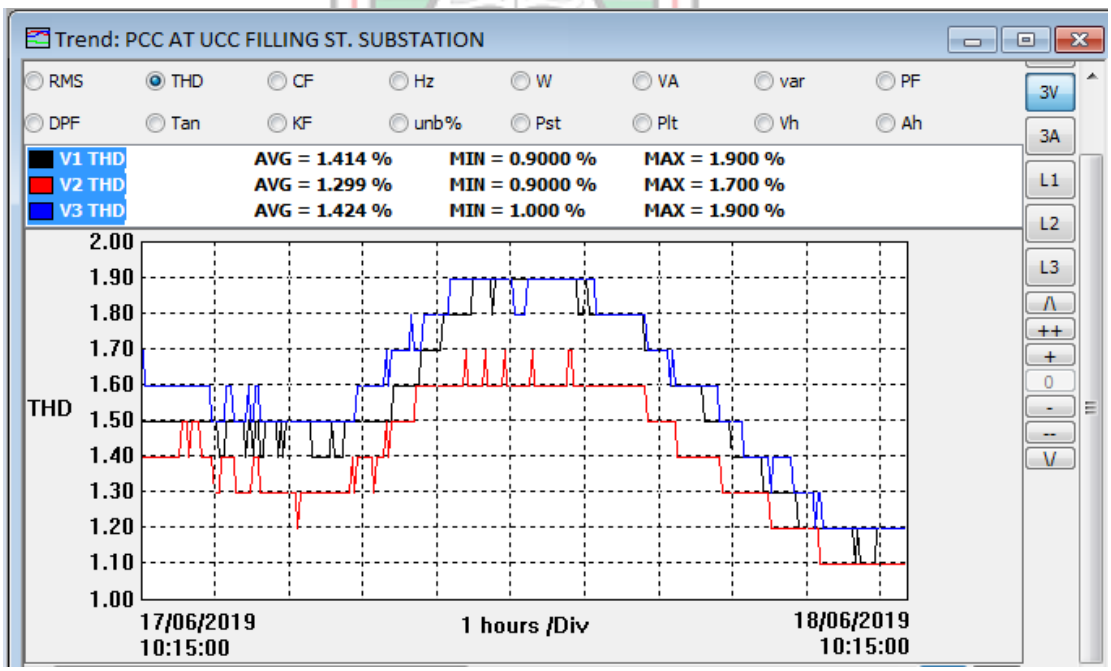

Fig. C42 Waveforms of THD_V at the UCC Filling St. PCC

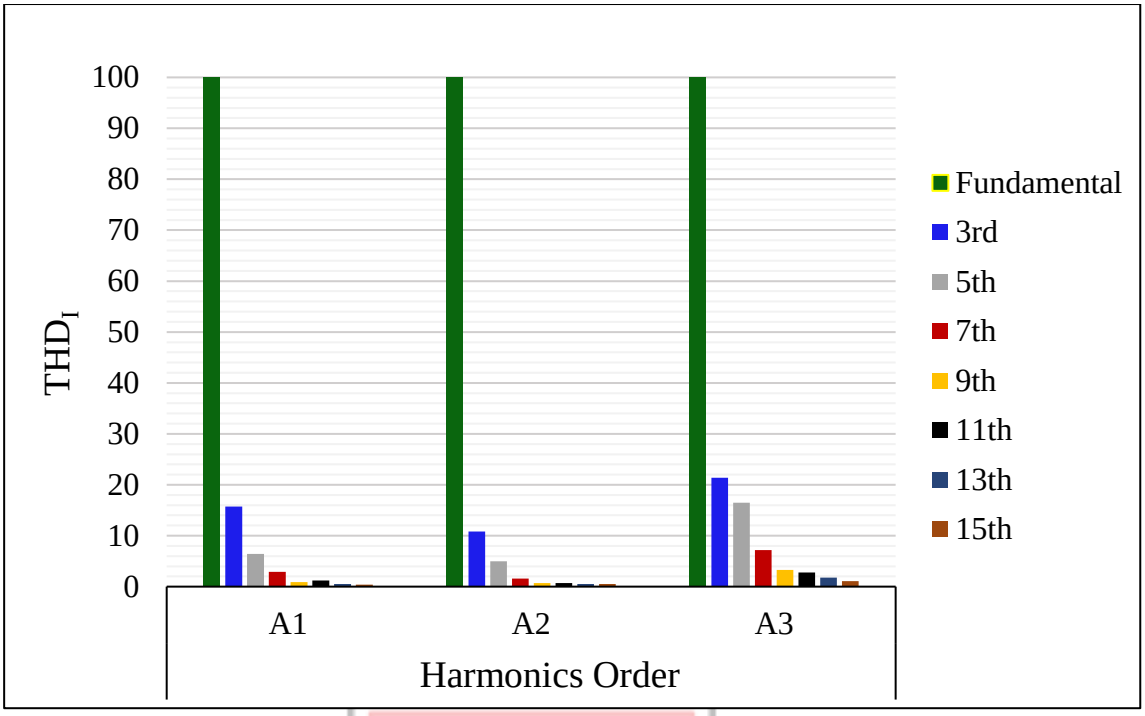

Fig. C43 Harmonic Voltage Spectrum for Filling Station PCC

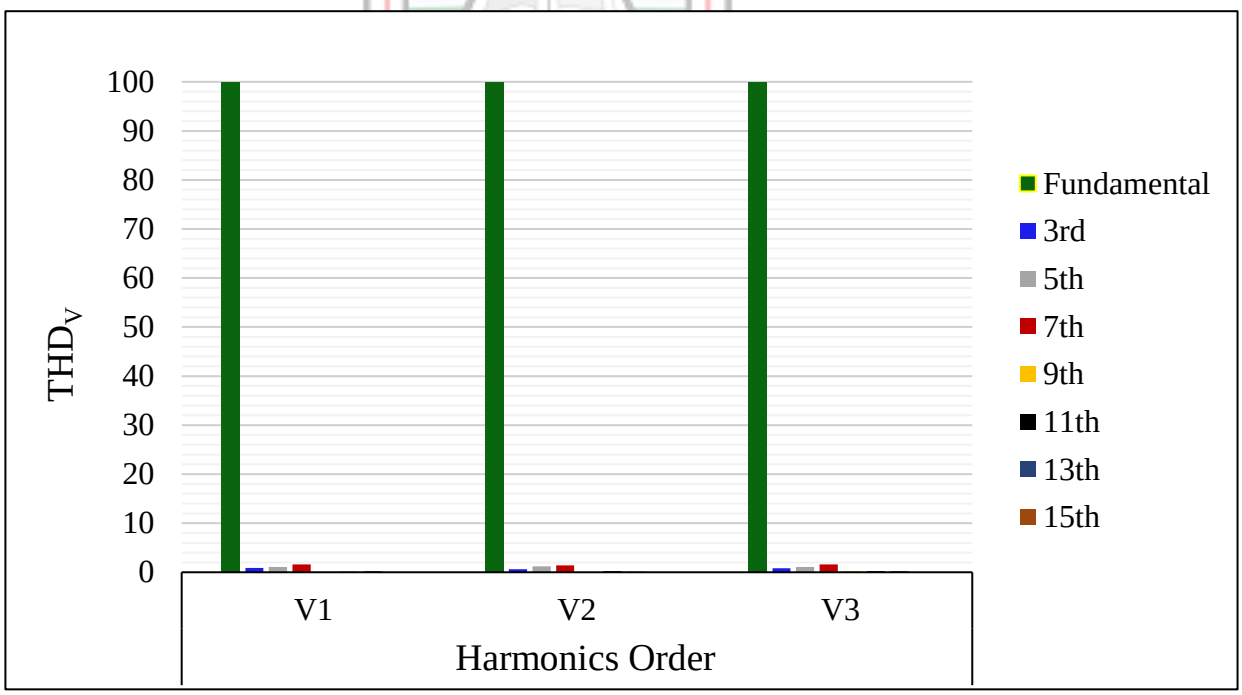

Fig. C44 Harmonic Voltage Spectrum for Filling Station PCC

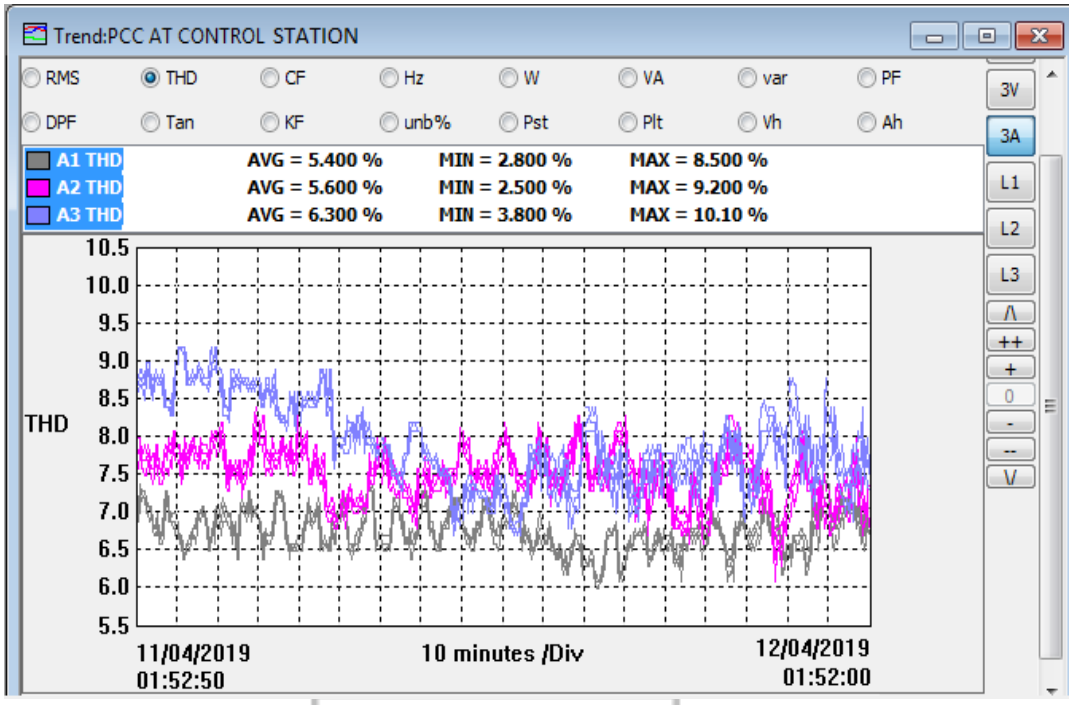

Fig. C45 Waveforms of THD_I at the Control Station PCC

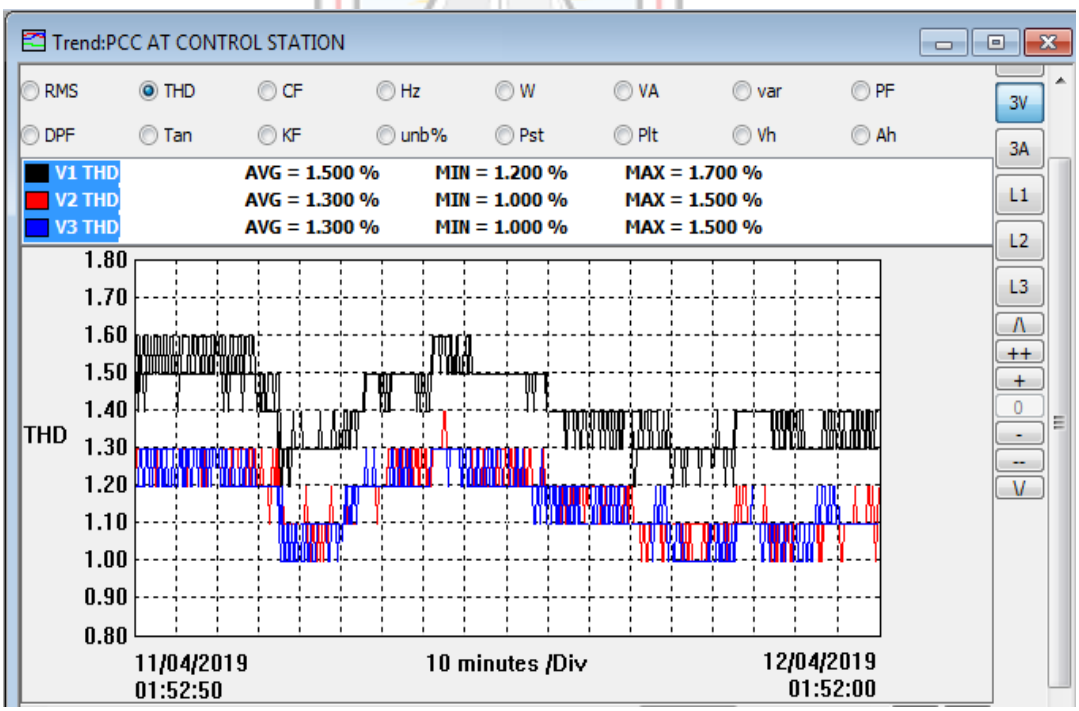

Fig. C46 Waveforms of THD_V at the Control Station PCC

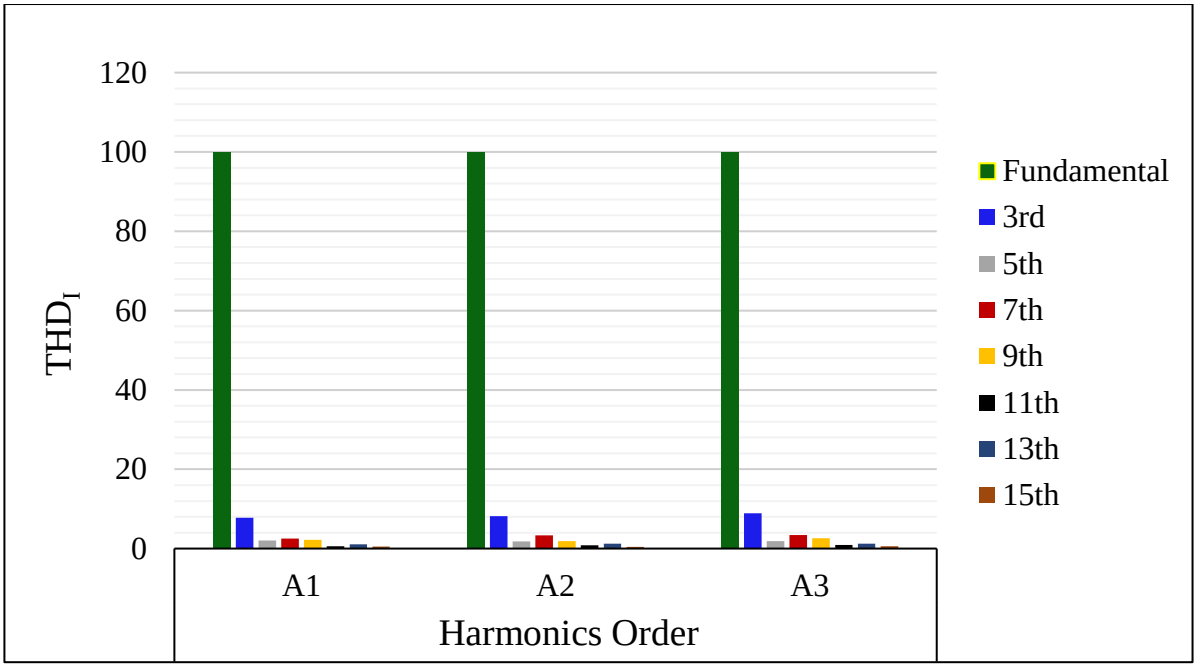

Fig. C47 Harmonic Current Spectrum for Control Station PCC

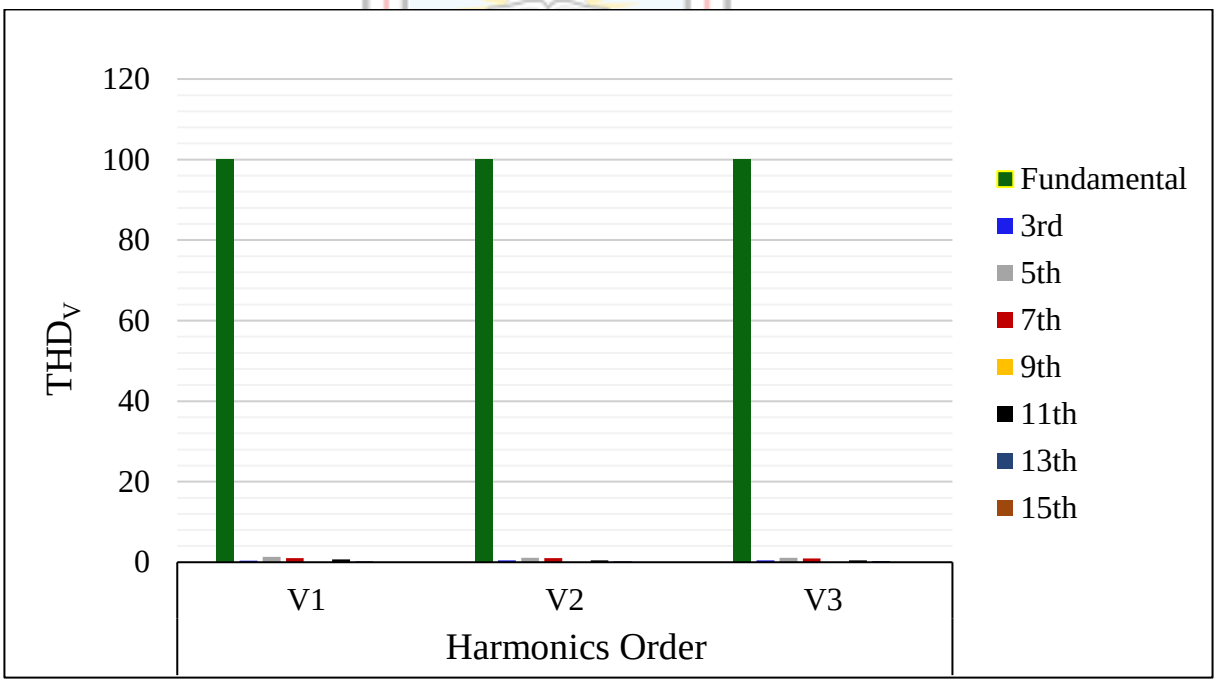

Fig. C48 Harmonic Voltage Spectrum for Control Station PCC

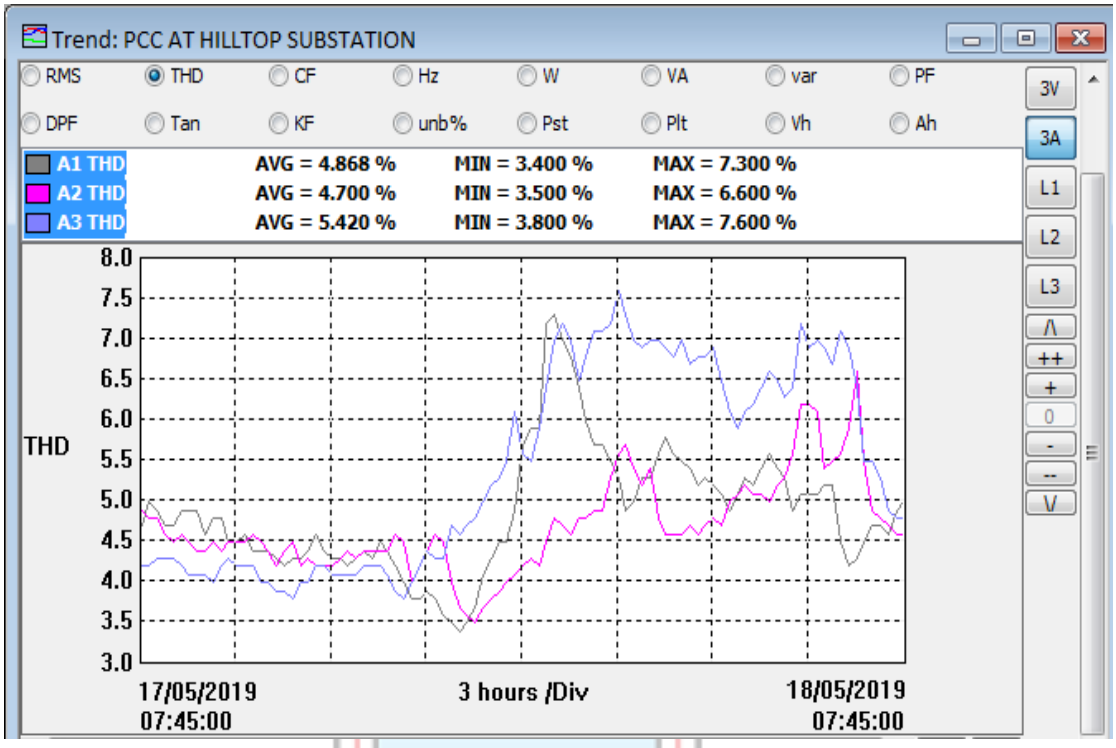

Fig. C49 Waveforms of THD_I at the Hilltop PCC

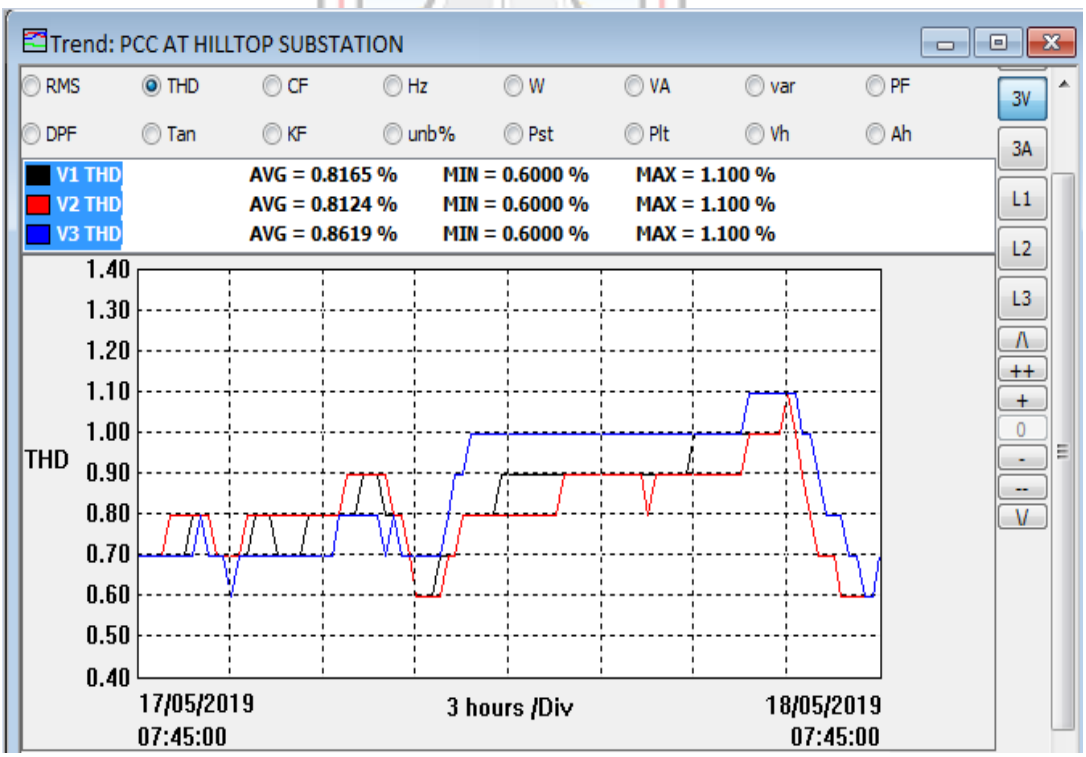

Fig. C50 Waveforms of THD_V at the Hilltop PCC

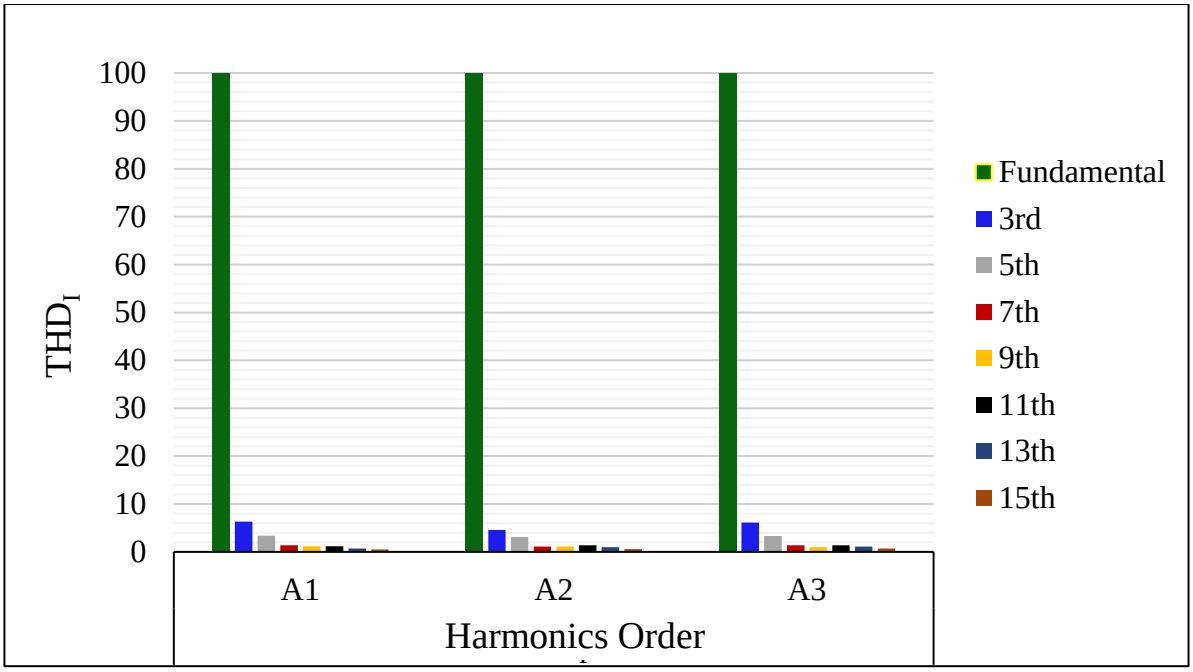

Fig. C51 Harmonic Current Spectrum for Hilltop PCC

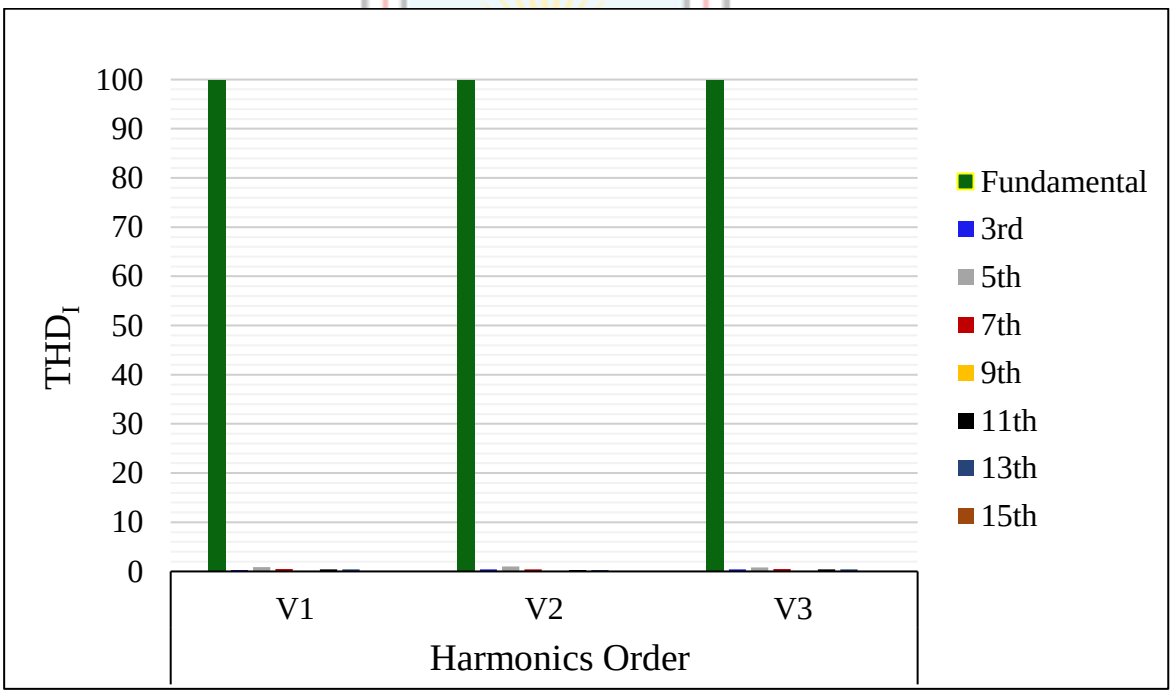

Fig. C52 Harmonic Voltage Spectrum for Hilltop PCC

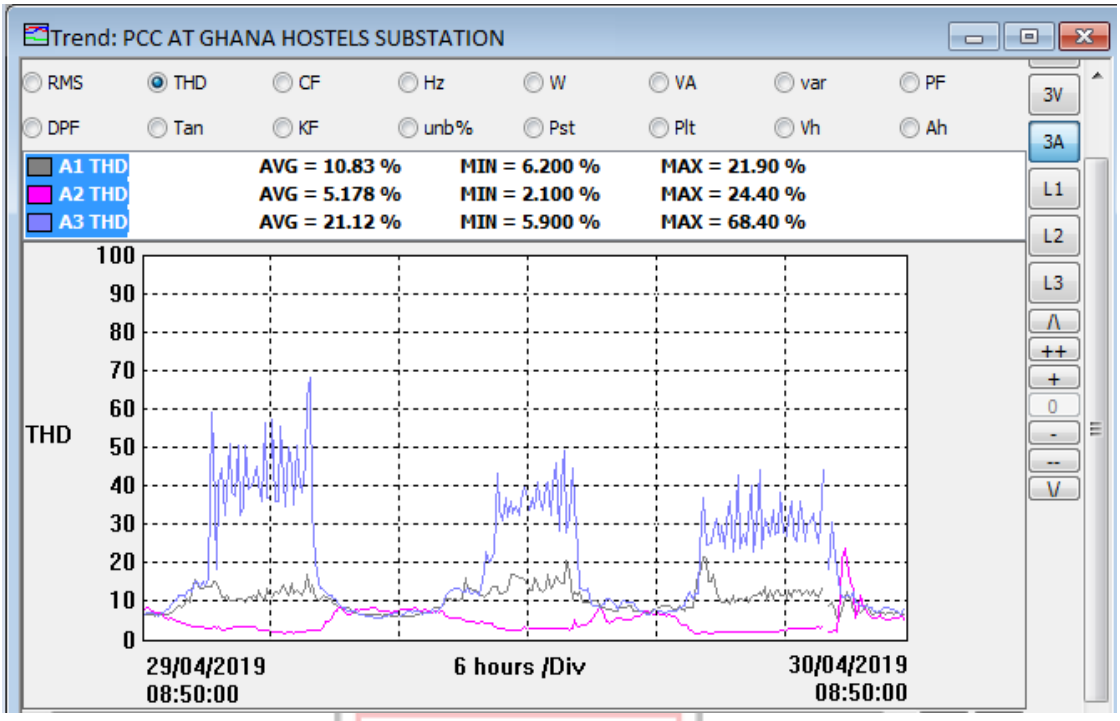

Fig. C53 Waveforms of THD_I at the Ghana Hostels PCC

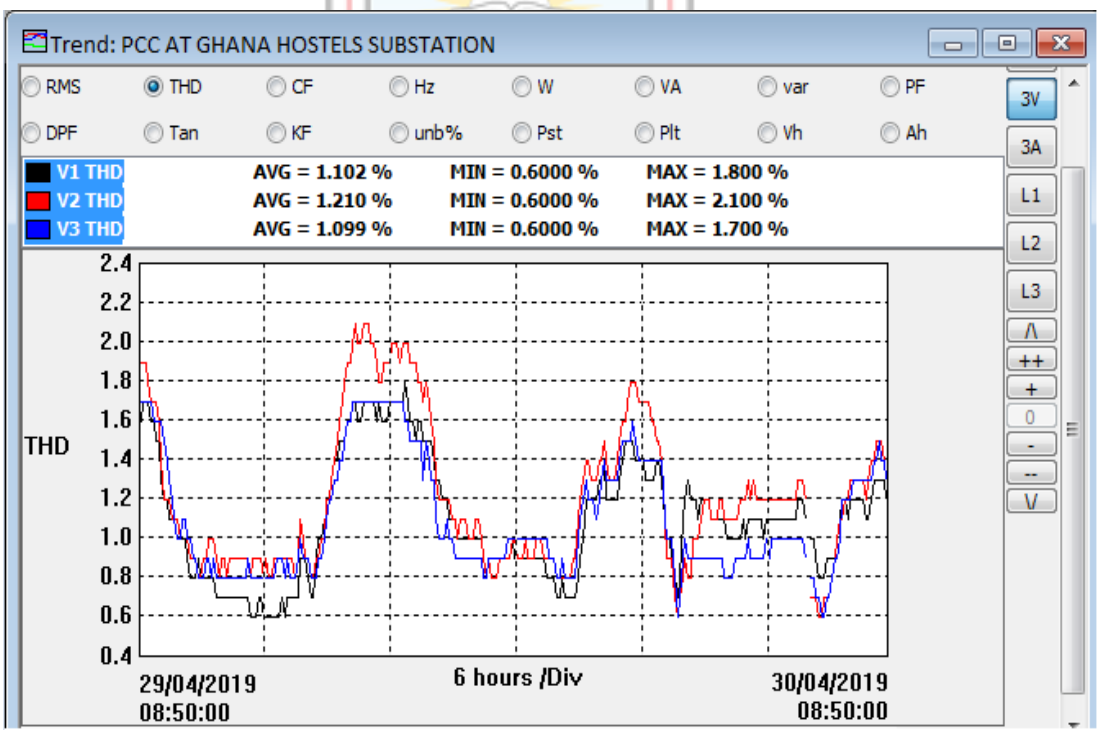

Fig. C54 Waveforms of THD_V at the Ghana Hostels PCC

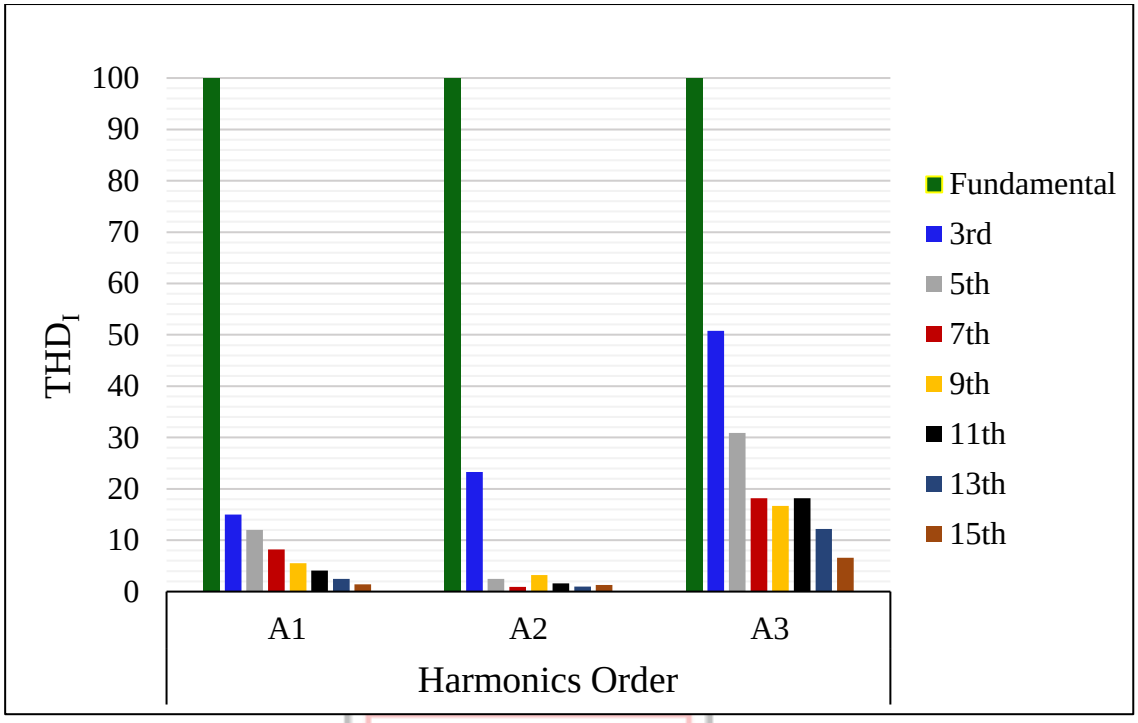

Fig. C55 Harmonic Current Spectrum for Ghana Hostels PCC

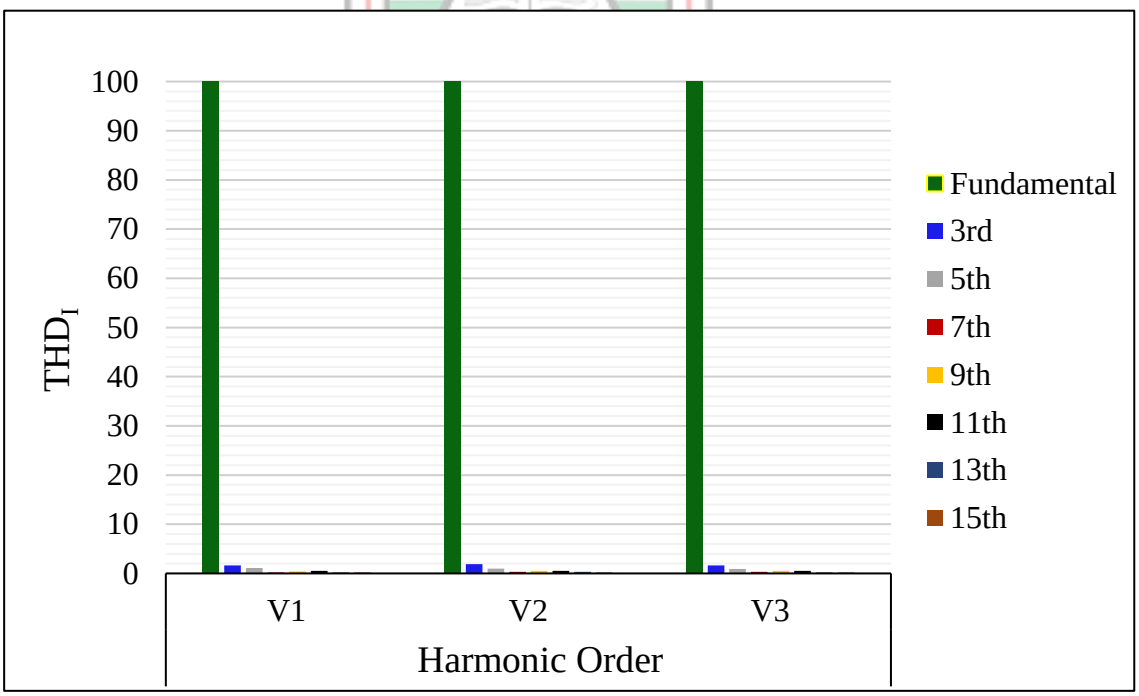

Fig. C56 Harmonic Voltage Spectrum for Ghana Hostels PCC

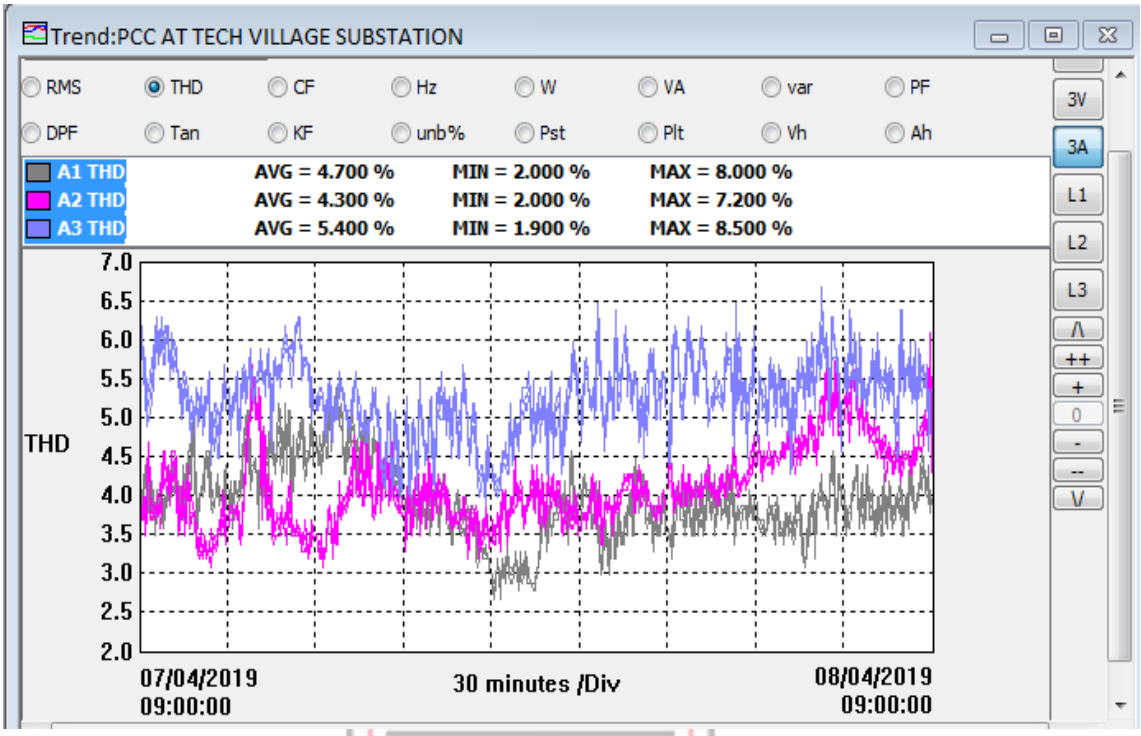

Fig. C57 Waveforms for THD_I at the Tech Village PCC

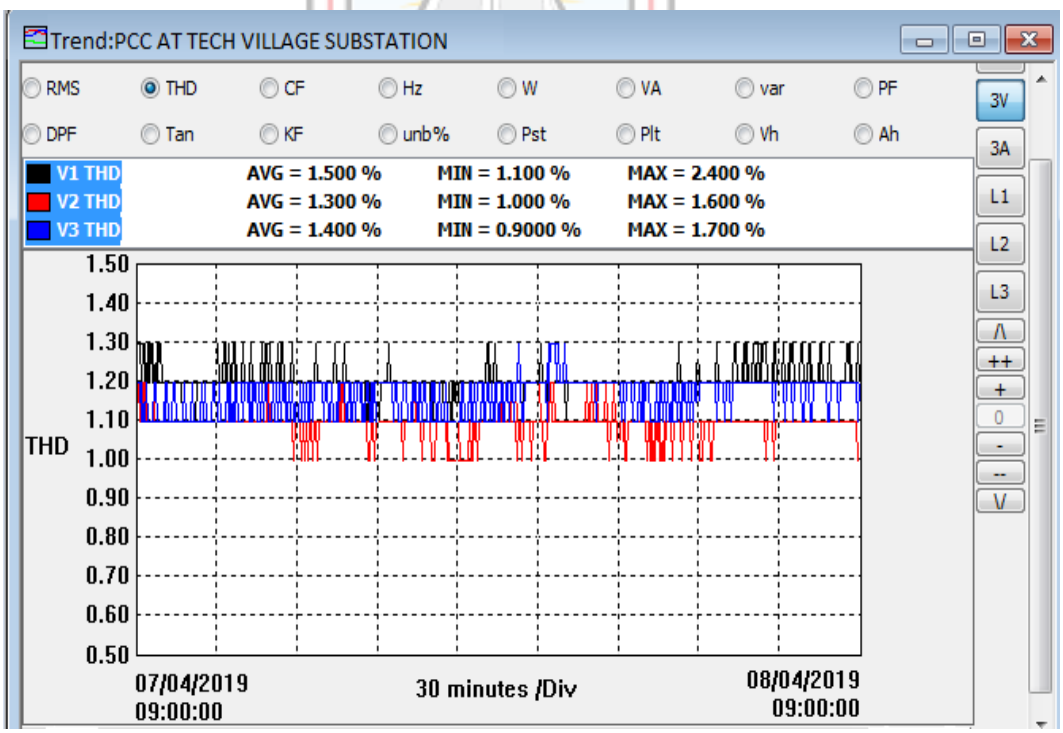

Fig. C58 Waveforms for THD_V at the Tech Village PCC

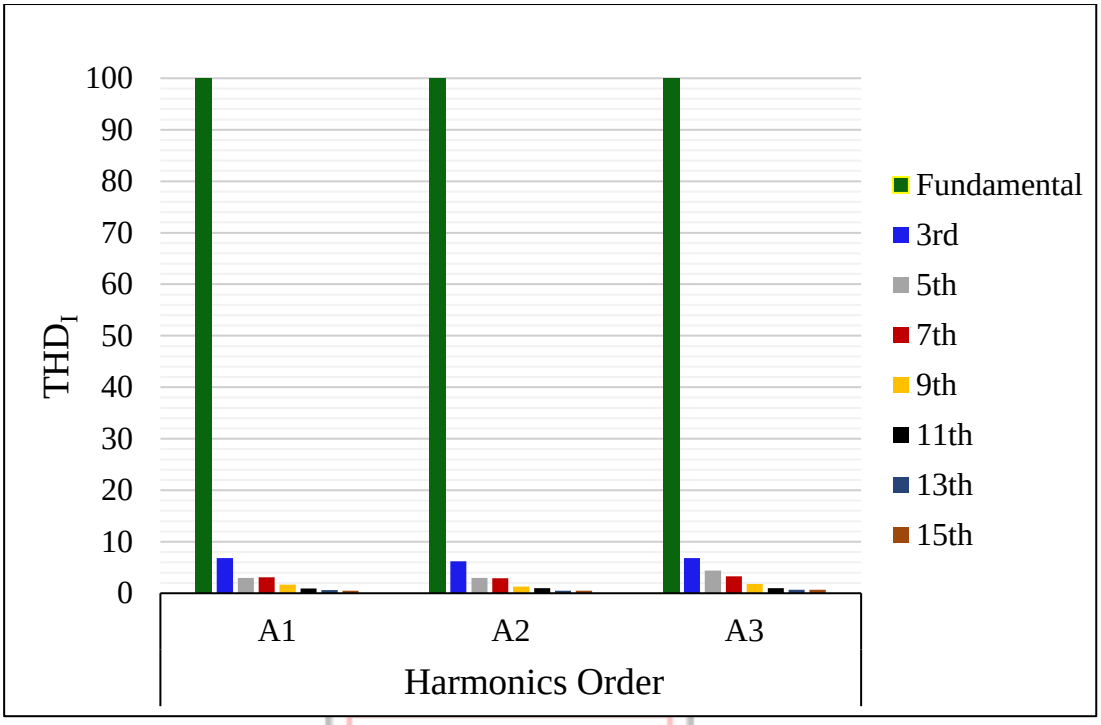

Fig. C59 Harmonic Current Spectrum for Tech Village PCC

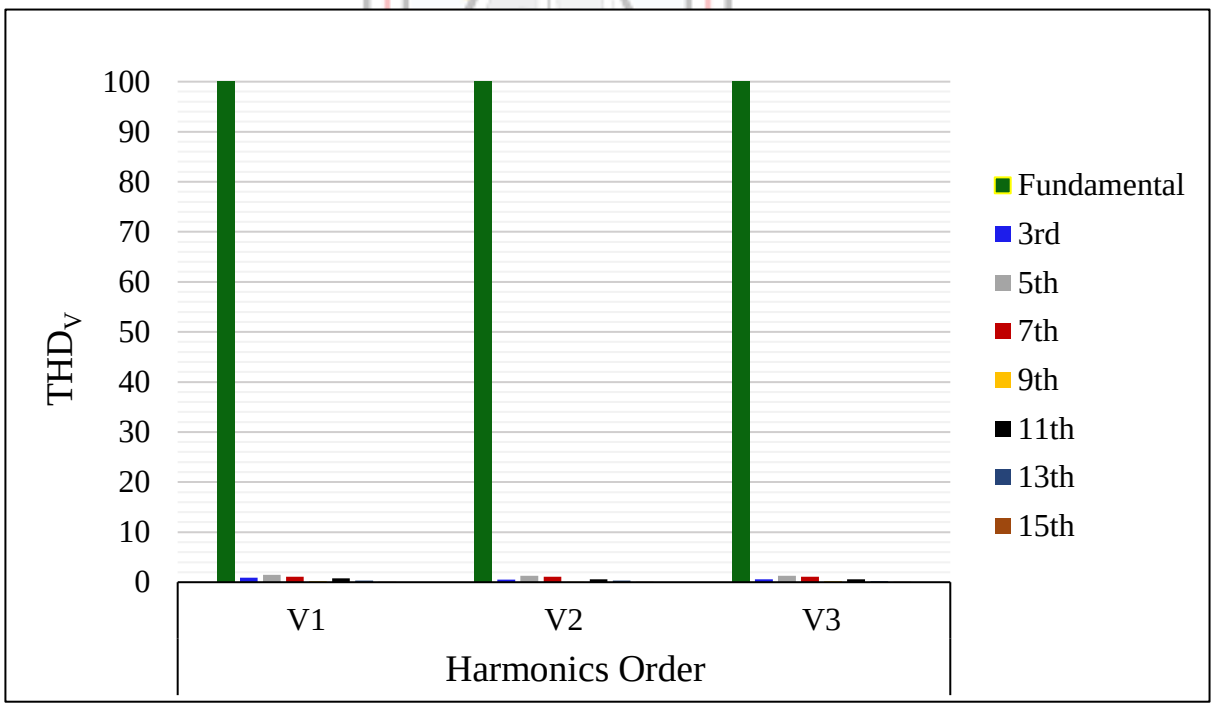

Fig. C60 Harmonic Voltage Spectrum for Tech Village PCC

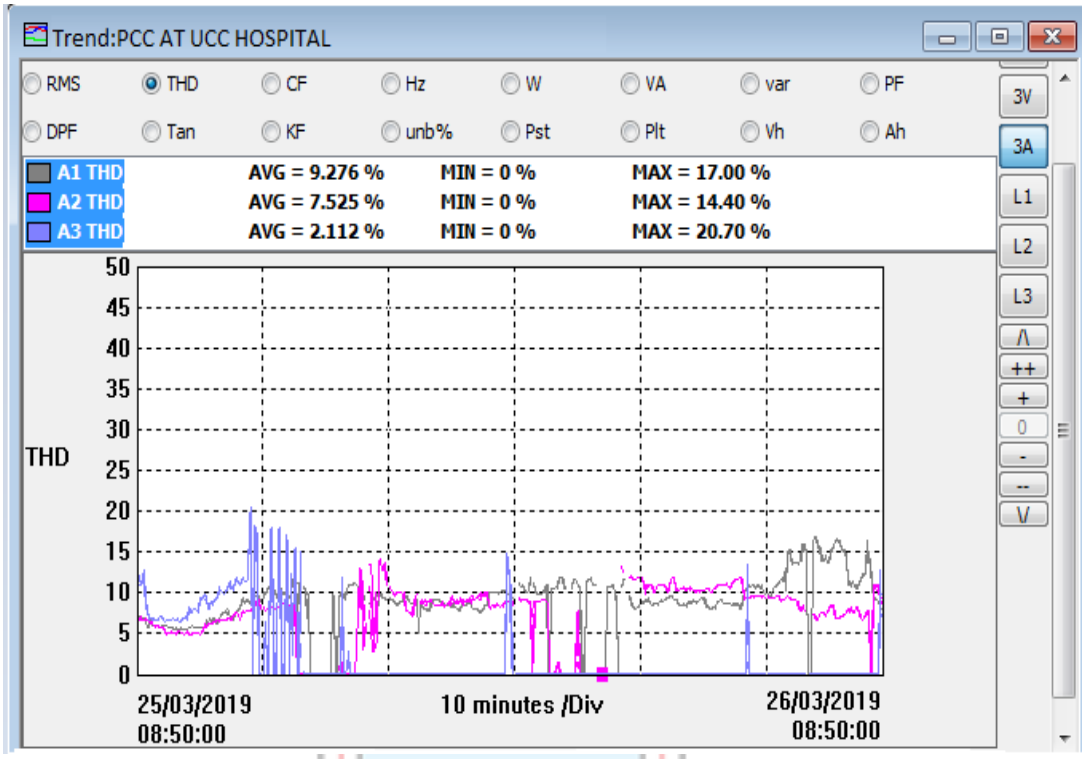

Fig. D61 Waveforms of THD_I at the University Hospital PCC

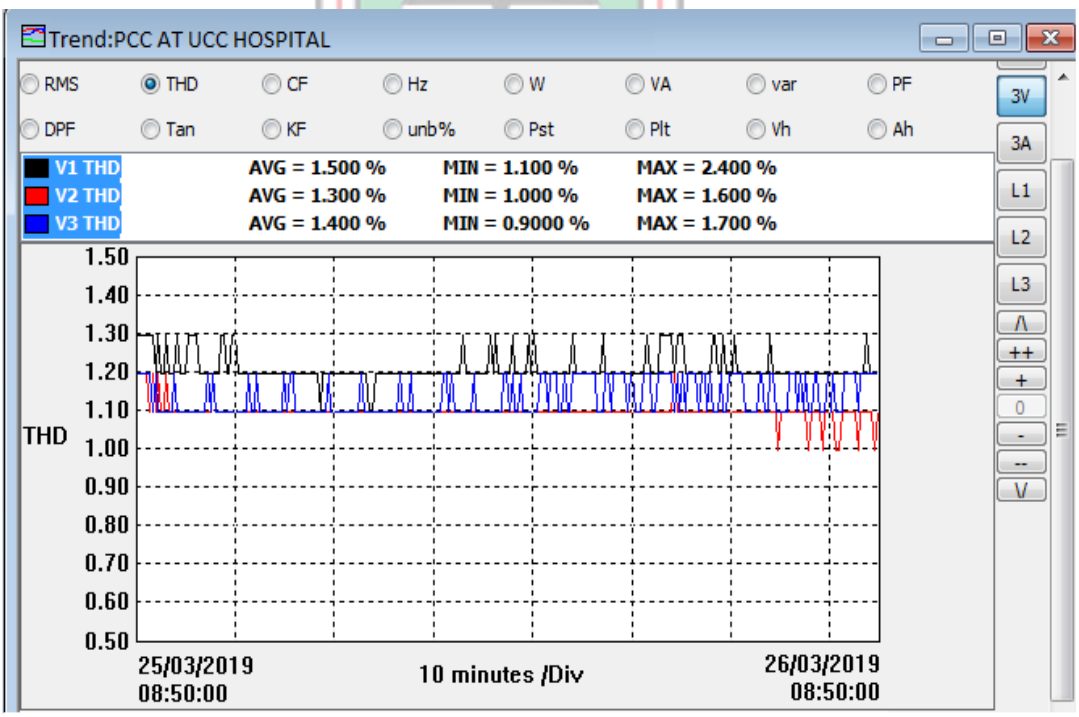

Fig. C62 Waveforms for THD_V at the University Hospital PCC

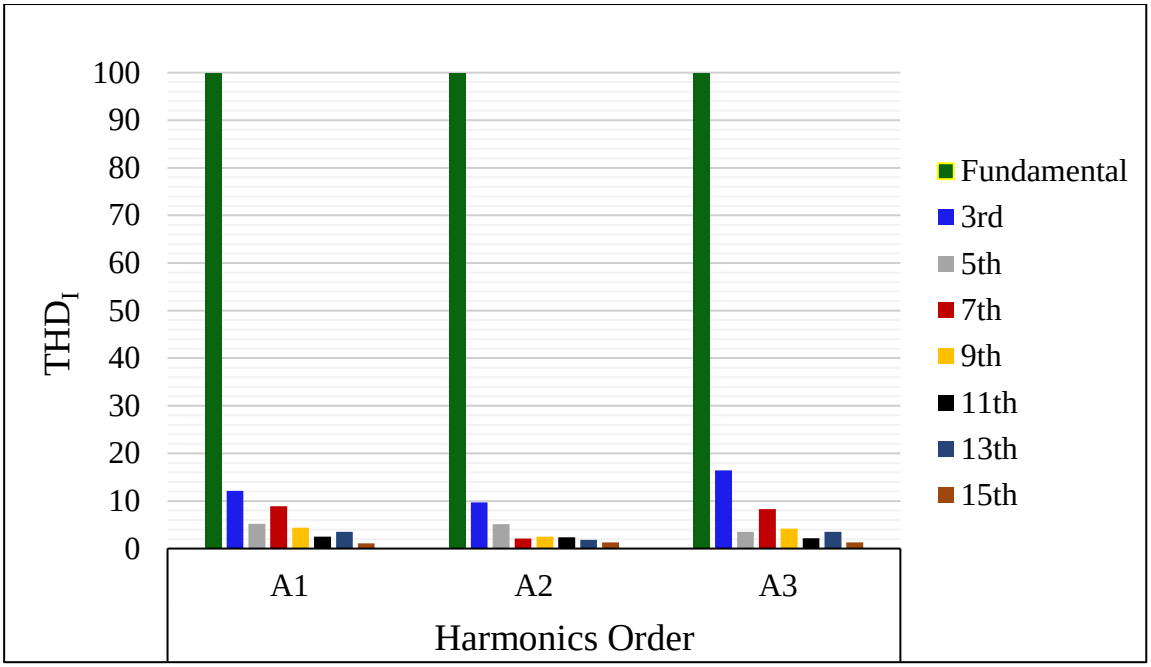

Fig. C63 Harmonic Voltage Spectrum for UCC Hospital PCC

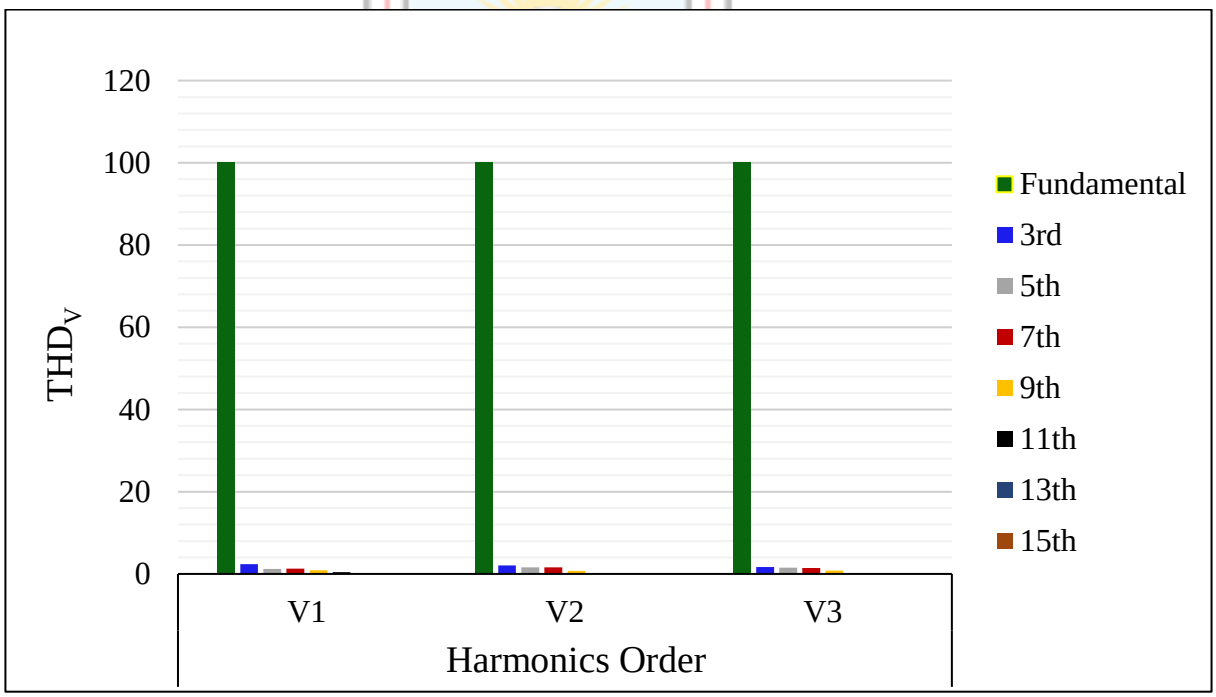

Fig. C64 Harmonic Voltage Spectrum for UCC Hospital PCC

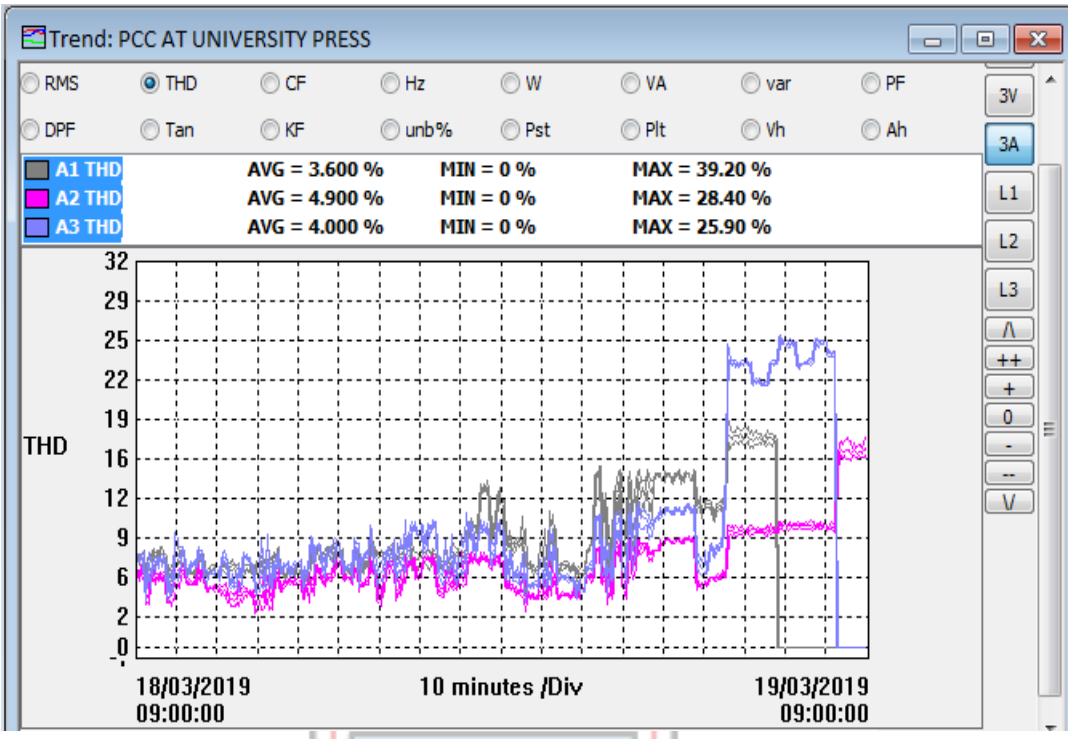

Fig. C65 Waveforms for THD_I at the University Press PCC

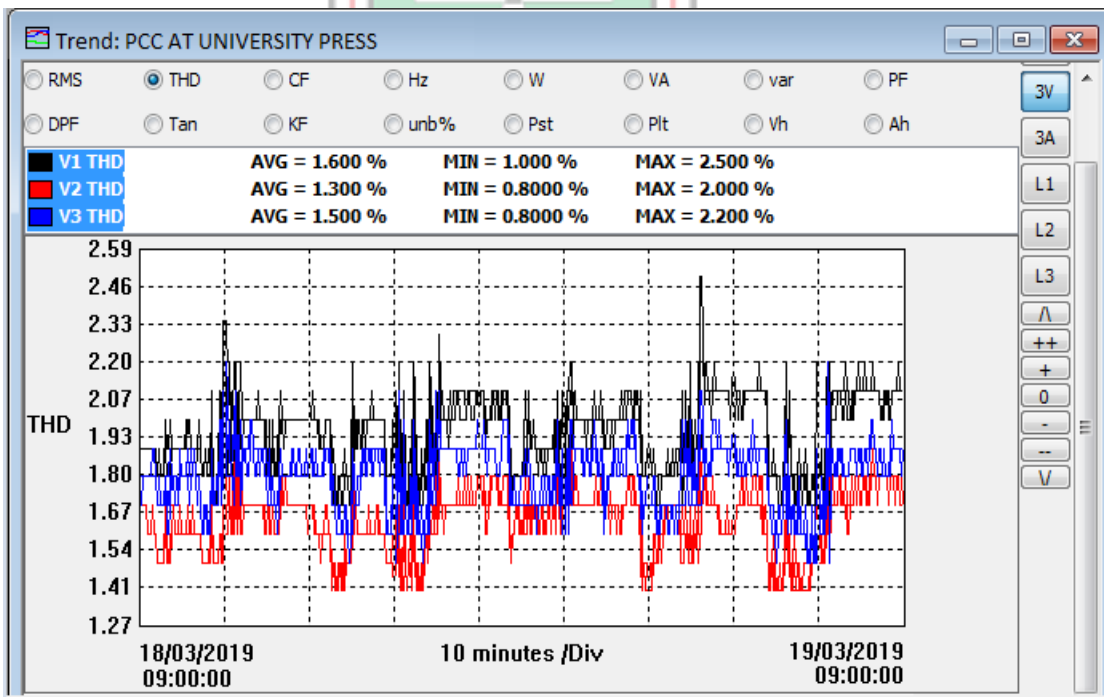

Fig. C66 Waveforms for THD_V at the University Press PCC

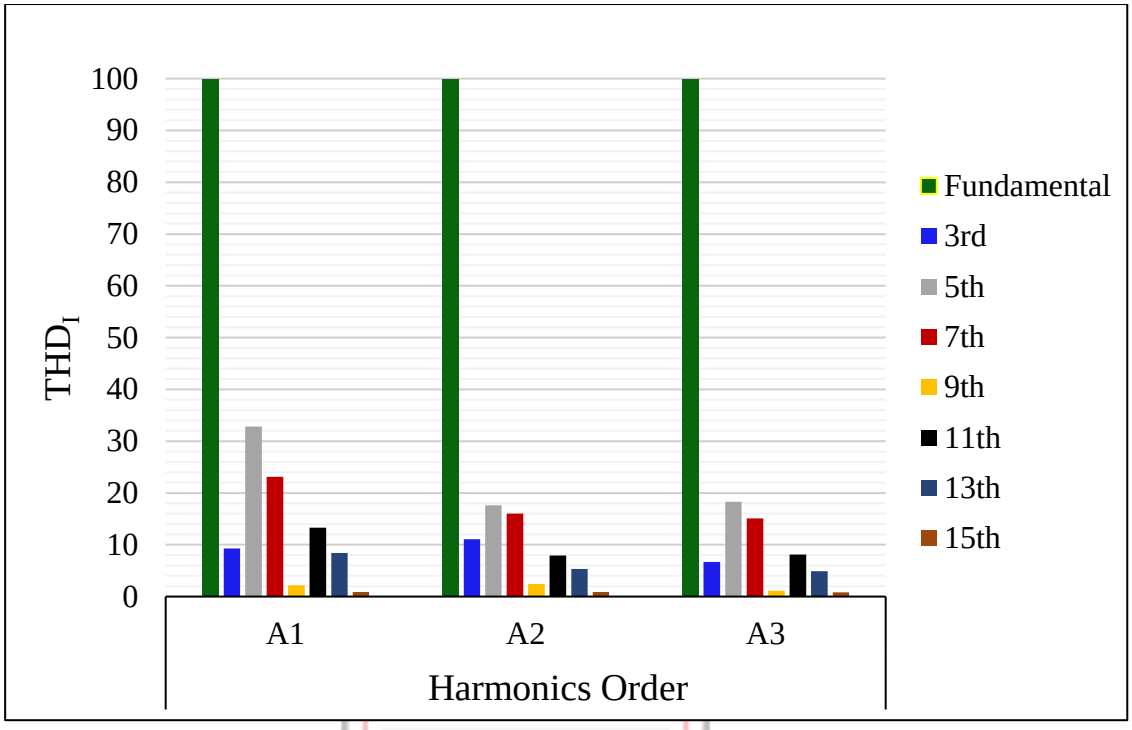

Fig. C67 Harmonic Voltage Spectrum for University Press PCC

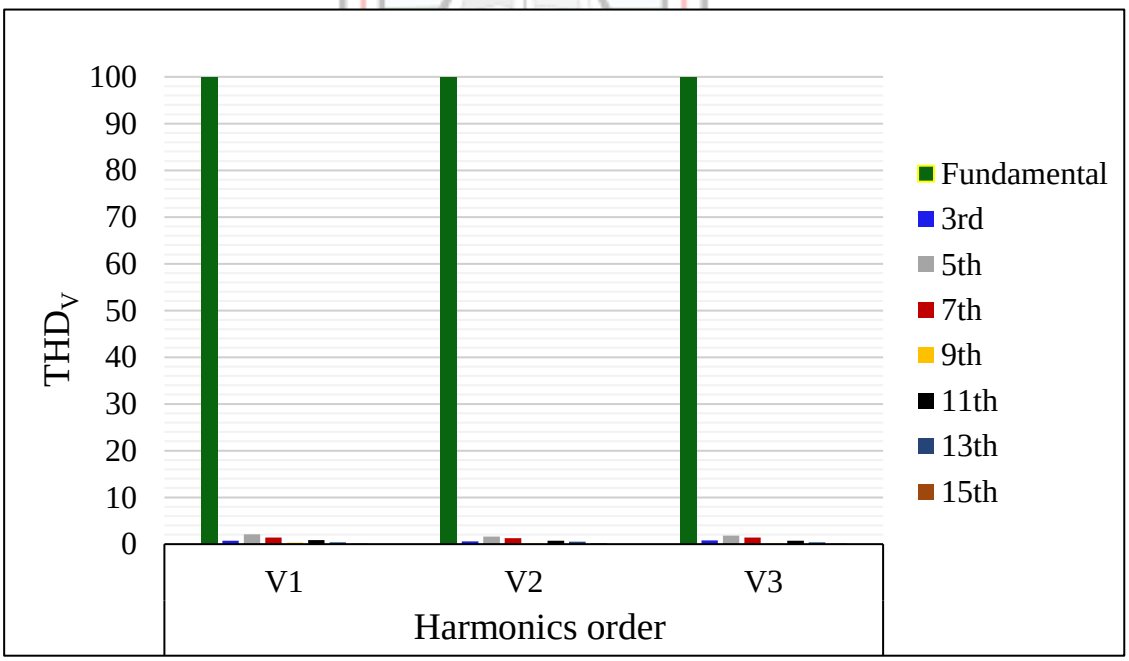

Fig. C68 Harmonic Voltage Spectrum for University Press PCC

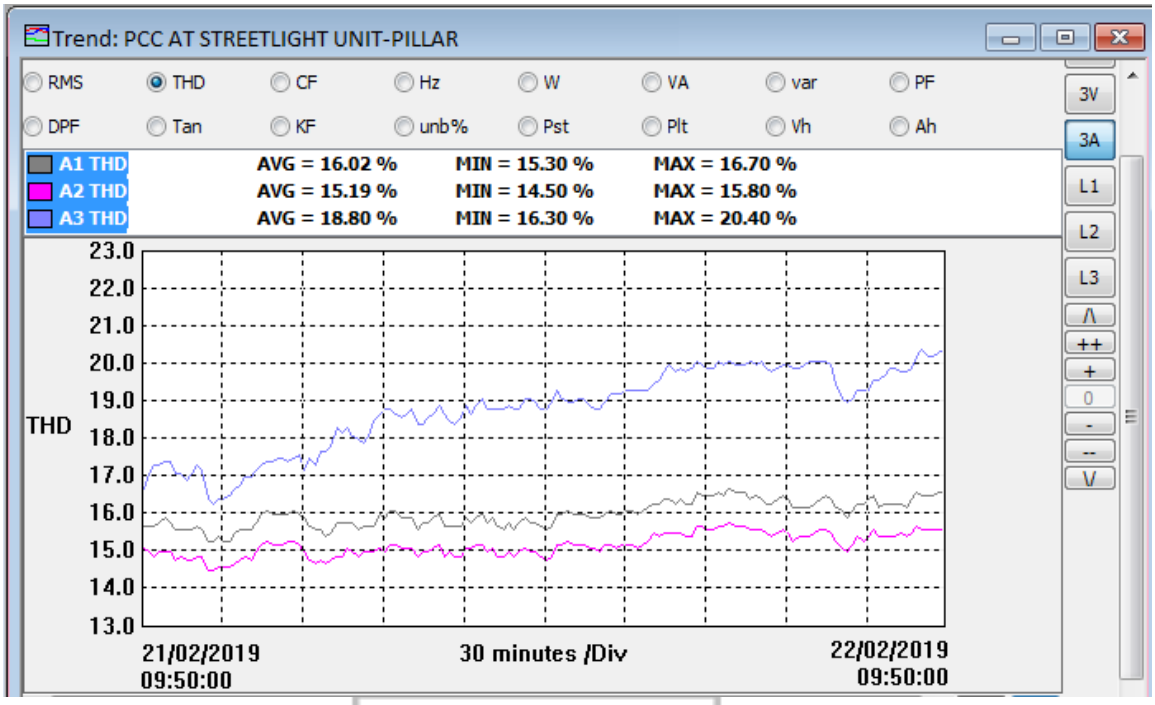

Fig.D69 Waveforms of THD_I at the Streetlight PCC

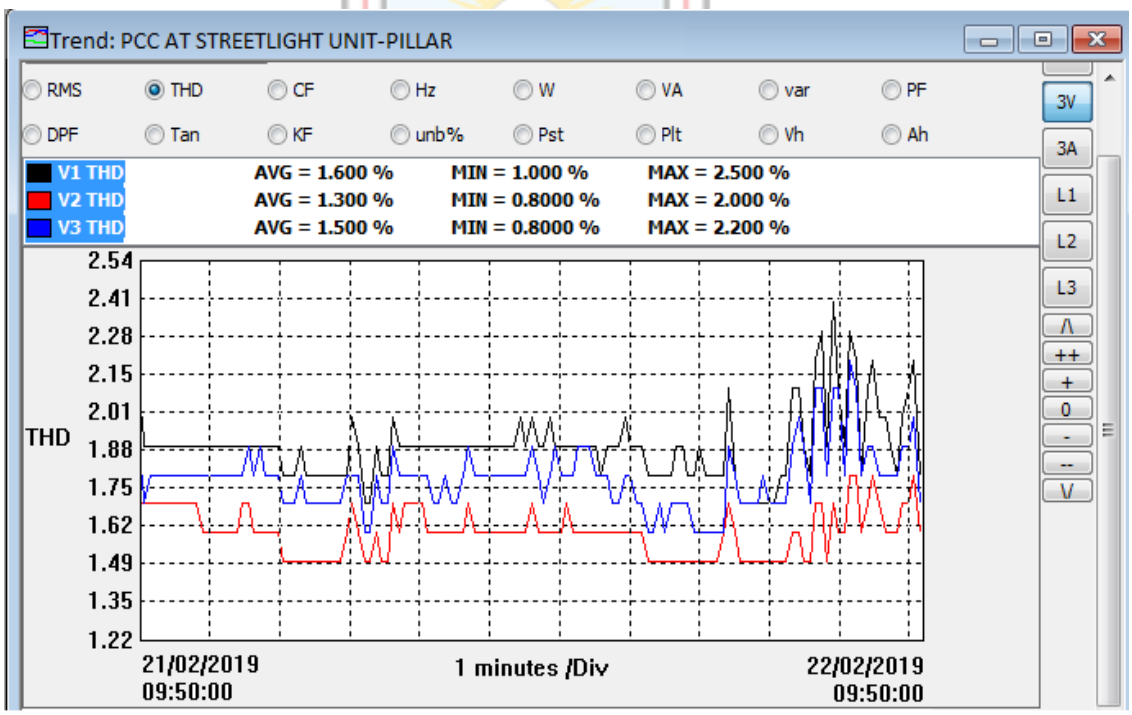

Fig. C70 Waveforms of THD_V at the Streetlight PCC

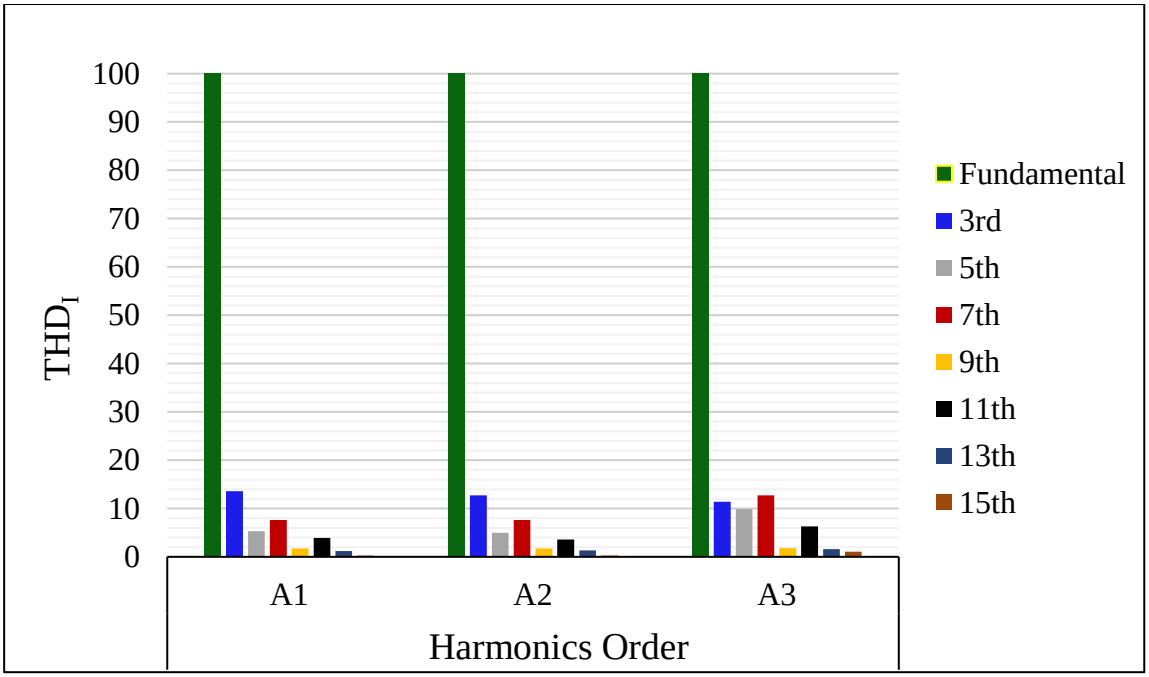

Fig. C71 Harmonic Current Spectrum for Streetlights PCC

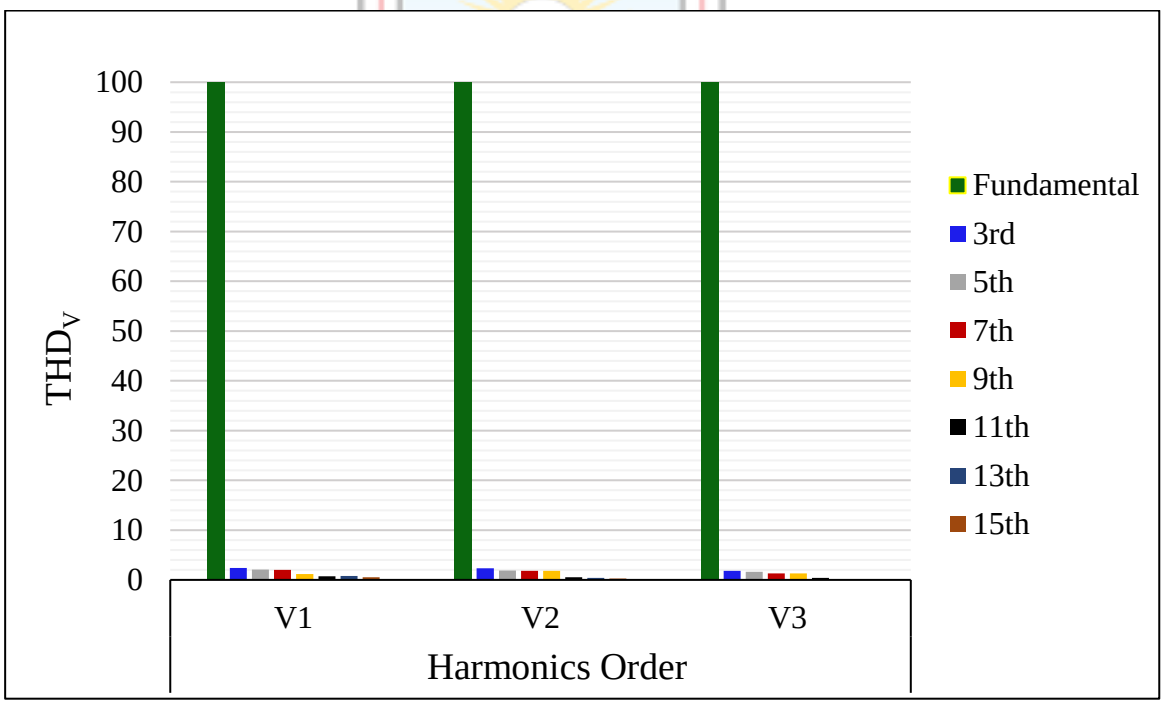

Fig. C72 Harmonic Voltage Spectrum for Streetlights PCC

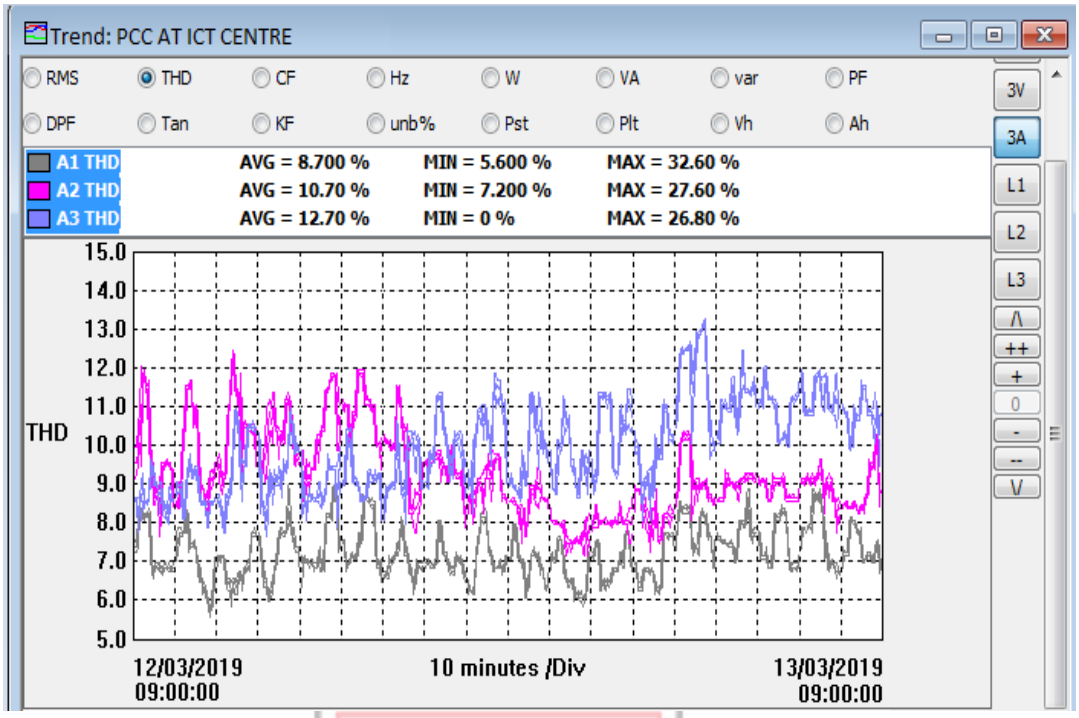

Fig. C73 Waveforms of THD_I at the ICT Centre PCC

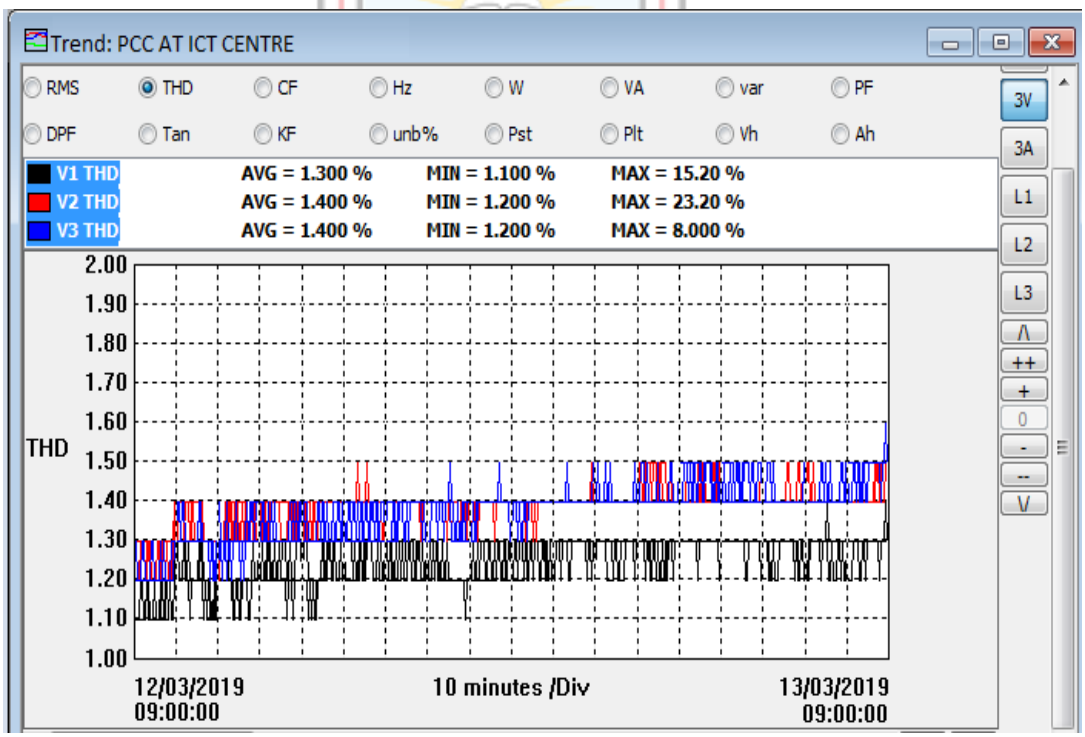

Fig. C74 Waveforms of THD_V at the ICT Centre PCC

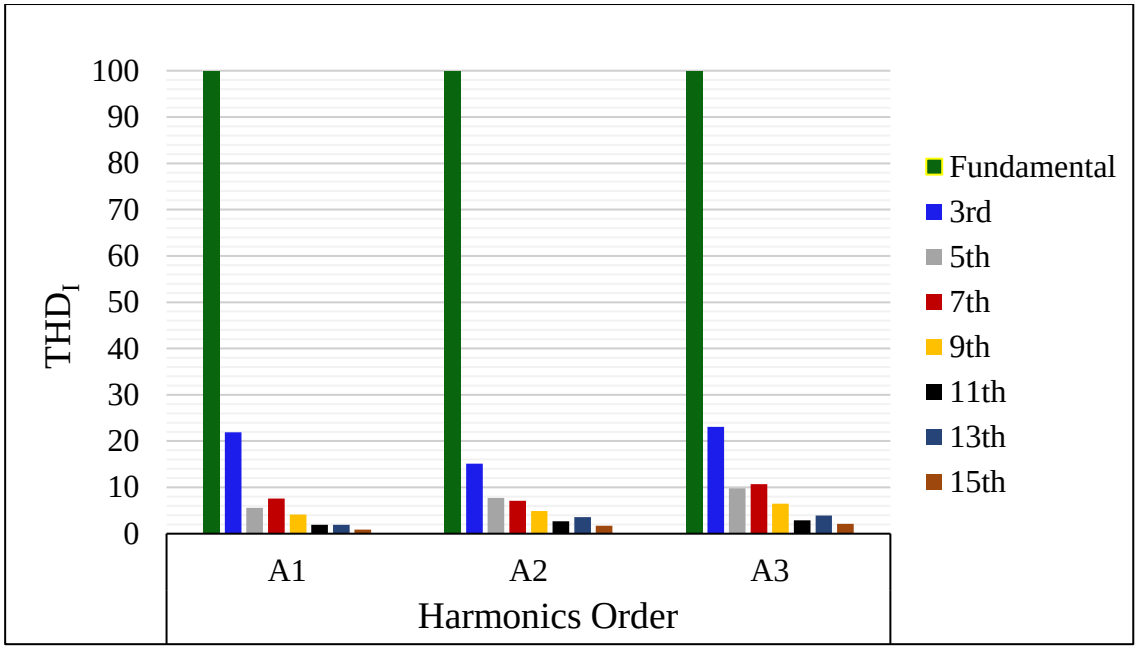

Fig. C75 Harmonic Current Spectrum for ICT Centre PCC

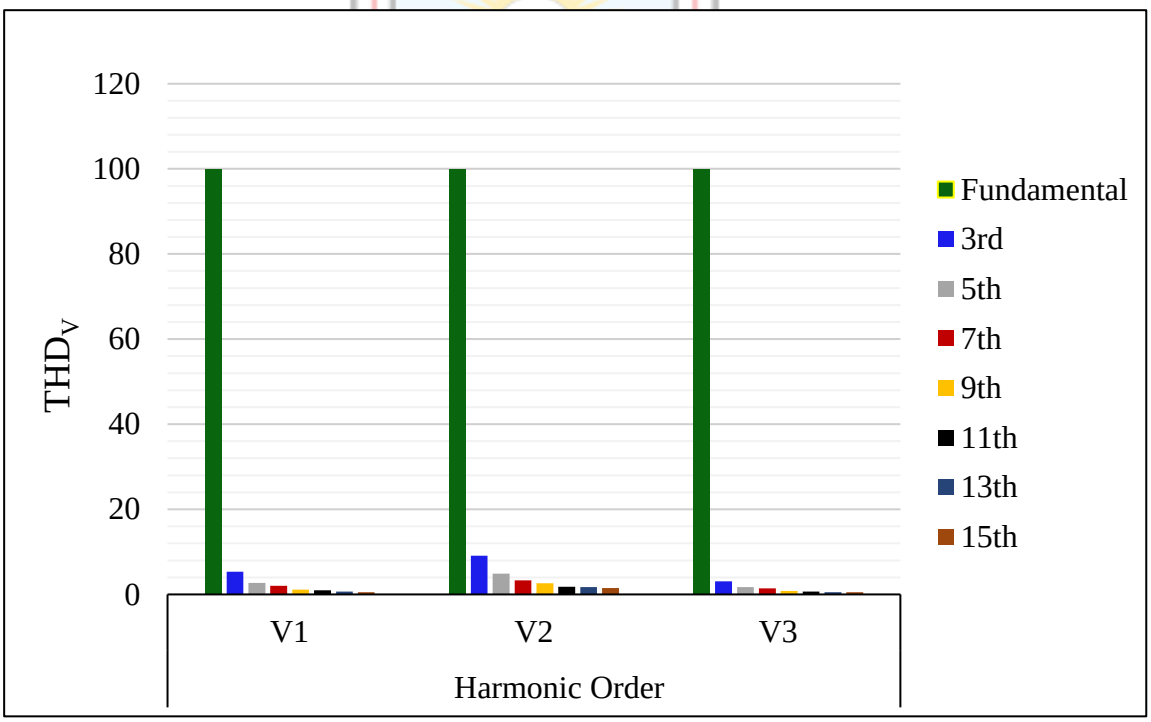

Fig. C76 Harmonic Voltage Spectrum for ICT Centre PCC

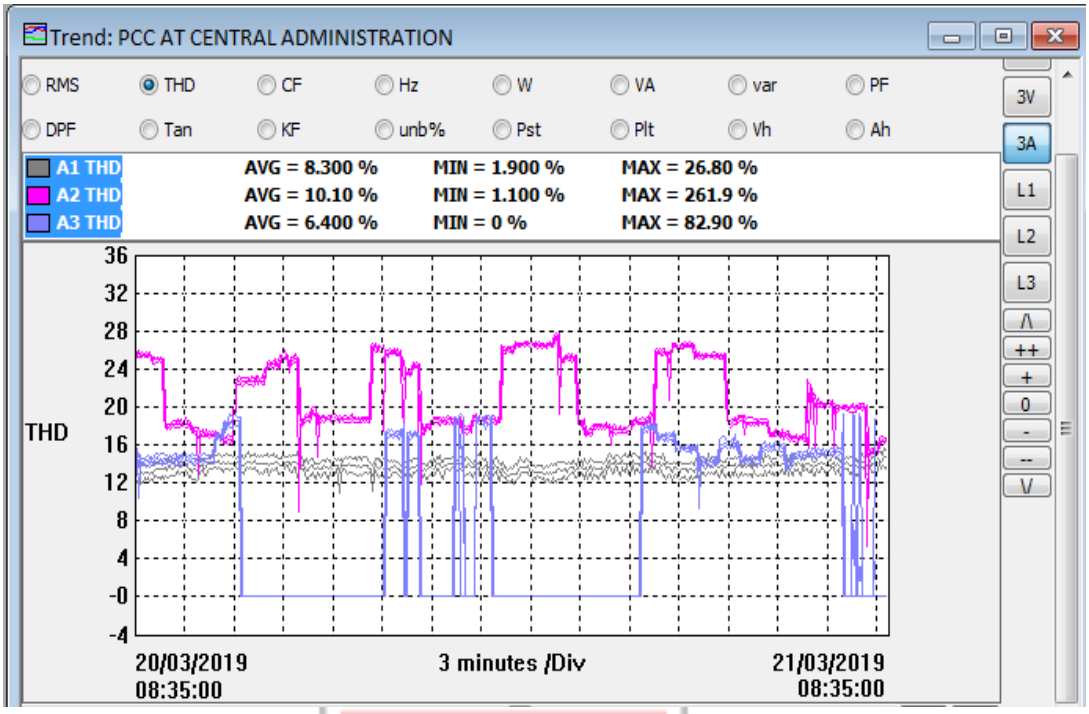

Fig. C77 Waveforms of THD_I at the Central Administration PCC

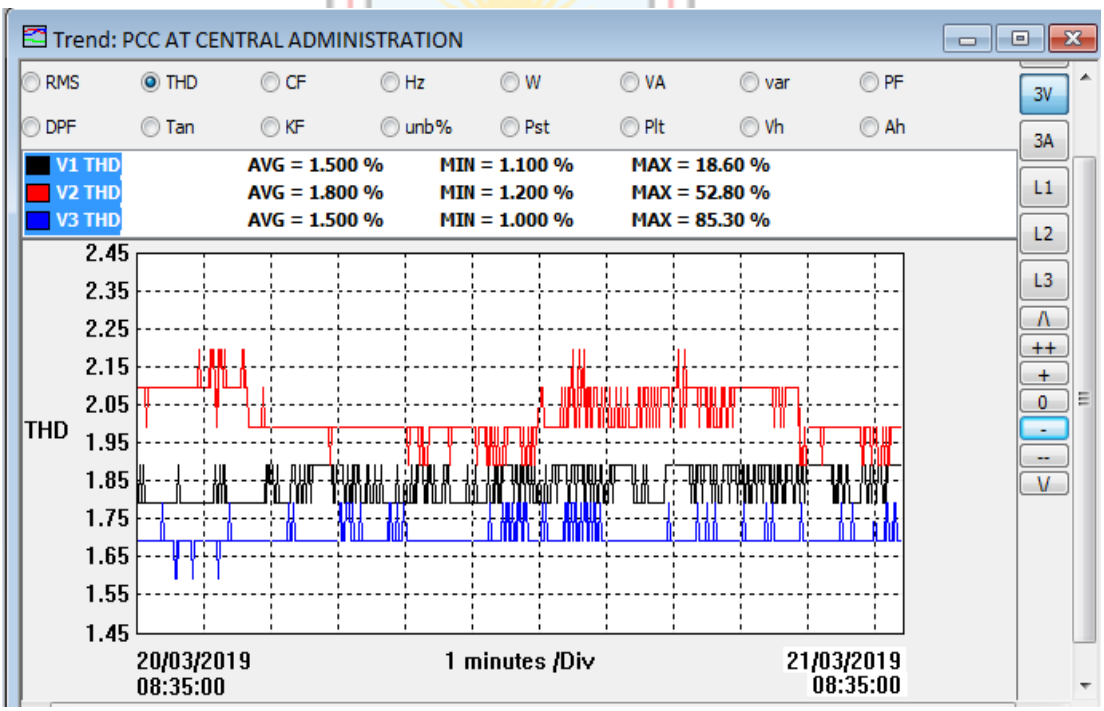

Fig. C78 Waveforms of THD_V at the Central Administration PCC

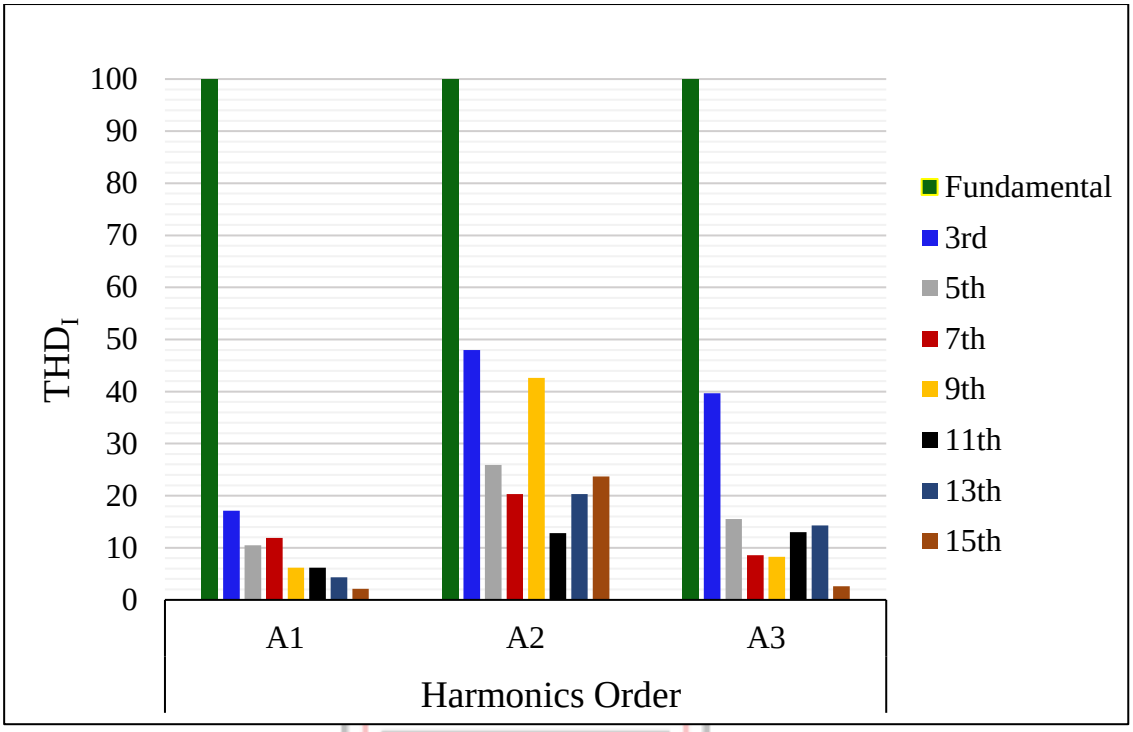

Fig. C79 Harmonic Current Spectrum for Central Administration PCC

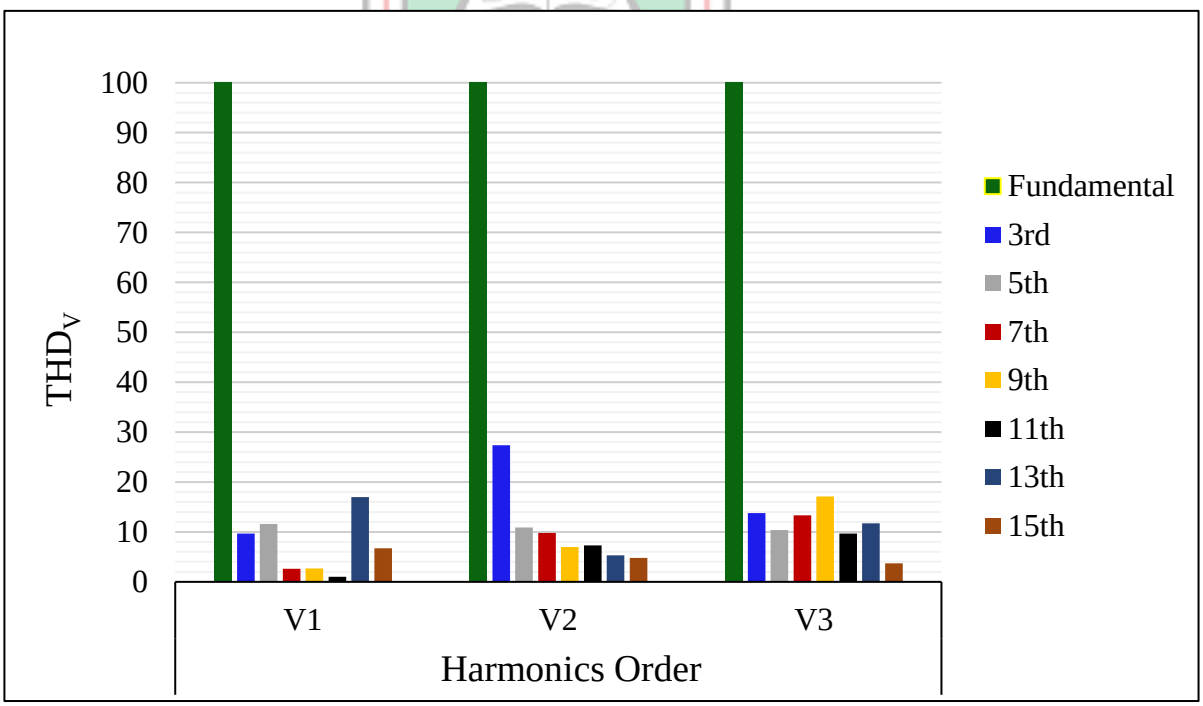

Fig. C80 Harmonic Voltage Spectrum for Central Administration PCC

APPENDIX D

TYPICAL SINGLE LINE DIAGRAMS OF UCC DISTRIBUTION NETWORK MODELLED IN ETAP

APPENDIX E

GENERATED REPORTS OF THE MODELLED COMPONENTS OF UCC DISTRIBUTION NETWORK IN ETAP

Table E1 2-Winding Transformer Input Data

Project:	MSc Thesis	ETAP		Page:	1
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

2-Winding Transformer Input Data

Transformer	Rating					Z Variation			% Tap Setting		Adjusted	Phase Shift	
ID	MVA	Prim. kV	Sec. kV	% Z1	X1/R1	+ 5%	- 5%	% Tol.	Prim.	Sec.	% Z	Type	Angle
ADT Xfmr	1.000	11.000	0.430	5.00	3.50	0	0	0	0	0	5.0000	Dyn	-30.000
ATL Xfmer	1.000	11.000	0.430	5.00	3.50	0	0	0	0	0	5.0000	Dyn	-30.000
CoDE Xfmr	1.000	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	-30.000
Ctrl St. Xfmr	1.000	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	30.000
F.ST. Xfmr	0.050	11.000	0.433	4.00	1.50	0	0	0	0	0	4.0000	Dyn	-30.000
GHHSTLXfmr	0.500	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	30.000
HILLTOP Xfmr	0.630	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	30.000
Lib Xfmr	1.000	11.000	0.430	5.00	3.50	0	0	0	0	0	5.0000	Dyn	-30.000
Nthn Xfmr	0.750	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	30.000
S/M Xfmr	1.000	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	30.000
Sci Co. Xfmr	1.000	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	-30.000
SDS Xfmr	0.200	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	30.000
SOUTHERN Xfmr	0.500	11.000	0.433	4.00	1.50	0	0	0	0	0	4.0000	Dyn	-30.000
SUPR Xfmr	1.000	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	30.000
T-V Xfmr	0.100	11.000	0.433	5.00	3.50	0	0	0	0	0	5.0000	Dyn	30.000
V-T Xfmr	0.500	11.000	0.433	4.00	1.50	0	0	0	0	0	4.0000	Dyn	-30.000
Xfmr1	0.750	11.000	0.433	4.00	1.50	0	0	0	0	0	4.0000	Dyn	30.000

2-Winding Transformer Grounding Input Data

Transformer	Rating			Grounding								
				Conn.	Primary				Secondary			
ID	MVA	Prim. kV	Sec. kV	Type	Type	kV	Amp	ohm	Type	kV	Amp	ohm
ADT Xfmr	1.000	11.000	0.430	D/Y					Solid			
ATL Xfmer	1.000	11.000	0.430	D/Y					Solid			
CoDE Xfmr	1.000	11.000	0.433	D/Y					Solid			
Ctrl St. Xfmr	1.000	11.000	0.433	D/Y					Solid			
F.ST. Xfmr	0.050	11.000	0.433	D/Y					Solid			
GHHSTLXfmr	0.500	11.000	0.433	D/Y					Solid			
HILLTOP Xfmr	0.630	11.000	0.433	D/Y					Solid			
Lib Xfmr	1.000	11.000	0.430	D/Y					Solid			
Nthn Xfmr	0.750	11.000	0.433	D/Y					Solid			
S/M Xfmr	1.000	11.000	0.433	D/Y					Solid			

Table E1 Cont'd

Project:	MSc Thesis	ETAP		Page:	2
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

2-Winding Transformer Grounding Input Data

Transformer	Rating			Grounding								
				Conn.	Primary				Secondary			
ID	MVA	Prim. kV	Sec. kV	Type	Type	kV	Amp	ohm	Type	kV	Amp	ohm
Sci Co. Xfmr	1.000	11.000	0.433	D/Y					Solid			
SDS Xfmr	0.200	11.000	0.433	D/Y					Solid			
SOUTHERN Xfmr	0.500	11.000	0.433	D/Y					Solid			
SUPR Xfmr	1.000	11.000	0.433	D/Y					Solid			
T-V Xfmr	0.100	11.000	0.433	D/Y					Solid			
V-T Xfmr	0.500	11.000	0.433	D/Y					Solid			
Xfmr1	0.750	11.000	0.433	D/Y					Solid			

Table E2 Branch Connections

Project:	MSc Thesis	ETAP		Page:	1
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

Branch Connections

CKT/Branch		Connected Bus ID		% Positive Sequence Impedance (100 MVA Base)			
ID	Type	From Bus	To Bus	R	X	Z	Y
ADT Xfmr	2W XFMR	AUDITORIUM	AUDITORIUM PCC	137.36	480.76	500.00	
ATL Xfmer	2W XFMR	ATLANTIC	ATLANTIC PCC	137.36	480.76	500.00	
CoDE Xfmr	2W XFMR	CoDE	CoDE PCC	137.36	480.76	500.00	
Ctrl St. Xfmr	2W XFMR	POWER DISTRIBUTION CENTER	CTRL ST. PCC	137.36	480.76	500.00	
F.ST. Xfmr	2W XFMR	FILLING STATION	FILLG.ST PCC	4437.60	6656.40	8000.00	
GHHSTLXfmr	2W XFMR	GHANA HOSTEL	GH HOSTEL PCC	274.72	961.52	1000.00	
HILLTOP Xfmr	2W XFMR	HILLTOP	HILLTOP PCC	218.03	763.11	793.65	
Lib Xfmr	2W XFMR	LIBRARY	LIBRARY PCC	137.36	480.76	500.00	
Nthn Xfmr	2W XFMR	NORTHERN	NORTHERN PCC	183.15	641.02	666.67	
S/M Xfmr	2W XFMR	SRC/MEDICAL	SRC/M PCC	137.36	480.76	500.00	
Sci Co. Xfmr	2W XFMR	SCIENCE CO. SUBSTATION1	SCI-COMPLEX PCC	137.36	480.76	500.00	
SDS Xfmr	2W XFMR	SDS	SDS PCC	686.80	2403.81	2500.00	
SOUTHERN Xfmr	2W XFMR	SOUTHERN	SOUTHERN PCC	443.76	665.64	800.00	
SUPR Xfmr	2W XFMR	SUPERANNUATION	SUPR PCC	137.36	480.76	500.00	
T-V Xfmr	2W XFMR	TECH VILLAGE	TECH VILLAGE PCC	1373.61	4807.62	5000.00	
V-T Xfmr	2W XFMR	VALCO-TRUST	VALCO TRUST PCC	443.76	665.64	800.00	
Xfmr1	2W XFMR	CASFORD	CASFORD PCC	295.84	443.76	533.33	
U/G 1	Cable	CASFORD	GHANA HOSTEL	7.77	5.92	9.77	0.0125873
U/G 4	Cable	GHANA HOSTEL	NORTHERN	31.08	23.70	39.08	0.0503491
U/G 5	Cable	NORTHERN	TECH VILLAGE	15.54	11.85	19.54	0.0251745
U/G 6	Cable	SUPERANNUATION	TECH VILLAGE	27.19	20.74	34.20	0.0440554
U/G 7	Cable	SRC/MEDICAL	SUPERANNUATION	4.74	3.61	5.96	0.0076732
U/G 8	Cable	NORTHERN	CoDE	6.66	5.08	8.37	0.0107891
U/G 9	Cable	CoDE	SDS	6.44	4.91	8.10	0.0104295
U/G 10	Cable	AUDITORIUM	LIBRARY	32.90	15.23	36.26	
U/G 11	Cable	SDS	LIBRARY	1.11	0.85	1.40	0.0017982
U/G 13	Cable	SCIENCE CO. SUBSTATION1	AUDITORIUM	2.22	1.69	2.79	0.0035964
U/G 14	Cable	VALCO-TRUST	SDS	2.33	1.78	2.93	0.0037762
U/G 15	Cable	POWER DISTRIBUTION CENTER	FILLING STATION	10.88	8.29	13.68	0.0176222
U/G 16	Cable	SOUTHERN	HILLTOP	2.00	1.52	2.51	0.0032367
U/G 17	Cable	CASFORD	SCIENCE CO. SUBSTATION1	11.65	8.89	14.66	0.0188809
U/G X	Cable	HILLTOP	ATLANTIC	8.88	6.77	11.17	0.0143855
U/G Y	Cable	FILLING STATION	SOUTHERN	4.16	3.17	5.23	0.0067432
U/G Z	Cable	POWER DISTRIBUTION CENTER	CASFORD	3.44	2.62	4.33	0.0055744

Table E3 Harmonic Library

Project:	MSc Thesis	ETAP		Page:	1
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

Harmonic Library

Current Harmonic Source in %

Manufacturer: Typical-IEEE
Model: XFMR Magnet

Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %
1.00	50.00	100.00	**3.00**	150.00	50.00	**5.00**	250.00	20.00	**7.00**	350.00	5.00	**9.00**	450.00	2.60			

Manufacturer: Typical-IEEE
Model: Fluorecent

Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %
1.00	50.00	100.00	**3.00**	150.00	20.00	**5.00**	250.00	10.00	**7.00**	350.00	5.00						

Manufacturer: Typical-IEEE
Model: 6 Pulse1

Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %	Order	Freq. Hz	Mag. %
1.00	50.00	100.00	**5.00**	250.00	20.00	**7.00**	350.00	14.30	**11.00**	550.00	9.10	**13.00**	650.00	7.70	**17.00**	850.00	5.90
19.00	950.00	5.30	**23.00**	1150.00	4.30	**25.00**	1250.00	4.00	**29.00**	1450.00	3.40	**31.00**	1550.00	3.20	**35.00**	1750.00	2.80
37.00	1850.00	2.70	**41.00**	2050.00	2.40	**43.00**	2150.00	2.30	**47.00**	2350.00	2.10	**49.00**	2450.00	2.00			

Table E4 Bus Input Data

Project:	MSc Thesis	ETAP		Page:	1
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

Bus Input Data

Bus			Initial Voltage		Load								% Limits	
					Constant kVA		Constant Z		Constant I		Generic			
ID	kV	Sub-sys	% Mag.	Ang.	MW	Mvar	MW	Mvar	MW	Mvar	MW	Mvar	VTHD	VIHD
ATLANTIC	11.000	1	100.0	0.0									0.00	0.00
ATLANTIC PCC	0.433	1	100.0	30.0	0.097	0.041	0.378	0.021					5.00	3.00
AUDITORIUM	11.000	1	100.0	0.0									0.00	0.00
AUDITORIUM PCC	0.433	1	100.0	30.0	0.150	0.075	0.419	0.048					5.00	3.00
CASFORD	11.000	1	100.0	0.0									5.00	3.00
CASFORD PCC	0.433	1	100.0	-30.0	0.272	0.168	0.278	0.121					5.00	3.00
CoDE	11.000	1	100.0	0.0									0.00	0.00
CoDE PCC	0.433	1	100.0	30.0	0.322	0.200	0.382	0.160					5.00	3.00
CTRL ST. PCC	0.433	1	100.0	-30.0	0.306	0.190	0.454	0.186					5.00	3.00
FILLG ST PCC	0.433	1	100.0	30.0			0.052	0.025					5.00	3.00
FILLING STATION	11.000	1	100.0	0.0									0.00	0.00
GH HOSTEL PCC	0.433	1	100.0	-30.0	0.306	0.190	0.454	0.186					5.00	3.00
GHANA HOSTEL	11.000	1	100.0	0.0									5.00	3.00
HILLTOP	11.000	1	100.0	0.0									0.00	0.00
HILLTOP PCC	0.433	1	100.0	-30.0	0.136	0.084	0.411	0.160					5.00	3.00
LIBRARY	11.000	1	100.0	0.0									0.00	0.00
LIBRARY PCC	0.433	1	100.0	30.0	0.341	0.212	0.440	0.237					5.00	3.00
NORTHERN	11.000	1	100.0	0.0									5.00	3.00
NORTHERN PCC	0.433	1	100.0	-30.0	0.272	0.169	0.395	0.186					5.00	3.00
POWER DISTRIBUTION CENTER	11.000	1	100.0	0.0									5.00	3.00
SCI-COMPLEX PCC	0.433	1	100.0	30.0	0.306	0.190	0.454	0.186					5.00	3.00
SCIENCE CO. SUBSTATION1	11.000	1	100.0	0.0									10.00	10.00
SDS	11.000	1	100.0	0.0									0.00	0.00
SDS PCC	0.433	1	100.0	-30.0	0.102	0.063	0.234	0.172					5.00	3.00
SOUTHERN	11.000	1	100.0	0.0									0.00	0.00
SOUTHERN PCC	0.433	1	100.0	30.0			0.355	0.006					5.00	3.00
SRC/M PCC	0.433	1	100.0	-30.0	0.272	0.169	0.445	0.181					5.00	3.00
SRC/MEDICAL	11.000	1	100.0	0.0									0.00	0.00
SUPERANNUATION	11.000	1	100.0	0.0									0.00	0.00
SUPR PCC	0.433	1	100.0	-30.0	0.306	0.190	0.454	0.186					5.00	3.00
TECH VILLAGE	11.000	1	100.0	0.0									5.00	1.50
TECH VILLAGE PCC	0.433	1	100.0	-30.0	0.136	0.084	0.411	0.160					5.00	3.00
VALCO TRUST PCC	0.433	1	100.0	30.0	0.306	0.190	0.454	0.186					5.00	3.00

Table E4 Cont'd

Project:	MSc Thesis	ETAP		Page:	2
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

Bus			Initial Voltage		Load								% Limits	
					Constant kVA		Constant Z		Constant I		Generic			
ID	kV	Sub-sys	% Mag.	Ang.	MW	Mvar	MW	Mvar	MW	Mvar	MW	Mvar	VTHD	VIHD
VALCO-TRUST	11.000	1	100.0	0.0									0.00	0.00
Total Number of Buses: 34					3.630	2.213	6.467	2.407	0.000	0.000	0.000	0.000		

Generation Bus				Voltage		Generation			Mvar Limits	
ID	kV	Type	Sub-sys	% Mag.	Angle	MW	Mvar	% PF	Max	Min
POWER DISTRIBUTION CENTER	11.000	Swing	1	100.0	0.0					
						0.000	0.000			

Table E5 Cable Input Data

Project:	MSc Thesis	ETAP		Page:	1
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

Cable Input Data

Cable	ohms or mhos / 1000 ft per Conductor											
			Length									
ID	Library	Size	Adj. (ft)	% Tol.	#/Phase	T (°C)	R1	X1	Y1	R0	X0	Y0
U/G 1	11NCUS3	185	2526.2	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 4	11NCUS3	185	10105.0	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 5	11NCUS3	185	5052.5	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 6	11NCUS3	185	8841.9	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 7	11NCUS3	185	1540.0	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 8	11NCUS3	185	2165.4	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 9	11NCUS3	185	2093.2	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 10	11NALS3	185	6496.1	10.0	1	75	0.061280	0.028377		0.097435	0.072077	
U/G 11	11NCUS3	185	360.9	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 13	11NCUS3	185	721.8	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 14	11NCUS3	185	757.9	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 15	11NCUS3	185	3536.7	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 16	11NCUS3	185	649.6	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G 17	11NCUS3	185	3789.4	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G X	11NCUS3	185	2887.1	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G Y	11NCUS3	185	1353.3	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	
U/G Z	11NCUS3	185	1118.8	10.0	1	75	0.037211	0.028377	0.0000412	0.059165	0.072076	

Cable resistances are listed at the specified temperatures.

Table E6 Filter Input Data

Project:	MSc Thesis	ETAP		Page:	1
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

Filter Input Data

Filter Type: Single-Tuned

Filter	Connected Bus	Capacitor C1			Inductor L1			R
ID	ID	kV	Max kV	kvar	Xl	Q Fact.	Max I	Ohm
3HF	TECH VILLAGE PCC	0.433	0.629	118.1	0.068600	50.00	200.0	40.0000
3HF3	GH HOSTEL PCC	0.433	0.526	90.8	0.0892000	50.00	200.0	50.0000
3rdHF	HILLTOP PCC	0.433	0.628	123.5	0.1805000	50.00	200.0	80.0000
5HF15	LIBRARY PCC	0.433	0.472	128.4	0.167800	50.00	180.0	40.0000
5HF55	HILLTOP PCC	0.433	0.589	127.2	0.063700	50.00	180.0	50.0000
ADT HF	AUDITORIUM PCC	0.433	0.472	181.7	0.1186000	50.00	200.0	40.0000
F.ST HF	FILLG.ST PCC	0.433	0.466	98.1	0.2152000	50.00	200.0	50.0000
HF2	CTRL ST. PCC	0.433	0.687	99.9	0.0811000	50.00	200.0	40.0000
HF3	SUPR PCC	0.433	0.659	136.2	0.0304000	50.00	200.0	50.0000
HF4	CASFORD PCC	0.433	0.687	145.3	0.0285000	50.00	200.0	40.0000
HF7	CoDE PCC	0.433	0.547	118.1	0.1825000	50.00	180.0	50.0000
HF10	CTRL ST. PCC	0.433	0.588	81.7	0.2635000	50.00	180.0	40.0000
HF11	SRC/M PCC	0.433	0.547	45.4	0.1784000	50.00	180.0	40.0000
HF16	NORTHERN PCC	0.433	0.674	126.0	0.032800	50.00	180.0	40.0000
HF17	SCI-COMPLEX PCC	0.433	0.658	136.2	0.1581000	50.00	180.0	40.0000
HF19	VALCO TRUST PCC	0.433	0.692	145.3	0.1482000	50.00	200.0	50.0000
HF21	SDS PCC	0.433	0.539	118.1	0.1825000	50.00	200.0	50.0000
HF23	SDS PCC	0.433	0.645	118.1	0.1825000	50.00	180.0	40.0000
HF28	NORTHERN PCC	0.433	0.614	118.1	0.068600	50.00	180.0	60.0000
HF29	NORTHERN PCC	0.433	0.579	118.1	0.1825000	50.00	200.0	30.0000
HF30	SUPR PCC	0.433	0.549	90.8	0.0892000	50.00	200.0	32.0000
HF32	SRC/M PCC	0.433	0.429	45.4	0.4744000	50.00	180.0	41.0000
HF35	TECH VILLAGE PCC	0.433	0.489	99.9	0.2156000	50.00	180.0	80.0000
HF37	GH HOSTEL PCC	0.433	0.527	118.1	0.1825000	50.00	200.0	40.0000
LIB HF4	ATLANTIC PCC	0.433	0.466	90.8	0.2372000	50.00	200.0	50.0000
STHN HF	SOUTHERN PCC	0.433	0.492	181.7	0.1186000	50.00	150.0	40.0000

Table E7 Harmonic Source from Library

Project:	MSc Thesis	ETAP		Page:	1
Location:		16.0.0C		Date:	17-03-2020
Contract:				SN:	4359168
Engineer:		Study Case:	Harmonic Analysis on UCC Dist. Network	Revision:	Base
Filename:	UCC Distribution Network			Config.:	Normal

Harmonic Source from Library

Harmonic Source Information

Bus ID	Device ID	Type	Manufacturer	Model	Fund. Freq.	Mod. Freq.
LIBRARY PCC	Load8	Current	Typical-IEEE	Fluorecent	0.00	0.00
NORTHERN PCC	Loads28	Current	Typical-IEEE	6 Pulse1	0.00	0.00
POWER DISTRIBUTION CENTER	Ctrl St. Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
CTRL ST. PCC	Ctrl St. Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
GHANA HOSTEL	GHHSTLXfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
GH HOSTEL PCC	GHHSTLXfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
HILLTOP	HILLTOP Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
HILLTOP PCC	HILLTOP Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
NORTHERN	Nthn Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
NORTHERN PCC	Nthn Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
SRC/MEDICAL	S/M Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
SRC/M PCC	S/M Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
SDS	SDS Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
SDS PCC	SDS Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
SUPERANNUATION	SUPR Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
SUPR PCC	SUPR Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
TECH VILLAGE	T-V Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00
TECH VILLAGE PCC	T-V Xfmr	Current	Typical-IEEE	XFMR Magnet	0.00	0.00

APPENDIX F

SAVINGS CALCULATIONS FROM MONTHLY ELECTRICITY SLT BILL FOR UNIVERSITY CAPE COAST

Table F1 Summary of Registered Power Components of Monthly Electricity SLT Bill for UCC in 2018

Month	Active Energy Consumed (kWh)	Apparent Energy Consumed (kVAh)	Maximum Demand (kVA)	Displacement Power Factor (DPF)	Distortion Power Factor (δPF)	True Power Factor (TPF)
Jan	537688.04	551532.06	1828.61	0.975	0.962	0.938
Feb	768095.99	779451.94	2062.97	0.985	0.952	0.938
Mar	868866.04	880646.00	2201.32	0.987	0.952	0.939
Apr	796263.51	805350.12	2239.79	0.989	0.951	0.940
May	799429.86	808357.06	2172.92	0.989	0.952	0.941
Jun	556301.35	565917.47	1571.94	0.983	0.958	0.942
July	567191.02	575525.99	1441.84	0.986	0.956	0.942
Aug	507380.40	517880.25	1381.44	0.980	0.962	0.943
Sept	668336.65	678986.53	1770.55	0.984	0.958	0.943
Oct	798548.15	807714.61	1981.81	0.989	0.955	0.944
Nov	854194.12	862575.7	2087.61	0.990	0.954	0.945
Dec	718707.00	728540.00	1835.00	0.987	0.959	0.946

Table F2 Calculated Consumption Elements of Monthly Electricity Bill for UCC in 2018

Month	Energy Charge (GH¢)		Calculated Reactive Energy ($kVArh_1$)	New True Power Factor (New TPF)	$kVAh_2$	kVArh2	$kVArh_{(diff)}$ ($kVArh^1$-$kVArh^2$)
	@ 0.7809	@ 0.5857					
Jan	419 880.59	-	122797.33	0.978	525866.31	114650.35	8146.99
Feb	599 806.16	-	132566.5	0.989	759323.80	117090.52	15475.98
Mar	678 497.49	-	143558.98	0.990	859982.55	125208.42	18350.57
Apr	-	466 371.54	120636.8	0.992	789794.78	102120.19	18516.61
May	-	468 226.07	119804.15	0.992	793127.22	100982.54	18821.62
Jun	-	325 825.70	103881.62	0.986	548595.81	93566.44	10315.18
July	-	332 203.78	97593.61	0.989	560762.69	86128.11	11465.49
Aug	-	297 172.70	103754.92	0.983	498681.64	95181.22	8573.7
Sept	-	391 444.78	119786.6	0.988	659955.66	106850.15	12936.46
Oct	-	467 709.65	121341.43	0.992	792008.12	102833.77	18507.67
Nov	-	500 301.50	119955.17	0.993	848596.61	98272.77	21682.41
Dec	-	420 946.69	119292.83	0.990	711271.99	104188.97	15103.86

Table F3 Calculated Energy Savings from Monthly Electricity Bill for UCC in 2018

Month	New True Power Factor (New TPF)	kVArh(diff) Converted To kWh for Costing	Energy Charge (GH¢)	
			@ 0.7809	@ 0.5857
Jan	0.978	38207.79	29 836.47	-
Feb	0.989	101520.11	79 277.05	-
Mar	0.990	127341.17	99 440.72	-
Apr	0.992	144379.87	-	84 563.29
May	0.992	149001.64	-	87 270.26
Jun	0.986	61329.12	-	35 920.46
July	0.989	75505.25	-	44 223.43
Aug	0.983	45703.64	-	26 768.62
Sept	0.988	80916.21	-	47 392.62
Oct	0.992	143719.95	-	84 176.77
Nov	0.993	188465.06	-	110 383.99
Dec	0.990	104188.11	-	61 022.97
Annual Cost Savings for 2018 (GH¢)			**790 276.65**	

Table F4 Summary of Registered Power Components of Monthly Electricity SLT Bill for UCC in 2019

Month	Active Energy Consumed (kWh)	Apparent Energy Consumed (kVAh)	Maximum Demand (kVA)	Displacement Power Factor (DPF)	Distortion Power Factor (δPF)	True Power Factor (TPF)
Jan	577460.39	584595.14	2033.85	0.988	0.958	0.946
Feb	813376.11	818741.59	2239.47	0.993	0.953	0.947
Mar	844861.14	851184.39	2230.44	0.993	0.955	0.948
Apr	843848.28	850583.11	2313.42	0.992	0.972	0.964
May	796653.67	804885.57	2233.84	0.990	0.959	0.949
Jun	558641.28	566921.64	760.58	0.985	0.963	0.949
Jul	586764.23	593899.65	1557.00	0.988	0.961	0.950
Aug	503017.21	509480.26	1293.10	0.987	0.962	0.950
Sept	674809.10	680863.58	1793.58	0.991	0.959	0.951
Oct	800255.30	807050.02	1892.57	0.992	0.959	0.951
Nov	847380.62	853754.15	2171.02	0.993	0.959	0.952
Dec	708150.01	715102.42	1862.16	0.990	0.962	0.952

Table F5 Calculated Consumption Elements of Monthly Electricity Bill for UCC in 2019

Month	Energy Charge (GH¢)			Calculated Reactive Energy (kVArh1)	New True Power Factor (New TPF)	$kVAh_2$	$kVArh_2$	$kVArh_{(diff)}$ ($kVArh_1$-$kVArh_2$)
	@ 0.5857	@ 0.7506	@ 0.7952					
Jan	338 218.55	-	-	91054.80	0.991	572235.19	78215.12	12839.67
Feb	476 394.39	-	-	93579.35	0.997	810627.50	67037.88	26541.47
Mar	494 835.17	-	-	103559.26	0.996	841264.14	78211.02	25348.24
Apr	494 241.94	-	-	106825.59	0.995	839841.52	82526.71	24298.88
Jun	327 196.20	-	-	96540.49	0.989	552240.65	85300.18	11240.31
Jul	-	440 425.23	-	91785.25	0.991	581566.73	78622.06	13163.19
Aug	-	377 564.72	-	80893.89	0.991	498222.90	69950.58	10943.31
Sept	-	506 511.71	-	90597.42	0.994	670945.30	72524.37	18073.06
Oct	-	-	636 363.01	104504.50	0.995	796053.08	82335.01	22169.48
Nov	-	-	673 837.07	104126.05	0.996	843741.84	78783.34	25342.71
Dec	-	-	563 120.89	99473.79	0.993	703505.74	81504.38	17969.40

Table F6 Calculated Energy Savings from Monthly Electricity Bill for UCC in 2019

Month	New True Power Factor (New TPF)	kVArh(diff) Converted To kWh for Costing	Energy Charge (GH¢)		
			@ 0.5857	@ 0.7506	@ 0.7952
Jan	0.991	94795.01	55 521.44	-	-
Feb	0.997	322029.79	188 612.85	-	-
Mar	0.996	273820.02	160 376.39	-	-
Apr	0.995	248459.79	145 522.90	-	-
May	0.993	164148.80	96 141.95	-	-
Jun	0.989	73614.19	43 115.83	-	-
Jul	0.991	98238.22	-	73 737.61	-
Aug	0.991	78693.74	-	59 067.52	-
Sept	0.994	168162.28	-	126 222.61	-
Oct	0.995	215476.33	-	-	171 346.78
Nov	0.996	272582.02	-	-	216 757.22
Dec	0.993	156126.98	-	-	124 152.18
Annual Cost Savings for 2019 (GH¢)			**1 460 575.27**		

APPENDIX G

ECONOMIC ANALYSIS OF HAMORNIC MITIGATION

Table G1 Summary of Economic Indicators

Economic Indicator	**Value**
Discount factor (%)	8
Inflation (%)	7.90
Exchange rate (Gh¢ →US$)	5.3323
Cost of Mitigation Equipment (US$)	822,600.00
Annual Projected CF (Gh¢)	1,161,493.71

Table G2 Determination of Net Present Value

Year	**Cash Flow Gh¢**	**Discount Factor**	**Present Value (Gh¢)**	**Payback Period (Gh¢)**
0	- 4,386,349.98	1	- 4,386,349.98	- 4,386,349.98
1	1,161,493.71	0.8628	1,002,151.60	- 3,384,198.38
2	1,161,493.71	0.7444	864,669.20	- 2,519,529.17
3	1,161,493.71	0.6423	746,047.63	- 1,773,481.54
4	1,161,493.71	0.5542	643,699.42	- 1,129,782.12
5	1,161,493.71	0.4782	555,392.08	- 574,390.04
6	1,161,493.71	0.4126	479,199.38	- 95,190.66
7	1,161,493.71	0.3560	413,459.34	318,268.68
8	1,161,493.71	0.3071	356,738.00	675,006.68
9	1,161,493.71	0.2650	307,798.10	982,804.78
10	1,161,493.71	0.2286	265,572.13	1,248,376.92
11	1,161,493.71	0.1973	229,139.03	1,477,515.94
12	1,161,493.71	0.1702	197,704.08	1,675,220.02
13	1,161,493.71	0.1469	170,581.60	1,845,801.63
14	1,161,493.71	0.1267	147,179.99	1,992,981.61
15	1,161,493.71	0.1093	126,988.77	2,119,970.39
16	1,161,493.71	0.0943	109,567.53	2,229,537.92

Table G2 Cont'd

Year	Cash Flow Gh¢	Discount Factor	Present Value (Gh¢)	Payback Period (Gh¢)
17	1,161,493.71	0.0814	94,536.27	2,324,074.19
18	1,161,493.71	0.0702	81,567.10	2,405,641.29
19	1,161,493.71	0.0606	70,377.13	2,476,018.42
20	1,161,493.71	0.0523	60,722.29	2,536,740.71
21	1,161,493.71	0.0451	52,391.97	2,589,132.68
22	1,161,493.71	0.0389	45,204.46	2,634,337.14
23	1,161,493.71	0.0336	39,002.98	2,673,340.12
24	1,161,493.71	0.0290	33,652.27	2,706,992.39
25	1,161,493.71	0.0250	29,035.61	2,736,028.00
			NPV	**2,736,028.00**

Table G3 Tabulation of Cost PVs

Year	Cost of Equipment (Gh¢)	Present Value (Gh¢)
0	4,386,349.98	4,386,349.98
1	-	-
2	-	-
3	-	-
4	-	-
5	-	-
6	-	-
7	-	-
8	-	-
9	-	-
10	-	-
11	-	-
12	-	-
13	-	-
14	-	-
15	-	-
16	-	-
17	-	-
18	-	-
19	-	-
20	-	-
21	-	-
22	-	-
23	-	-
24	-	-
25	-	-
	∑ Cost PVs (Gh¢)	**4,386,349.98**

Table G4 Tabulation of Benefit PVs

Year	Benefits	Present Value
0	-	-
1	1,161,493.71	1,002,151.60
2	1,161,493.71	864,669.20
3	1,161,493.71	746,047.63
4	1,161,493.71	643,699.42
5	1,161,493.71	555,392.08
6	1,161,493.71	479,199.38
7	1,161,493.71	413,459.34
8	1,161,493.71	356,738.00
9	1,161,493.71	307,798.10
10	1,161,493.71	265,572.13
11	1,161,493.71	229,139.03
12	1,161,493.71	197,704.08
13	1,161,493.71	170,581.60
14	1,161,493.71	147,179.99
15	1,161,493.71	126,988.77
16	1,161,493.71	109,567.53
17	1,161,493.71	94,536.27
18	1,161,493.71	81,567.10
19	1,161,493.71	70,377.13
20	1,161,493.71	60,722.29
21	1,161,493.71	52,391.97
22	1,161,493.71	45,204.46
23	1,161,493.71	39,002.98
24	1,161,493.71	33,652.27
25	1,161,493.71	29,035.61
	∑ Benefit PVs (Gh¢)	**7,122,377.98**

Table G5 Determination of NPV Using 10% Worse Assumption

Year	Cash flow Gh¢	Discount Factor	Present Value Gh¢	Payback Period Gh¢
0	- 5,307,483.48	1	- 5,307,483.48	- 5,307,483.48
1	1,045,344.34	0.8511	889,730.48	- 4,417,753.00
2	1,045,344.34	0.7244	757,281.88	- 3,660,471.12
3	1,045,344.34	0.6166	644,550.07	- 3,015,921.05
4	1,045,344.34	0.5248	548,599.94	- 2,467,321.11
5	1,045,344.34	0.4467	466,933.31	- 2,000,387.80
6	1,045,344.34	0.3802	397,423.87	- 1,602,963.93
7	1,045,344.34	0.3236	338,261.87	- 1,264,702.06
8	1,045,344.34	0.2754	287,906.95	- 976,795.12
9	1,045,344.34	0.2344	245,048.04	- 731,747.07
10	1,045,344.34	0.1995	208,569.28	- 523,177.80
11	1,045,344.34	0.1698	177,520.87	- 345,656.92
12	1,045,344.34	0.1445	151,094.45	- 194,562.47
13	1,045,344.34	0.1230	128,601.97	- 65,960.50
14	1,045,344.34	0.1047	109,457.80	43,497.30
15	1,045,344.34	0.0891	93,163.50	136,660.81
16	1,045,344.34	0.0759	79,294.84	215,955.64
17	1,045,344.34	0.0646	67,490.71	283,446.36
18	1,045,344.34	0.0550	57,443.79	340,890.15
19	1,045,344.34	0.0468	48,892.49	389,782.64
20	1,045,344.34	0.0398	41,614.18	431,396.82
21	1,045,344.34	0.0339	35,419.33	466,816.15
22	1,045,344.34	0.0288	30,146.68	496,962.83
23	1,045,344.34	0.0245	25,658.93	522,621.76
24	1,045,344.34	0.0209	21,839.25	544,461.01
25	1,045,344.34	0.0178	18,588.18	563,049.19
	NPV		**563,049.19**	

Table G6 Summary of Sensitivity Analysis Result

Economic Indicator	Forecast	Assumption (10% worse)	Change (%)
Cost of Investment	822,600.00	904,860.00	10
Annual Project CF	1,161,493.71	1,045,344.34	-10
Exchange Rate (Gh¢→US$)	5.3323	5.8655	10
Inflation (%)	7.9	8.69	10
Discount Factor (%)	8	8.80	10
NPV (Gh¢)	2,736,028.00	563,049.19	-79.42
Discounted Payback Period	6.23 Years	13.6 Years	7.73 Years